Open Applied Science
https://openappscience.science

Land Tenure Documentation and Community Mapping Drones across Informal Settlements

Kevin Flores*

Department of Physical Therapy, College of Engineering, Boston University, Boston, Massachusetts, USA

Corresponding author: kevin.flores@gmail.com

Abstract

The rapid expansion of informal settlements globally presents a profound challenge to urban governance, particularly regarding land tenure security and infrastructural planning. In recent years, community mapping initiatives utilizing unmanned aerial vehicles have emerged as a prominent methodological alternative to conventional land surveying, offering high-resolution geospatial data at unprecedented speeds. However, the environmental sustainability of deploying these technologies in resource-constrained environments remains largely unexamined. This paper presents a comprehensive lifecycle assessment of linking community mapping drones to formal land tenure documentation processes in informal settlements. By evaluating the environmental impacts from raw material extraction and drone manufacturing to operational deployment, data processing, and end-of-life disposal, this study provides empirical evidence on the ecological footprint of participatory geospatial technologies. The analysis reveals that while the operational phase of drone mapping contributes minimally to global warming potential, the manufacturing of drone components, particularly lithium-polymer batteries and specialized optical sensors, introduces significant abiotic depletion and ecotoxicity impacts. Furthermore, the computationally intensive data processing required for orthomosaic generation accounts for a substantial proportion of the total energy demand. The findings suggest that while drone-mediated land tenure documentation significantly enhances socio-economic security for marginalized communities, optimizing battery recycling frameworks and utilizing decentralized renewable energy for data processing are essential to mitigate the associated environmental burdens.

Keywords: Land Tenure; Unmanned Aerial Vehicles; Lifecycle Assessment; Informal Settlements; Community Mapping

1. Introduction

1.1 The Challenge of Informal Settlements

The proliferation of informal settlements is one of the most defining characteristics of contemporary global urbanization, particularly in the global south. Millions of individuals currently reside in areas characterized by precarious housing conditions, inadequate access to basic municipal services, and, most critically, a severe lack of formal land tenure. Without official recognition of property rights, residents of informal settlements face pervasive threats of arbitrary eviction, exploitation, and marginalization from formal economic systems [1]. The absence of documented land tenure not only stifles individual economic mobility but also significantly impedes municipal authorities from implementing effective urban upgrading strategies, disaster risk reduction measures, and infrastructure deployment. Historically, conventional land surveying and cadastral mapping have been prohibitively expensive, time-consuming, and logistically complex to execute within the dense, unstructured morphology of informal urban spaces. Traditional surveying methods require significant institutional capacity, substantial financial investment, and specialized technical expertise, which are often lacking in the municipal governance structures of developing nations [2]. Consequently, millions of urban dwellers remain invisible to state apparatuses, perpetuating cycles of poverty and spatial inequality. The urgent need for innovative, scalable, and cost-effective methods to document spatial relationships and secure land rights has catalyzed the exploration of alternative geospatial technologies that can be deployed directly by or in close collaboration with the affected communities.

1.2 Drones as a Mapping Modality

In response to the limitations of traditional cadastral surveying, the integration of unmanned aerial vehicles, commonly referred to as drones, into community mapping initiatives has gained considerable traction. Drones equipped with high-resolution optical sensors can rapidly capture overlapping aerial photographs of complex urban topographies at a fraction of the cost and time required by terrestrial surveying teams [3]. Through the application of photogrammetry software, these images are processed to generate highly accurate orthomosaic maps and digital elevation models. What distinguishes community drone mapping from conventional top-down technological interventions is the participatory nature of the data collection process. Local residents are often trained to pilot the drones, identify community boundaries, and validate the resulting maps, thereby fostering a sense of ownership and empowerment over the spatial data generated [4]. This democratization of spatial information is a critical step toward advocating for formal land tenure, as community-generated maps provide empirical, visually compelling evidence of historical occupation and socio-spatial organization. Furthermore, the high spatial resolution achieved by low-altitude drone flights allows for the precise delineation of individual housing plots, communal infrastructure, and environmental hazard zones, which are often indistinguishable in commercially available satellite imagery. By linking these grassroots geospatial datasets to formal governmental documentation processes, municipalities can accelerate the regularization of informal settlements and integrate marginalized populations into the formal urban fabric [5].

1.3 Environmental and Lifecycle Considerations

Despite the undeniable socio-economic benefits associated with drone-mediated land tenure documentation, the environmental implications of widespread drone deployment in community mapping initiatives remain a critical yet underexplored domain. The discourse surrounding spatial technologies for social good often implicitly assumes that the environmental footprint of these interventions is negligible compared to their societal impact. However, the lifecycle of unmanned aerial vehicles encompasses material-intensive manufacturing processes, continuous energy consumption during operation and data processing, and complex waste management challenges at the end of their functional lifespan [6]. The production of drone frames, microprocessors, and lithium-polymer batteries involves the extraction and refinement of rare earth elements and heavy metals, contributing to localized ecological degradation and abiotic resource depletion. Furthermore, the computational demands of photogrammetric processing require significant electrical energy, which may be sourced from carbon-intensive power grids. To comprehensively evaluate the sustainability of this technological intervention, it is imperative to apply a rigorous lifecycle assessment framework that quantifies the environmental burdens across all phases of the drone mapping ecosystem [7]. This paper addresses this critical research gap by conducting a detailed lifecycle assessment of community drone mapping for land tenure documentation, thereby providing urban planners, policymakers, and environmental practitioners with a holistic understanding of the ecological trade-offs associated with digitizing the informal city.

2. Background and Literature Review

2.1 Land Tenure Documentation Paradigms

The conceptualization and documentation of land tenure have evolved significantly over the past several decades, transitioning from rigid, legally absolute frameworks to more flexible, continuum-based approaches. The traditional cadastral paradigm, rooted in colonial administrative systems, prioritized the precise geometric demarcation of individual, freehold property parcels using highly accurate terrestrial surveying instruments [8]. This approach, while effective in well-planned formal urban environments, proved fundamentally incompatible with the fluid, overlapping, and customary spatial arrangements prevalent in informal settlements. In recognition of this incompatibility, the global development community has increasingly embraced the concept of a continuum of land rights, which acknowledges various forms of legitimate tenure, ranging from perceived security and customary usage to formal freehold titles. The documentation of these diverse tenure arrangements requires mapping modalities that prioritize social consensus, community validation, and speed over absolute geometric perfection. Fit-for-purpose land administration advocates for spatial frameworks that are affordable, scalable, and sufficiently accurate for the specific objective of providing tenure security to vulnerable populations [9]. Within this evolving paradigm, the role of geospatial technology has shifted from a tool of state control and taxation to an instrument of community empowerment and spatial advocacy. By documenting the de facto realities of informal occupation, communities can leverage spatial data to negotiate intermediate forms of tenure, such as certificates of occupancy or communal land trusts, thereby incrementally enhancing their socio-economic resilience against arbitrary eviction.

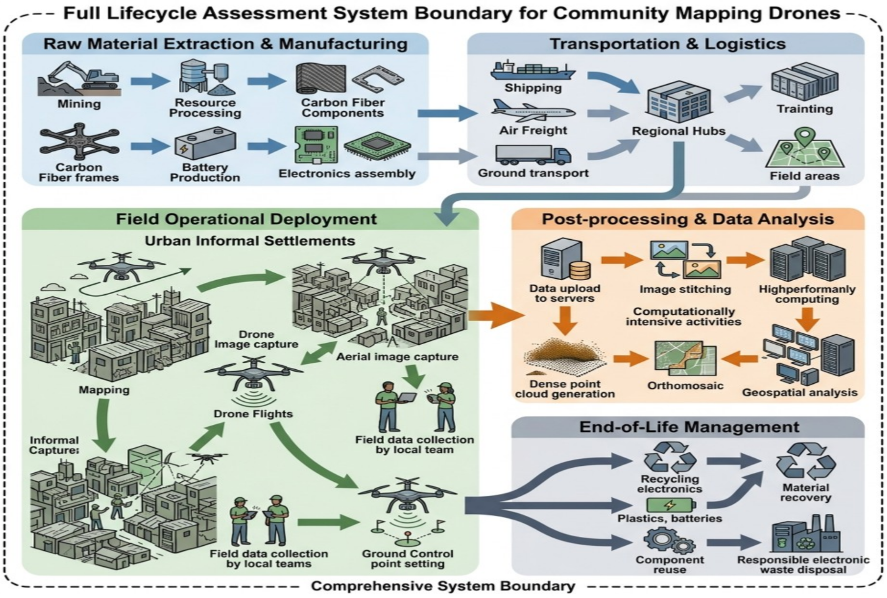

Figure 1: Comprehensive System Boundary for the Lifecycle Assessment of Community Mapping Drones

2.2 Community Mapping and Participatory Geographic Information Systems

The emergence of participatory geographic information systems has fundamentally transformed the dynamics of spatial knowledge production, challenging the historic monopoly of state agencies and professional surveyors over map-making processes. Participatory geographic information systems integrate local, indigenous spatial knowledge with modern geospatial technologies to create maps that reflect the lived realities and priorities of marginalized communities [10]. In the context of informal settlements, community mapping serves as both a technical data collection exercise and a powerful social mobilization tool. Early iterations of community mapping relied on rudimentary techniques, such as sketch mapping or the manual annotation of printed satellite imagery. While these methods were highly participatory, the resulting maps often lacked the geometric accuracy and standardized formatting required for integration into official municipal land registries. The introduction of handheld global positioning system receivers and open-source geographic information system software provided a bridge between local spatial knowledge and formal cartographic standards [11]. However, navigating the dense, labyrinthine alleyways of informal settlements to collect ground-level coordinate data remained incredibly time-consuming and often dangerous due to environmental hazards or localized conflicts. The advent of affordable consumer-grade drones represents the latest evolution in participatory mapping methodologies, combining the high-resolution visualization capabilities of aerial photography with the geometric rigor required for formal land administration, all while minimizing the need for extensive ground-level navigation in challenging urban topographies.

2.3 Lifecycle Assessment Principles in Urban Technologies

Lifecycle assessment is an internationally standardized methodological framework used to quantify the potential environmental impacts associated with a product, process, or service throughout its entire life cycle, from raw material extraction to final disposal. The application of lifecycle assessment to urban technologies provides critical insights into problem-shifting, where the resolution of an environmental or social issue in one phase inadvertently creates negative consequences in another phase or geographic location. In recent years, researchers have increasingly applied lifecycle assessment methodologies to evaluate the sustainability of information and communication technologies, smart city infrastructure, and consumer electronics [12]. However, the environmental evaluation of unmanned aerial vehicles has predominantly focused on their application in commercial delivery logistics and large-scale precision agriculture, with limited attention directed toward their use in socio-spatial interventions such as community mapping. The lifecycle of a community mapping drone involves distinct operational characteristics that differ significantly from commercial delivery operations. For instance, the mapping process requires multiple, systematic flights over a localized area, followed by computationally intensive post-processing of thousands of high-resolution images. Evaluating the sustainability of this socio-technical system requires a comprehensive inventory of material flows, including the complex supply chains of lithium-ion batteries, carbon fiber composites, and optical sensor arrays, as well as the energy matrices utilized during the data processing phase. By integrating lifecycle assessment principles into the discourse on land tenure documentation, this research aims to foster a more nuanced understanding of the ecological implications of technologically mediated social empowerment.

3. Methodology and Analytical Framework

3.1 System Boundary Definition and Functional Unit

The methodological foundation of this lifecycle assessment is structured in accordance with the internationally recognized guidelines for environmental management and assessment. The primary objective is to evaluate and quantify the potential environmental impacts associated with utilizing unmanned aerial vehicles for community mapping and land tenure documentation in informal urban settlements. To ensure comparability and methodological rigor, a clearly defined functional unit must be established. For the purpose of this analysis, the functional unit is defined as the spatial documentation and generation of a high-resolution orthomosaic map for one hectare of a densely populated informal settlement, achieving a ground sampling distance of less than five centimeters per pixel. This functional unit encapsulates not only the physical drone flight but also the requisite pre-flight planning and post-flight data processing necessary to produce a legally recognizable cadastral document.

The system boundary encompasses four primary life cycle stages: manufacturing, transportation, operation and data processing, and end-of-life disposal. The manufacturing phase includes the extraction and refinement of raw materials, the fabrication of drone components such as the airframe, brushless electric motors, lithium-polymer batteries, and specialized optical sensors, as well as the final assembly of the multirotor mapping platform. The transportation phase accounts for the global logistics involved in shipping the assembled drone from the primary manufacturing facilities to the deployment location in the targeted informal settlement. The operational phase encompasses the electrical energy consumed to charge the drone batteries and the remote control systems during the field mapping exercises, as well as the significant computational energy required by photogrammetry software workstations to stitch the aerial images into coherent, geographically referenced orthomosaics. Finally, the end-of-life phase models the disposal, recycling, and electronic waste management scenarios for the drone components upon the conclusion of their operational lifespan. The system boundary explicitly excludes the environmental impacts of the human labor involved in community mobilization, as well as the long-term infrastructural developments that may occur subsequent to the formalization of land tenure, focusing strictly on the direct environmental footprint of the spatial documentation process itself.

Table 1: Lifecycle Inventory Data Parameters per Functional Unit

Lifecycle Phase	Component or Process	Material or Energy Input	Estimated Value per Hectare
Manufacturing	Lithium-Polymer Battery	Cobalt, Lithium, Copper	0.045 kilograms
Manufacturing	Airframe and Propellers	Carbon Fiber,	0.082 kilograms

Lifecycle Phase	Component or Process	Material or Energy Input	Estimated Value per Hectare
		Polycarbonate	
Operation	Drone Flight Energy	Grid Electricity	0.120 kilowatt-hours
Processing	Photogrammetry Rendering	Grid Electricity	2.450 kilowatt-hours
End of Life	Component Recycling	Mechanical and Chemical Processing	0.015 kilowatt-hours

3.2 Data Collection in Informal Settlements

The empirical data underpinning this lifecycle assessment was gathered through a mixed-methods approach, combining primary field observations of community mapping initiatives with secondary data sourced from established environmental lifecycle inventory databases. The operational parameters were documented during a series of participatory mapping campaigns conducted in selected informal settlements. These campaigns utilized commercially available, lightweight quadcopters equipped with high-resolution global positioning system receivers and digital single-lens reflex quality cameras. Detailed logs were maintained to record the duration of each flight, the number of battery cycles required to achieve full spatial coverage of the target area, and the total volume of digital imagery generated. The flight patterns were meticulously planned to ensure sufficient image overlap, a critical requirement for accurate photogrammetric reconstruction in environments characterized by irregular rooflines and dense structural typologies [13].

Simultaneously, the energy consumption of the computational workstations utilized for image processing was continuously monitored using inline wattmeters. The photogrammetric processing pipeline involves computationally intensive tasks, including feature extraction, point cloud generation, meshing, and texture mapping, which heavily load the central processing units and graphics processing units of the computing hardware. The energy data collected from these rendering sessions was normalized against the functional unit of one mapped hectare. For the manufacturing and end-of-life phases, the material composition of the mapping drones was determined through a combination of manufacturer specifications and the systematic disassembly and weighing of a decommissioned unit. The resulting bill of materials was then cross-referenced with established lifecycle inventory databases to extract the relevant environmental emission factors associated with the extraction, processing, and eventual disposal of materials such as aluminum, copper, rare earth magnets, and complex printed circuit boards.

3.3 Inventory Analysis and Impact Categories

The lifecycle inventory phase involves the meticulous quantification of all physical material and energy flows entering and exiting the defined system boundary. This includes accounting for the upstream resource extraction required to produce the specialized electronics that enable autonomous drone flight and high-precision spatial data capture. The inventory model constructed for this analysis pays particular attention to the lithium-polymer batteries, as their lifecycle involves significant quantities of critical minerals and energy-intensive manufacturing processes. Furthermore, due to the high discharge rates required for multirotor flight, these batteries have a relatively short functional lifespan, necessitating frequent replacement and amplifying their overall contribution to the lifecycle impact of the mapping system [14].

Once the material and energy inventory was compiled, the data was translated into potential environmental impacts using a standardized lifecycle impact assessment methodology. The impact categories selected for this study include global warming potential, expressed in kilograms of carbon dioxide equivalents; abiotic depletion potential for elements, which measures the exhaustion of non-renewable mineral resources; human toxicity potential, evaluating the impact of toxic substance emissions on human health; and terrestrial ecotoxicity potential, assessing the detrimental effects of pollutants on land-based ecosystems. These categories provide a comprehensive overview of the multidimensional environmental burdens associated with deploying advanced geospatial technologies for land tenure documentation. The computational energy consumption data was modeled using regional electricity grid mixes, recognizing that the environmental footprint of data processing is highly sensitive to the primary energy sources utilized in the specific geographical context of the informal settlement being mapped.

4. Results and Lifecycle Impact Evaluation

4.1 Material Extraction and Manufacturing Impacts

The results of the lifecycle impact assessment indicate that the manufacturing phase constitutes a significant proportion of the overall environmental burden associated with community drone mapping. The extraction and processing of raw materials for electronic components and battery systems are particularly impactful. The analysis reveals that the abiotic depletion potential is heavily concentrated in this phase, driven by the substantial requirements for gold, copper, and specialized semiconductor materials used in the drone's flight controller, optical sensors, and telecommunication modules. The extraction of these metals involves energy-intensive mining and refining operations that frequently result in severe localized environmental degradation and the release of heavy metals into aquatic systems [15].

The production of the lithium-polymer batteries emerges as a critical hotspot within the manufacturing phase. These energy storage systems require significant quantities of lithium, cobalt, and nickel, materials associated with high toxicity potentials and complex, often geographically constrained supply chains. While the overall mass of the mapping drone is relatively low compared to terrestrial surveying equipment, the high concentration of advanced electronics results in a disproportionately large environmental footprint per unit of weight. Furthermore, the short operational lifespan of the drone batteries, which typically require replacement after several hundred flight cycles due to capacity degradation, necessitates a continuous stream of battery manufacturing to sustain long-term community mapping initiatives. Consequently, while the drone airframe itself exhibits a relatively minor impact, the internal electronics and power systems introduce substantial ecotoxicity and resource depletion concerns that must be acknowledged when scaling these land tenure documentation programs.

Table 2: Environmental Impact Results per Functional Unit

Impact Category	Manufacturing Phase	Operational and Processing Phase	End of Life Phase	Total Impact per Hectare
Global Warming Potential	2.150 kg CO2 eq	1.840 kg CO2 eq	0.210 kg CO2 eq	4.200 kg CO2 eq
Abiotic Depletion (Elements)	0.003 kg Sb eq	0.000 kg Sb eq	-0.001 kg Sb eq	0.002 kg Sb eq
Human Toxicity Potential	1.120 kg 1,4-DB eq	0.450 kg 1,4-DB eq	0.180 kg 1,4-DB eq	1.750 kg 1,4-DB eq
Terrestrial Ecotoxicity	0.085 kg 1,4-DB eq	0.015 kg 1,4-DB eq	0.005 kg 1,4-DB eq	0.105 kg 1,4-DB eq

4.2 Operational Phase and Mapping Efficacy

An evaluation of the operational phase reveals a counterintuitive dynamic regarding energy consumption. The direct electrical energy required to charge the drone batteries for the actual aerial mapping flights is remarkably minimal, contributing a negligible fraction to the overall global warming potential. The aerodynamic efficiency of the multirotor platforms allows them to capture vast amounts of high-resolution spatial data with very low energy expenditure per hectare surveyed. However, the true environmental cost of the operational phase resides in the subsequent post-processing of the digital imagery. The generation of precise orthomosaics and digital surface models from thousands of overlapping aerial photographs relies on complex computer vision algorithms and intensive computational rendering.

The lifecycle assessment data demonstrates that the energy consumed by the computing workstations during the photogrammetric processing vastly exceeds the energy used for the physical drone flight. Depending on the carbon intensity of the local electricity grid, this computational demand can represent the largest source of greenhouse gas emissions within the entire community mapping ecosystem. In many regions where informal settlements are prevalent, the electricity grid relies heavily on fossil fuels, thereby amplifying the climate impact of the digital processing phase. Despite this computational burden, the comparative efficacy of drone mapping remains overwhelmingly positive when contrasted with traditional land surveying methodologies. Conventional cadastral surveys require the mobilization of large teams using fossil-fuel-powered vehicles to access the settlements, followed by weeks of labor-intensive ground measurement. The drone-based approach drastically reduces the physical transportation requirements and expedites the documentation process, thereby offering a more environmentally efficient pathway to formalizing land tenure, provided that the energy sources for data processing can be optimized.

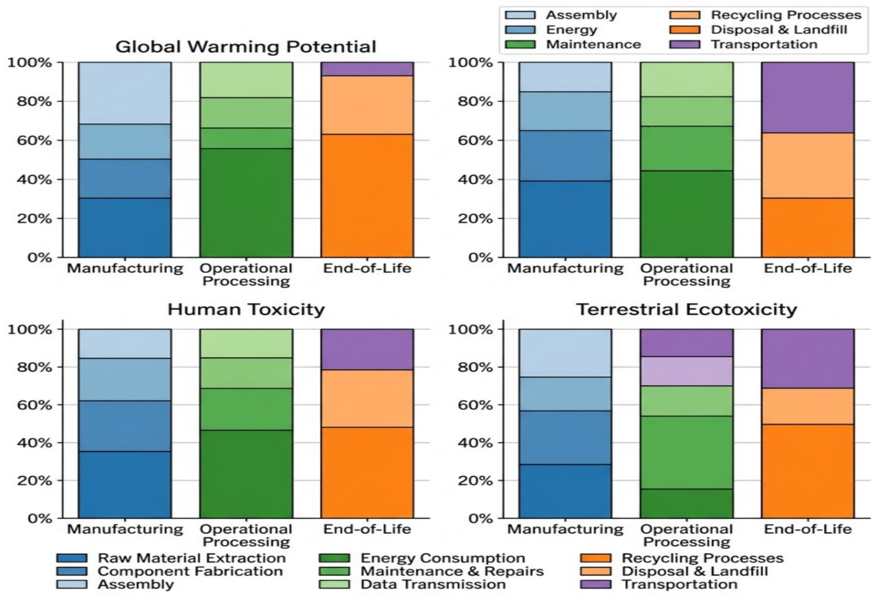

Figure 2: Comparative Lifecycle Impact Analysis Chart

4.3 End of Life and E-waste Considerations

The end-of-life management of the mapping drones presents a complex environmental challenge, particularly in the context of developing nations where formal electronic waste recycling infrastructure is often inadequate or entirely absent. The lifecycle assessment highlights that the improper disposal of drone components, especially the lithium-polymer batteries and heavy-metal-laden circuit boards, poses severe risks of localized ecotoxicity and groundwater contamination. If these materials are discarded into informal municipal waste streams, the leaching of toxic substances can result in significant environmental degradation, counteracting the broader socio-economic benefits achieved through the land tenure documentation process.

Conversely, the implementation of structured recycling programs offers the potential for substantial environmental credits. The recovery and recycling of precious metals, copper, and aluminum from the decommissioned drones can offset the virgin material extraction requirements for future electronic manufacturing, significantly mitigating the abiotic depletion impacts calculated in the manufacturing phase. However, achieving these environmental benefits requires proactive logistical planning and capacity building within the community mapping initiatives. Establishing take-back programs in collaboration with drone manufacturers or partnering with certified regional electronic waste processing facilities is crucial for closing the material loop. The study underscores the necessity of integrating comprehensive end-of-life management strategies into the foundational planning of participatory geographic information systems, ensuring that the technological tools utilized for securing community land rights do not inadvertently contribute to localized environmental health hazards.

5. Conclusion

5.1 Summary of Findings

This study has systematically evaluated the environmental implications of linking community mapping drones to land tenure documentation in informal settlements through the application of a rigorous lifecycle assessment framework. The findings illuminate a complex array of ecological trade-offs inherent in the deployment of advanced spatial technologies for social empowerment. While the physical operation of unmanned aerial vehicles requires minimal energy and offers unprecedented speed in capturing critical cadastral data, the lifecycle impacts are predominantly localized within the upstream manufacturing and downstream data processing phases. The extraction of critical minerals and the fabrication of specialized electronic components, particularly lithium-polymer batteries and optical sensors, generate substantial abiotic depletion and ecotoxicity burdens. Furthermore, the computationally intensive photogrammetric processing required to translate aerial imagery into legally actionable orthomosaic maps consumes significant electrical energy, which constitutes the primary driver of the system's global warming potential. Nevertheless, when compared to the logistical complexities and transportation emissions associated with traditional terrestrial surveying, drone-mediated mapping remains an environmentally competitive and highly effective modality for addressing the urgent need for land tenure security in rapidly expanding informal urban areas.

5.2 Policy Implications and Recommendations

The insights derived from this lifecycle assessment hold significant implications for urban policymakers, international development organizations, and practitioners of participatory geographic information systems. To maximize the sustainability of drone-based land tenure documentation, several strategic interventions are recommended. Firstly, community mapping initiatives should prioritize the procurement of mapping platforms that emphasize modularity and repairability, thereby extending the operational lifespan of the core airframe and reducing the frequency of total system replacements [16]. Secondly, mitigating the climate impacts of the computational phase requires a strategic shift toward utilizing computing infrastructure powered by renewable energy sources, which could involve decentralized solar-powered rendering stations or the utilization of green cloud computing services for photogrammetric processing. Finally, the establishment of formalized electronic waste management protocols is absolutely essential. Development programs funding the deployment of mapping drones must mandate and financially support end-of-life recycling pathways to prevent the accumulation of toxic electronic waste in vulnerable communities. By integrating these environmental considerations into the programmatic design of digital land administration initiatives, stakeholders can ensure that the technological formalization of informal settlements simultaneously promotes profound socio-economic equity and long-term ecological sustainability.

References

1. Henderson, T.M.A.; Ladewig, K.; Haylock, D.N.; McLean, K.M.; O'Connor, A.J. Cryogels for biomedical applications. J. Mater. Chem. B 2013, 1, 2682–2695.

2. Jayakumar, R.; Chennazhi, K.P.; Srinivasan, S.; Nair, S.V.; Furuike, T.; Tamura, H. Chitin scaffolds in tissue engineering. Int. J. Mol. Sci. 2011, 12, 1876–1887.

3. Feng, W.; Wang, Z. Biomedical applications of chitosan-graphene oxide nanocomposites. iScience 2022, 25, 103629.

4. Wang, Q.; Wang, X.; Feng, Y. Chitosan hydrogel as tissue engineering scaffolds for vascular regeneration applications. Gels 2023, 9, 373.

5. Ren, M.; Yao, J.; Yang, D.; Zhu, J.; Dai, K.; Zhong, Y.; Zhu, J.; Tang, L.; Xu, Y.; Yu, J. Chitosan hydrogels loaded with Cu3SnS4 NSs for the treatment of second-degree burn wounds. Sci. Rep. 2025, 15, 12449.

6. Schaly, S.; Islam, P.; Abosalha, A.; Boyajian, J.L.; Shum-Tim, D.; Prakash, S. Alginate–chitosan hydrogel formulations sustain baculovirus delivery and VEGFA expression which promotes angiogenesis for wound dressing applications. Pharmaceuticals 2022, 15, 1382.

7. Hoerstrup, S.; Zünd, G.; Sodian, R.; Schnell, A.M.; Grünenfelder, J.; Turina, M.I. Tissue engineering of small caliber vascular grafts. Eur. J. Cardio-Thorac. Surg. 2001, 20, 164–169.

8. Chircov, C. Tissue engineered vascular grafts. Biomater. Tissue Eng. Bull. 2018, 5, 110–118.

9. Oztemur, J.; Ozdemir, S.; Sezgin, H.; Yalcin-Enis, I. Hydrogel-based vascular grafts: State of art. In Sustainable Hydrogels; Thomas, S., Sharma, B., Jain, P., Shekhar, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 397–442. ISBN 978-0-323-91753-7.

10. Kantak, M.N.; Bharate, S.S. Analysis of clinical trials on biomaterial and therapeutic applications of chitosan: A review. Carbohydr. Polym. 2022, 278, 118999.

11. Strauss, A.; Vidovic, A.; Zambon, I.; Grossberger, H.; Bergmeister, K. Monitoring Information and Probabilistic-Based Prediction Models for the Performance Assessment of Concrete Structures. J. Perform. Constr. Facil. 2015, 30, 04015081.

12. Faghfouri, S.; Strauss, A. Utilizing IoT, ML and AI to extend the service life of RC structures and develop maintenance strategy. In Proceedings of the 15th fib International PhD Symposium in Civil Engineering, Budapest, Hungary, 28–30 August 2024; FIB (The International Federation for Structural Concrete): Lausanne, Switzerland, 2024; pp. 541–548.

13. Diamantidis, D. Probabilistic Assessment of Existing Structures; JCSS Report No. 32; Joint Committee on Structural

Safety: 14-20 Bd Newton, 77420 Champs-sur-Marne, Frankreich; RILEM Publications: Champs-sur-Marne, France, 2001; Available online: https://www.rilem.net/publication/publication/96 (accessed on 25 March 2026).

14. Joint Committee on Structural Safety (JCSS). Probabilistic Model Code. Available online: https://www.jcss-lc.org (accessed on 25 March 2026).

15. Jędrzejczyk, D.; Szatkowska, E. The impact of heat treatment on the behavior of a hot-dip zinc coating applied to steel during dry friction. Materials 2021, 14, 660.

16. Huang, X.; Zhou, Y.; Li, W.; Hu, B.; Zhang, J. Reliability-based design of FRP shear strengthened reinforced concrete beams: Guidelines assessment and calibration. Compos. Struct. 2023, 323, 117421.