Towards a Transformative Cadastre: Integrating Fit-for-Purpose, 3D Spatial Standards, Forensic Approaches, and Operational Efficiency for Sustainable Land Administration in Indonesia

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Key words: FFP-LA, forensic, management operational, cadastre, land administration

SUMMARY

Indonesia's land administration system is currently undergoing a transformative reform in response to persistent challenges of incomplete land registration, vertical land use conflicts, unresolved disputes, and inefficiencies in budget allocation. This paper proposes a multidimensional framework that integrates four complementary pillars: Fit-for-Purpose Land Administration (FFP-LA), 3D cadastre, forensic cadastre, and operational efficiency. Each pillar addresses a critical gap within Indonesia's cadastral system while collectively offering a holistic model for sustainable land governance.

The FFP-LA approach emphasizes flexibility and inclusivity, aligning with global best practices to rapidly expand tenure security through the Complete Systematic Land Registration (PTSL) program. However, conventional two-dimensional systems fall short in capturing urban vertical complexities, leading to the introduction of 3D cadastre. This innovation standardizes vertical boundaries using land use/land cover (LU/LC) and surface feature height (SFH), providing a technical and legal basis for managing multi-level property rights.

In parallel, forensic cadastre introduces principles of forensic science recognition, identification, individualization, and evaluation of evidence into dispute resolution. By applying evidence-based methodologies, it enhances transparency, objectivity, and legal defensibility in addressing overlapping ownership and boundary conflicts. Complementing these legal and technical innovations, operational efficiency is assessed through Data Envelopment Analysis (DEA), which evaluates the integration of cadastral programs such as PTSL, land value zoning (ZNT), and regional land stewardship (NPTR). Findings from South Lampung demonstrate that agricultural areas, despite higher operational costs, achieved better efficiency than urban settlements, challenging conventional assumptions about cadastral resource allocation.

Taken together, these four dimensions create a transformative cadastral framework that is both nationally relevant and globally transferable. By incorporating inclusivity, spatial innovation, scientific dispute resolution, and cost efficiency, the model offers Indonesia a strategic pathway toward sustainable land administration, while contributing to the broader global discourse promoted by FIG, UN-GGIM, and the SDGs.

Towards a Transformative Cadastre: Integrating Fit-for-Purpose, 3D Spatial Standards, Forensic Approaches, and Operational Efficiency for Sustainable Land Administration in Indonesia

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2. LITERATURE REVIEW

2.1 Fit-for-Purpose Land Administration (FFP-LA)

The Fit-for-Purpose Land Administration (FFP-LA) approach has emerged as a global paradigm for accelerating land registration, particularly in developing countries with limited resources (Enemark et al., 2014; Bennett et al., 2018). It emphasizes flexibility, inclusivity, and affordability rather than strict adherence to high-cost technical specifications. Indonesia's implementation of the Complete Systematic Land Registration (PTSL) resonates with the FFP-LA concept by prioritizing rapid coverage to provide tenure security for millions of unregistered parcels (Huda et al., 2024). However, while FFP-LA provides strategic direction for coverage, gaps remain in addressing complex spatial configurations and vertical land use that extend beyond the 2D framework.

The study by Nurul Huda et al. (2024) investigates the persistent challenges in Indonesia's cadastral system, particularly the issue of poor-quality registered parcels categorized under K-4 typology. As input, the research collected secondary cadastral datasets, institutional policy documents, and stakeholder perspectives relevant to land registration under the Complete Systematic Land Registration (PTSL) program. These inputs provided a comprehensive foundation for identifying structural, institutional, and technical weaknesses in the land administration system (Huda et al., 2024; Enemark, 2016).
In terms of process, the study employed an integrated PESTEL (Political, Economic, Social, Technological, Environmental, Legal) framework, combined with a SWOT analysis, to systematically evaluate the external and internal factors affecting cadastral data quality. This dual-method approach allowed the authors to assess not only technical aspects of land registration but also broader governance and policy dimensions that influence data quality and land tenure security (Huda et al., 2024; Zevenbergen et al., 2013).

The analysis revealed that political commitment and community participation are strong drivers for improving cadastral coverage. At the same time, weaknesses include limited technical capacity, fragmented regulations, and insufficient integration of spatial and legal data (Huda et al., 2024; UN-Habitat, 2012). Opportunities were identified in the adoption of digital platforms and international collaboration, whereas threats include land disputes, bureaucratic resistance, and the risk of incomplete certification (Huda et al., 2024; Lemmen et al., 2015). The integration

of SWOT-PESTEL produced a strategic matrix for incremental improvement of land data quality across Indonesia.

In the discussion, the study emphasized that cadastral reform must move beyond technical mapping activities and embrace a strategic, incremental, and adaptive approach. Rather than aiming for perfection from the outset, incremental improvements supported by strong governance and community engagement can accelerate coverage and gradually enhance data reliability (Huda et al., 2024; FIG, 2014). The findings also highlight the critical role of institutional coordination between the Ministry of Agrarian Affairs and Spatial Planning/National Land Agency (Ministry of Agrarian Affairs and Spatial Planning/National Land Agency) and local governments in achieving systematic improvements in cadastral systems. For the Transformative Cadastre paper, Nurul Huda's work provides a crucial literature base under the FFP-LA pillar. It supports the argument that inclusive and adaptive strategies are crucial for closing coverage gaps in Indonesia. By demonstrating how PESTEL and SWOT can inform incremental improvements, the paper enhances the broader framework of the transformative cadastre, which integrates inclusivity (FFP-LA), spatial innovation (3D cadastre), dispute resolution (forensic cadastre), and operational efficiency (Huda et al., 2024; World Bank, 2020). Thus, Huda et al.'s contribution directly complements the literature review by linking strategic land data improvement to Indonesia's long-term cadastral transformation agenda.

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2.2 3D Cadastre and Vertical Land Rights

The need for 3D cadastre arises from rapid urbanization and increasing use of underground and above-ground spaces. Traditional two-dimensional systems are unable to adequately represent multi-level rights, restrictions, and responsibilities (Stoter & van Oosterom, 2020; Kalogianni et al., 2020). Research in Bekasi Regency demonstrates the potential of standardizing vertical boundaries through land use/land cover (LU/LC) and surface feature height (SFH) as proxies for 3D land rights delimitation (Rebong et al., 2025). This provides a technical and legal basis for managing spatial complexity in urban environments (Dimopoulou et al., 2018; Kitsakis et al., 2020). Despite its importance, Indonesia's cadastral reform has yet to fully integrate 3D standards, leaving a gap between regulatory frameworks and the realities of vertical development (Zevenbergen et al., 2015; Ying et al., 2015).

The paper by Fransisko Rebong et al. (2025) addresses the growing demand for a 3D cadastral system in Indonesia, where rapid urbanization and vertical land use increasingly expose the limitations of conventional 2D registration. As input, the study collected cadastral datasets, land-use/land-cover (LU/LC) information, and surface feature height (SFH) parameters. These inputs reflect the need for a more precise representation of property rights in high-density urban environments, particularly for multi-level buildings and underground infrastructure (Rajabifard et al., 2018; Shojaei et al., 2017).

The research process involved converting 2D cadastral maps into 3D models by standardizing vertical boundaries based on LU/LC categories and SFH values. A systematic workflow was developed to classify parcels according to their functional land use and to assign standardized vertical extents to each category (Rebong et al., 2025). This methodological innovation bridged cadastral mapping with spatial planning practices, creating a more reliable model for representing complex land rights.

The study's output demonstrated that the proposed LU/LC–SFH approach provided a practical and scalable method for implementing 3D cadastres. The results showed clear differentiation of vertical rights across residential, commercial, industrial, and infrastructure zones. By applying standardized vertical boundaries, the study reduced ambiguity in land rights representation and provided a foundation for avoiding overlaps between underground and above-ground developments (Shojaei et al., 2016; Thompson et al., 2016).

In the discussion, the authors emphasized that implementing a 3D cadastre requires both technical innovation and regulatory reform. While the proposed model improves accuracy and usability, its success depends on alignment with national cadastral regulations and coordination among institutions responsible for land registration and spatial planning. The study also highlighted that 3D cadastre is not only a technical issue but also a legal and policy challenge, requiring integration into existing land administration frameworks (van Oosterom et al., 2019; Paasch et al., 2015).

For the Transformative Cadastre paper, Rebong et al.'s study contributes directly to the 3D cadastre pillar. It provides a robust methodology for addressing vertical complexity in Indonesia's cadastral system, complementing the inclusivity goals of FFP-LA, the legal rigor of forensic cadastre, and the sustainability dimension of operational efficiency. By showing how 2D systems can be systematically upgraded to 3D using LU/LC and SFH, this paper strengthens the literature review. It reinforces the argument that Indonesia's cadastral reform must embrace spatial innovation to remain relevant in rapidly urbanizing contexts.

2.3 Forensic Cadastre for Dispute Resolution

Land disputes persist as a significant obstacle to effective land governance in Indonesia, often stemming from overlapping claims, inaccurate boundary data, and incomplete documentation (Prabajati et al., 2025; Zakout et al., 2007). Conventional mediation and litigation approaches frequently fail to resolve conflicts efficiently (Palmer et al., 2009). The forensic cadastre approach introduces principles of forensic science—recognition, identification,

individualization, and evaluation of evidence—into cadastral practice (Saers, 2019; Houck & Siegel, 2015). By applying evidence-based methodologies, forensic cadastre enhances transparency, objectivity, and legal defensibility in dispute resolution (Bennett & Alemie, 2016). This is particularly relevant in contexts like Majalengka Regency, where disputes between state and private landowners could not be resolved through standard mediation, underscoring the necessity of scientifically validated methods (Prabajati et al., 2025).

The paper by Hias Prabajati et al. (2025) focuses on the application of forensic science principles to resolving cadastral disputes in Indonesia, specifically in Majalengka Regency. As input, the study compiled a comprehensive set of evidence, including ownership documents (land books, deeds, tax records), cadastral maps, measurement letters, and supporting administrative documents. These were complemented by identity records, statements of physical land possession, and satellite imagery, forming the evidentiary foundation for analyzing land disputes that could not be resolved through mediation (Enemark et al., 2014). In terms of process, the study adopted the four main stages of forensic science—recognition, identification, individualization, and evaluation of evidence—to systematically investigate cadastral disputes (Prabajati et al., 2025; Houck, 2018). Complaints were first categorized into technical and juridical cases, with technical anomalies such as overlapping parcels and unclear boundaries selected for forensic examination. Expert judgment and validation were then applied to ensure that the methodology aligned with professional and scientific standards (Kalantari et al., 2015).

The output revealed that the forensic cadastre provided an objective and transparent mechanism for dispute resolution. For example, in the case of overlapping claims between state-owned land and three private parcels, the forensic process identified inconsistencies in ownership documentation and boundary evidence, highlighting the weakness of parties lacking complete legal proof (Prabajati et al., 2025). Statistical validation (Cronbach's Alpha = 0.855) confirmed the reliability of the forensic cadastre framework as an evaluative tool for dispute resolution (Gliem & Gliem, 2003).

The discussion emphasized that a forensic cadastre not only improves accuracy in dispute settlement but also enhances public trust and institutional legitimacy. By introducing a structured, evidence-based methodology, the approach reduces reliance on subjective mediation and mitigates the risk of prolonged litigation (Williamson et al., 2010). The authors argued that a forensic cadastre is particularly valuable in contexts with incomplete data, overlapping claims, or conflicting regulations—conditions that are common in Indonesia's land administration system (Prabajati et al., 2025; van der Molen, 2002).

For the Transformative Cadastre paper, Prabajati et al.'s study strengthens the forensic cadastre pillar by showing how scientific validation can be embedded into dispute resolution. This directly complements the inclusivity focus of FFP-LA, the spatial innovation of 3D cadastre, and the sustainability goal of operational efficiency. By integrating forensic methods, the transformative framework gains a robust legal dimension, ensuring that cadastral reforms not

only expand coverage and improve accuracy but also resolve disputes in a transparent and defensible manner.

2.4 Operational Efficiency in Cadastral Mapping

"Operational inefficiency is another pressing challenge in Indonesia's land administration. Fragmented implementation of programs such as PTSL, ZNT (Zona Nilai Tanah), and NPTR (Neraca Penatagunaan Tanah) often results in duplicated efforts and inflated costs (Apriyadi et al., 2025; Budhathoki et al., 2020). Applying operational management tools, particularly Data Envelopment Analysis (DEA), has proven effective in measuring and improving efficiency by identifying overlapping parameters and optimizing resource allocation (Coelli et al., 2005; Banker et al., 2011). Findings from South Lampung Regency reveal that agricultural areas, despite higher operational costs, demonstrated better efficiency than urban settlements, challenging conventional assumptions about cost structures in cadastral operations (Apriyadi et al., 2025; Villalba-Romero et al., 2016). This suggests that integrated management approaches can deliver both cost savings and improved performance (Bennett et al., 2023; Antwi et al., 2020).

The paper by Seto Apriyadi et al. (2025) addresses inefficiencies in Indonesia's cadastral mapping system, particularly the duplication of resources across different land administration programs. As input, the study utilized financial records, cadastral activity budgets, and operational data from programs such as Complete Systematic Land Registration (PTSL), Land Value Zoning (ZNT), and the Regional Land Stewardship Balance (NPTR). These datasets provided a basis for identifying overlapping expenditures in aspects such as aerial mapping, transportation, office supplies, and socialization activities. The process involved applying an operational management approach combined with Data Envelopment Analysis (DEA) to measure cost efficiency.

The research began with a content analysis to identify overlapping activities among the three programs, followed by the construction of an integrated cadastral mapping model. DEA was then used to evaluate the efficiency of decision-making units (DMUs) before and after integration. At the same time, the reliability and validity of the questionnaire-based data were tested using Cronbach's Alpha. The output demonstrated that integrating operational parameters across programs resulted in significant cost reductions without compromising data quality. Contrary to expectations, the study revealed that efficiency scores were higher in agricultural areas compared to urban zones, suggesting that integrated management could offset the traditionally higher costs of rural mapping (Apriyadi et al., 2025; Färe et al., 1994).

The discussion emphasized that adopting an operational management lens allows cadastral authorities to optimize financial and human resources while minimizing waste. By streamlining overlapping tasks and expenditures, the study highlighted the potential for sustainably scaling cadastral reforms. The findings also reinforced the importance of cost governance as a determinant of long-term program viability, complementing technical and legal dimensions of cadastral reform (Williamson et al., 2010; Rajabifard et al., 2017).

For the Transformative Cadastre paper, Apriyadi et al.'s research directly supports the operational efficiency pillar. It demonstrates how management science and quantitative tools, such as DEA, can be applied to land administration to ensure financial sustainability. This contribution complements the inclusivity goals of FFP-LA, the spatial innovation of 3D cadastre, and the legal rigor of forensic cadastre, together forming a holistic framework for Indonesia's cadastral transformation that is both technically sound and economically sustainable.

2.5 Towards an Integrated Framework

While each of these four pillars—FFP-LA, 3D cadastre, forensic cadastre, and operational efficiency—has been studied individually, the literature reveals a lack of integration across these dimensions. Existing research often isolates legal, technical, and economic perspectives, leaving policymakers without a comprehensive model for reform. Integrating these approaches offers the potential to address Indonesia's cadastral challenges holistically: FFP-LA ensures inclusivity, 3D cadastre captures vertical complexity, forensic cadastre provides scientific tools for dispute resolution, and operational management ensures sustainability through efficiency. Together, they form a transformative cadastral framework aligned with international agendas such as the SDGs, UN-GGIM's geospatial vision, and FIG's professional standards (Enemark, 2018; UN-GGIM, 2020).

The work of Nurul Huda et al. (2024) highlights the persistent coverage gap in Indonesia's cadastral system, particularly parcels classified under *K-4 typology*. By employing an integrated PESTEL–SWOT framework, the study demonstrated that incremental improvement strategies, supported by political will, community participation, and digital innovation, can gradually enhance the quality of cadastral data. This aligns closely with the Fit-for-Purpose Land Administration (FFP-LA) pillar, which emphasizes inclusivity and adaptability over rigid technical specifications, offering a practical pathway to achieve nationwide land registration.
Complementing this, Fransisko Rebong et al. (2025) addressed the challenge of vertical complexity in urban land administration. By integrating *land use/land cover (LU/LC)* and *surface feature height (SFH)* as proxies for vertical delimitation, the study developed a standardized approach for converting 2D cadastral maps into 3D representations. The findings demonstrated that adopting 3D cadastre methods reduces ambiguity in property rights, particularly in high-density urban areas where underground and above-ground spaces overlap. This directly contributes to the 3D Cadastre pillar, ensuring that cadastral systems remain relevant in rapidly urbanizing contexts.

Meanwhile, Hias Prabajati et al. (2025) applied forensic science principles—recognition, identification, individualization, and evaluation of evidence—to cadastral disputes in Majalengka Regency. By systematically analyzing ownership documents, cadastral maps, and boundary evidence, the study demonstrated that a forensic cadastre can provide transparent and defensible resolutions when mediation fails. The results underscore the importance of embedding scientific validation into dispute resolution, strengthening the Forensic Cadastre

pillar within Indonesia's reform agenda, and enhancing public trust in land administration institutions.

On the economic and management side, Seto Apriyadi et al. (2025) investigated cost inefficiencies in integrated cadastral mapping by analyzing overlapping expenditures across PTSL, ZNT, and NPTR programs. Using Data Envelopment Analysis (DEA), the study revealed that integration not only optimized financial resources but also yielded higher efficiency scores in agricultural areas compared to urban zones. These findings reinforce the Operational Efficiency pillar, demonstrating that sustainable cadastral reform requires robust financial governance, efficient resource allocation, and legal and technical innovation.

Taken together, these four studies illustrate that no single approach is sufficient to achieve comprehensive cadastral reform in Indonesia. Instead, the synthesis of FFP-LA, 3D cadastre, forensic cadastre, and operational efficiency forms the basis of a Transformative Cadastre Framework. By aligning inclusivity, spatial sophistication, legal rigor, and financial sustainability, the framework addresses Indonesia's domestic challenges while also providing transferable lessons for the Global South. This integrated perspective not only supports the achievement of the SDGs but also resonates with the priorities of UN-GGIM and the FIG 2026 Congress agenda on building sustainable land administration systems.

3. METHODOLOGY

3.1 Comparative Synthesis Approach

This study employed a comparative synthesis approach to integrate findings from multiple research strands addressing Indonesia's cadastral challenges. Rather than focusing on a single thematic perspective, the analysis compared outcomes from different methodologies—strategic planning, spatial modeling, forensic analysis, and operational management—to identify commonalities and complementarities. The synthesis was guided by the premise that a transformative cadastre requires multidimensional reform, aligning legal, technical, economic, and governance aspects (Bennett et al., 2018; Enemark, 2018).

3.2 Case Study Selection

Four case studies were selected from recent empirical research to represent the diversity of Indonesia's cadastral issues:

- Land Data Quality and Strategic Development – Bandung Regency, addressing *K-4 typology* and PTSL implementation through PESTEL and SWOT analysis (Huda et al., 2024).
- 3D Cadastre Conversion – Bekasi Regency, focusing on vertical boundary standardization based on *land use/land cover (LU/LC)* and *surface feature height (SFH)* to manage complex urban development (Rebong et al., 2025).

- Forensic Cadastre in Dispute Resolution – Majalengka Regency, applying forensic science stages—recognition, identification, individualization, and evaluation—to resolve overlapping land ownership between state and private parcels (Prabajati et al., 2025).
- Operational Efficiency of Cadastral Mapping – South Lampung Regency, measuring cost-effectiveness of integrated PTSL, ZNT, and NPTR programs using Data Envelopment Analysis (DEA) (Apriyadi et al., 2025).

These case studies were selected purposively to reflect different cadastral dimensions: legal certainty, spatial complexity, dispute settlement, and operational sustainability.

3.3 Data Collection and Analytical Framework

The methodology combined documentary analysis, secondary data, and evaluation metrics from the four case studies. For the FFP-LA case, data were derived from PTSL records and quality-improvement reports. The 3D cadastre case relied on LU/LC classification and SFH mapping datasets. Forensic cadastre analysis used dispute documentation, cadastral maps, and ownership records. Operational efficiency evaluation applied budgetary records and DEA outputs. Comparative synthesis then mapped these findings against the three pillars of FFP-LA: spatial, legal, and institutional frameworks (Enemark et al., 2014), as well as efficiency indicators (Bennett et al., 2023).

3.4 Model Framework Development

A multidimensional model framework was developed to integrate the four pillars into a single conceptual scheme:

- **FFP-LA** provided the strategic entry point for inclusive coverage and institutional strengthening.
- **3D cadastre** ensured the technical ability to capture vertical and spatial complexities of land use.
- **Forensic cadastre** introduced scientific rigor into legal dispute resolution, enhancing transparency and public trust.
- **Operational efficiency** guaranteed the financial sustainability of cadastral programs through integrated resource management.

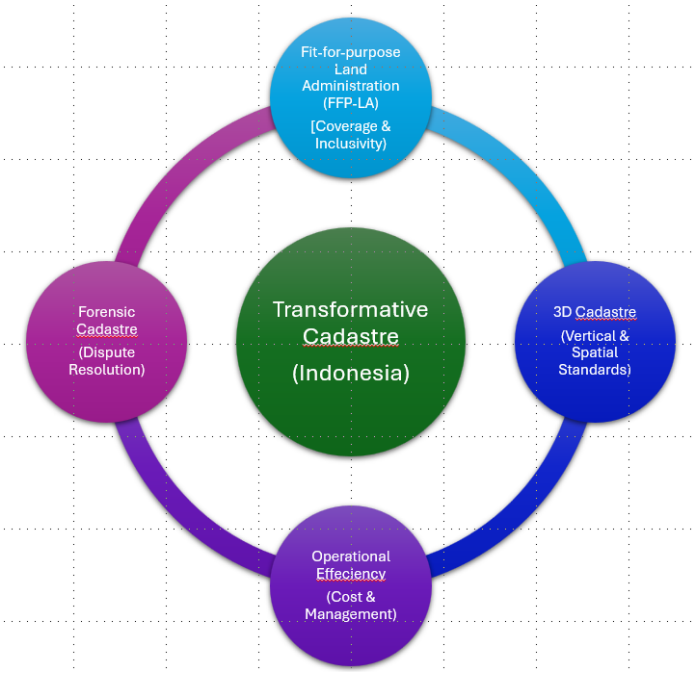

Fig. 1. Transformative cadastre framework

These components were combined into a transformative cadastre framework designed for Indonesia but with potential transferability to other Global South contexts. The model framework was validated through cross-case triangulation, ensuring consistency between findings and relevance to international agendas such as the SDGs, UN-GGIM, and FIG professional standards.

3.5 Research Validation

The validation of Huda et al. (2024) focused on the reliability of the PESTEL–SWOT framework used to analyze cadastral data quality in Indonesia. Triangulation of multiple data sources, including cadastral records, institutional documents, and stakeholder inputs, ensured credibility. The findings were consistent across all dimensions— political, economic, social, technological, environmental, and legal —which confirmed the robustness of the analysis. By aligning with internationally recognized Fit-for-Purpose Land Administration (FFP-LA) principles, the study demonstrated both conceptual validity and practical relevance in addressing Indonesia's land registration coverage gap.

The research of Rebong et al. (2025) on 3D cadastre was validated through technical modeling and scenario-based testing. The approach combined *land use/land cover (LU/LC)* classifications with *surface feature height (SFH)* data to define standardized vertical boundaries. Reliability was achieved by applying the method consistently across different parcel typologies, while external validity was strengthened through benchmarking against international 3D cadastre literature. The compatibility of the proposed method with Indonesia's

regulatory framework further confirmed its applicability and relevance for addressing vertical land administration challenges.

In the case of Prabajati et al. (2025), validation was achieved through a combination of expert judgment and statistical testing. A structured questionnaire distributed to cadastral professionals yielded a Cronbach's alpha value of 0.855, indicating a high level of internal consistency. Construct validity was also demonstrated, as 80% of questionnaire items correlated significantly with the overall forensic cadastre construct. Triangulation of cadastral maps, ownership records, and satellite imagery reinforced the reliability of the recognition–identification–individualization–evaluation process, confirming the method's potential to produce transparent and legally defensible outcomes.

The study by Apriyadi et al. (2025) employed quantitative validation techniques to evaluate the cost efficiency of integrated cadastral mapping. Using Data Envelopment Analysis (DEA), the research compared the efficiency scores of decision-making units before and after integration, demonstrating the methodological robustness of the approach. Questionnaire-based data on operational aspects, such as aerial mapping, transportation, and allowances, were tested for reliability, yielding a Cronbach's Alpha of 0.968, which indicated excellent internal consistency. Pearson's correlation analysis confirmed that 26 out of 27 items were valid, reinforcing the robustness of the efficiency model.

Taken together, these validation strategies—triangulation in FFP-LA, technical benchmarking in 3D cadastre, expert judgment and reliability testing in forensic cadastre, and statistical validation in operational efficiency—establish a strong empirical foundation for the Transformative Cadastre Framework. The methodological rigor across these four dimensions demonstrates that the framework is not only conceptually sound but also practically tested. This ensures its credibility for policy application in Indonesia while enhancing its relevance and transferability to other countries in the Global South, making it highly significant for the global discussions at FIG 2026

4. RESULTS

The comparative synthesis across four case studies highlights the multidimensional challenges and opportunities for cadastral reform in Indonesia. Each case provides specific insights into different dimensions of land administration—coverage, spatial complexity, dispute resolution, and efficiency—that together inform a holistic framework for a transformative cadastre. See Table 1.

First, the study on land data quality in Bandung Regency demonstrates the persistent coverage gap in Indonesia's cadastral system. By employing PESTEL and SWOT analysis, the research revealed structural weaknesses in land registration data, particularly in the K-4 category, where parcels are registered but spatially inconsistent (Huda et al., 2024). The findings underscore the importance of adopting FFP-LA strategies to enhance land data quality and incrementally expand coverage nationwide.

Second, the 3D cadastre study in Bekasi Regency identified the limitations of the existing two-dimensional system in managing vertical property rights. Through the use of *land use/land cover* (LU/LC) and *surface feature height* (SFH) as proxies for vertical delimitation, the study proposed standardized methods for converting 2D to 3D cadastral maps (Rebong et al., 2025). The findings underscore the need to adopt 3D standards to support urban development and mitigate spatial conflicts in densely populated metropolitan areas.

Third, the forensic cadastre case in Majalengka Regency illustrates the potential of forensic science methods in dispute resolution. The study applied the stages of recognition, identification, individualization, and evaluation to an unresolved conflict involving overlapping parcels between state-owned and private land (Prabajati et al., 2025). This approach produced transparent and scientifically valid outcomes, strengthening the legitimacy of cadastral evidence in legal processes and providing an alternative to prolonged mediation or litigation.

Finally, the operational efficiency study in South Lampung Regency analyzed budget optimization across integrated programs (PTSL, ZNT, NPTR) using Data Envelopment Analysis (DEA). Contrary to common assumptions, agricultural areas displayed higher efficiency compared to urban regions, suggesting that integrated operational management can deliver substantial cost savings while maintaining service quality (Apriyadi et al., 2025). The results emphasize that sustainable cadastral reform must strike a balance between technical innovation and financial efficiency.

Together, these findings provide a comprehensive evidence base for developing a transformative cadastral framework that integrates inclusivity (FFP-LA), spatial innovation (3D cadastre), dispute resolution (forensic cadastre), and cost-effectiveness (operational efficiency).

Table 1. Comparative summary of case studies

Case Study & Location	Methodology	Key Findings	Contribution to Transformative Cadastre
Bandung Regency – Land Data Quality (K-4) (Huda et al., 2024)	PESTEL & SWOT Analysis	Identified typologies of poor-quality registered parcels; highlighted systemic weaknesses in data accuracy.	Supports **FFP-LA** by providing incremental strategies to close coverage gaps.
Bekasi Regency – 3D Conversion (Rebong et al., 2025)	LU/LC & SFH-based modeling	Proposed standardized approach for converting 2D to 3D cadastral maps.	Advances **3D Cadastre** for vertical property rights and urban management.
Majalengka Regency – Dispute Resolution (Prabajati et al., 2025)	Forensic science stages (recognition, identification, individualization, evaluation)	Resolved overlapping land claims through scientific validation of cadastral evidence.	Strengthens **Forensic Cadastre** as a transparent, evidence-based dispute mechanism.

Case Study & Location	Methodology	Key Findings	Contribution to Transformative Cadastre
South Lampung Regency – Operational Efficiency (Apriyadi et al., 2025)	Data Envelopment Analysis (DEA)	Agricultural areas more efficient than urban; identified cost-saving opportunities in program integration.	Embeds **Operational Efficiency** into cadastral reform for financial sustainability.

5. DISCUSSION

The comparative results across four case studies confirm that isolated interventions are insufficient to address cadastral reform in Indonesia. Each pillar—FFP-LA, 3D cadastre, forensic cadastre, and operational efficiency—offers valuable contributions, but their true potential emerges when integrated into a unified framework. This section discusses the synergies, challenges, and global relevance of such integration.

5.1 Integrating Inclusivity and Spatial Innovation

The first synergy arises from combining FFP-LA with 3D cadastre. While FFP-LA provides the strategic foundation to close registration gaps through cost-effective and inclusive approaches, it risks oversimplification if not complemented by advanced spatial representation. The adoption of 3D standards addresses the limitations of 2D cadastre by capturing vertical complexity in urban and peri-urban environments (Rebong et al., 2025; Enemark et al., 2014). Together, they ensure that both coverage and accuracy are achieved, aligning tenure security with the realities of modern land use.

5.2 Embedding Scientific Rigor in Dispute Resolution

The integration of forensic cadastre strengthens the institutional and legal dimensions of cadastral reform. While FFP-LA and 3D cadastre enhance inclusivity and technical accuracy, disputes inevitably arise due to overlapping claims or incomplete records. Forensic cadastre, through evidence-based methodologies, ensures that such disputes are resolved transparently and objectively (Prabajati et al., 2025; Saers, 2019). Embedding forensic approaches into mainstream cadastral practice enhances legal defensibility and improves public trust—critical factors for sustainable land governance.

5.3 Ensuring Financial and Operational Sustainability

No cadastral reform can succeed without sustainable financing. The operational efficiency pillar addresses this by applying management science and performance measurement tools, such as DEA, to minimize duplication of resources and optimize cost structures (Apriyadi et al., 2025). Integrating efficiency considerations ensures that cadastral innovation—whether in FFP-LA, 3D, or forensic practices—remains scalable and financially viable. This dimension links the

reform agenda to broader principles of good governance and accountability (Bennett et al., 2023).

5.4 Towards a Transformative Cadastre Framework

When combined, the four pillars form a Transformative Cadastre Framework tailored to Indonesia's context yet relevant to other developing nations. The framework emphasizes inclusivity, spatial sophistication, legal rigor, and cost-effectiveness as interconnected dimensions rather than parallel tracks. This holistic model addresses not only domestic challenges—such as coverage gaps, disputes, and inefficiency—but also contributes to international debates on land administration reform. By operationalizing this framework, Indonesia positions itself as a frontrunner in advancing sustainable land administration in the Global South.

5.5 Relevance to FIG 2026 and Global Agendas

The proposed framework resonates strongly with the FIG Congress 2026 agenda in Cape Town, which emphasizes innovation, inclusivity, and sustainability in land administration. It aligns with the Sustainable Development Goals (SDGs) by promoting secure tenure (SDG 1, 5), sustainable urbanization (SDG 11), and institutional justice (SDG 16). It also responds to UN-GGIM's call for integrated geospatial and land information management to support global development (UN-GGIM, 2020). By presenting Indonesia's experience, the paper contributes to comparative knowledge sharing, offering lessons for countries across Africa, Asia, and Latin America that face similar cadastral challenges.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This study demonstrates that Indonesia's cadastral reform requires a multidimensional and integrated approach to address persistent challenges of coverage gaps, vertical complexity, unresolved disputes, and low operational efficiency. Drawing from four case studies, the proposed Transformative Cadastre Framework integrates:

- Fit-for-Purpose Land Administration (FFP-LA) to accelerate coverage through inclusivity and adaptability.
- 3D Cadastre to represent vertical property rights and manage spatial complexity in urban environments.
- Forensic Cadastre to resolve disputes scientifically and transparently, reinforcing legal certainty.
- Operational Efficiency to ensure financial sustainability and scalability of cadastral programs.

Together, these pillars strengthen Indonesia's capacity to deliver secure tenure, improve governance, and align land administration with the dynamics of modern development. The framework also provides a transferable model for other countries in the Global South.

4.2 Recommendations

- **For Indonesia:**
  - Institutionalize the integration of FFP-LA, 3D cadastre, forensic methods, and operational management into national cadastral policy.
  - Prioritize regulatory reforms to support 3D registration and embed forensic standards in dispute resolution.
  - Scale up efficiency models, such as DEA-based program integration, to reduce duplication and optimize resources across Ministry of Agrarian Affairs and Spatial Planning/National Land Agency activities.
- **For the Global Agenda:**
  - Align cadastral reform with the SDGs, particularly SDG 1 (No Poverty), SDG 11 (Sustainable Cities and Communities), and SDG 16 (Peace, Justice, and Strong Institutions).
  - Contribute to UN-GGIM's vision of integrated land and geospatial information systems by demonstrating practical pathways for developing nations.
  - Position Indonesia's reform experience as a case study for FIG Congress 2026, enabling knowledge exchange with other regions, especially Africa and Latin America.
  -

By operationalizing the Transformative Cadastre Framework, Indonesia not only advances its national land administration reform but also contributes to the global discourse on building sustainable, inclusive, and efficient cadastral systems.

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