AI-DRIVEN LAND TENURE MAPPING FOR SUSTAINABLE LAND GOVERNANCE: A REVIEW WITH REFERENCE TO NEPAL

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KEYWORDS: Artificial Intelligence, Land Tenure Mapping, Sustainable Land Governance, GIS, Nepal, Cadastral Mapping

ABSTRACT

Land tenure insecurity is a major challenge in Nepal, affecting millions of households across its diverse socio-economic and geographic landscape. A large portion of Nepal's land system is composed of informal, customary, and communal tenure arrangements, which are challenging to fully capture using traditional cadastral mapping techniques and are also often slow and expensive. To improve the land tenure system and sustainable land governance in Nepal, this paper examines the use of AI-driven methods integrating Machine Learning (ML), Deep Learning (DL), Geographic Information Systems (GIS), and participatory mapping. The study analyses how Artificial Intelligence (AI) can automate parcel boundary detection, land-use classification, change detection, and the integration of informal tenure into formal land administration systems, drawing on secondary data from government and international sources, evidence from comparative international practices, and Nepal's national land reform context. Secondary data indicate that approximately 35% of Nepal's land remains unregistered in the cadastral system; informality rates are particularly high in mountainous and hilly regions. The study suggests that AI-driven mapping can enhance evidence-based policymaking, reduce costs, and increase mapping efficiency. However, issues such as algorithmic bias, gaps in digital infrastructure, limited institutional capacity, and unclear legal frameworks for AI-generated outputs must be addressed immediately. The study concludes that AI-based land tenure mapping offers a viable route to just and sustainable land governance in Nepal when incorporated into inclusive governance frameworks and backed by legislative reforms.

1. INTRODUCTION

Land is among the fundamental resources in any society, which supports economic growth, food security, livelihoods, and environmental sustainability. Due to the country's varied topography, a history of feudal land concentration, numerous overlapping legal frameworks, and long-standing informality in land occupancy and transactions, Nepal has a particularly complex land tenure system. Despite multiple government land reform efforts since the 1960s, the country still faces issues such as unequal land distribution, unregistered land rights, inadequate cadastral coverage, and poor institutional coordination (Adhikari, 2011). Only about 65% of Nepal's total land area is covered by the Department of Land Management and Archives' (DoLMA) national cadastral database; the remaining 5.1 million hectares are not officially registered (MoLMCPA,2019). This number is disproportionately concentrated in isolated, hilly, and mountainous regions, where marginalised groups like women, Dalits, and indigenous peoples face the highest rates of tenure insecurity. (MoLMCPA,2019). According to Enemark et al. (2014), traditional cadastral mapping methods that depend on manual digitisation, plane table methods, and ground surveys are costly, time-consuming, and often unavailable to these communities. This hinders agricultural investment and fuels ongoing land conflicts. According to a 2020 World Bank assessment, over 1.2 million parcels in the Terai region alone remain disputed or informally occupied, discouraging agricultural investment and contributing to ongoing land conflicts. The rapid advancement of AI, GIS, and Remote Sensing (RS) technologies is creating revolutionary new opportunities for global land administration (Mishra et al., 2025; Ndiema, 2024). At scales and speeds previously unattainable with manual methods, machine learning algorithms applied to high-resolution satellite imagery and UAV data can automate parcel boundary detection, land use classification, and change monitoring (Cigna & Tapete, 2021). According to Mishra et al. (2025) and Zhu et al. (2017), deep learning architectures such as Convolutional Neural Networks (CNNs) have achieved land cover classification accuracies exceeding 90% across heterogeneous landscapes, including those typical of Nepal's mixed terrain environments. International frameworks such as the Fit-for-Purpose (FFP) Land Administration approach (Enemark et al., 2014) and the FAO Voluntary Guidelines on the Responsible Governance of Tenure (VGGT) (FAO, 2012) guide accessible, inclusive, and technology-enabled land documentation (Ansari & Ghimire, 2024).

This study examines the potential benefits of AI-driven land tenure mapping for Nepal's sustainable land governance. It analyses the current state of land tenure. It also evaluates the institutional and technical aspects of AI integration. Additionally, it draws comparisons with international practices in countries that have made notable advancements in digital land administration, using secondary data from Nepal's government records, reports from international organisations, and published academic research.

The objectives of this study are: 1) to find out how much land tenure mapping processes can be automated and enhanced by using Deep Learning (DL) , Machine Learning (ML) , Artificial Intelligence (AI), and GIS; and 2) to assess how much participatory methods can help advance tenure security, sustainable land governance, and the inclusion of informal tenure arrangements in the Nepalese context when combined with AI-driven mapping technologies.

2. METHODOLOGY

This study's qualitative, desk-based research design is predicated on a comprehensive analysis and compilation of secondary data. Given the complexity of land tenure governance, the variety of AI applications, and the requirement to interpret contextual evidence from Nepal's institutional and geographic setting, a qualitative approach is appropriate. Instead of relying on primary field surveys, the study includes information from government policy documents, published academic literature, documented national programs, technical reports from international organisations, and case studies of AI-driven land administration from similar developing country contexts.

The study adopts a three-stage analytical approach: (i) secondary data synthesis from national and international sources to establish the baseline context of Nepal's land tenure situation; (ii) a conceptual analysis of AI and GIS methodologies and their technical applicability to land tenure mapping challenges; (iii) a structured comparative analysis of international case studies from Rwanda, India and Kenya to identify transferable lessons and adaptations. The three-stage approach allows for the systematic triangulation of evidence across technical, institutional and governance dimensions.

2.1. Secondary Data Sources

Secondary data was systematically gathered from multiple authoritative sources to ensure reliability and comprehensiveness. A literature search was conducted across databases. National-level data on land administration, cadastral coverage, and tenure insecurity were collected from the Ministry of Land Reform and Management, the National Land Policy (Government of Nepal, 2019), the Central Bureau of Statistics (CBS) and the Department of Land Management and Archives (DoLMA) annual reports. Data on land conflict, compensation, and governance practices were drawn from the Nepal Land Governance Assessment Framework (World Bank, 2020) and the Land Alliance Nepal reports (2021). Population and demographic data were obtained from the National Population and Housing Census (CBS, 2021). International comparative data were obtained from FAO technical reports, UN-Habitat publications, World Bank assessments, and peer-reviewed academic journals, including Remote Sensing, Land Use Policy, and the Journal of Computer Science and Technology.

2.2. AI, GIS, and Participatory Mapping Techniques

The conceptual analysis of AI-driven land tenure mapping draws on three interconnected technological methodologies, consistent with the integrated framework described by Mishra et al. (2025) for smart land use planning.

2.3. Machine Learning and Deep Learning for Parcel Mapping

Machine learning (ML) algorithms like Random Forest (RF), Support Vector Machines (SVM), and Gradient Boosting are used to categorise land use and land cover (LULC) categories essential for tenure mapping, such as agricultural land, forest, settlement, and water bodies. (Landsat-8, Sentinel-2)(Mishra et al., 2025; Belgiu and Dragut, 2016). Standard deep learning algorithms, particularly Convolutional Neural Networks (CNNs) and semantic segmentation models such as U-Net, enable pixel-level boundary delineation and object detection from very high-resolution imagery obtained from UAVs and commercial satellites (Zhu et al., 2017). Long Short-Term Memory (LSTM) networks are applied to multi-temporal datasets to detect land use change and model tenure transition dynamics (Reichstein et al., 2019).

2.4. Comparative Analysis Framework

To situate Nepal's experience within broader global trends, a structured comparative analysis was conducted examining AI and digital land administration practices in Rwanda, India, and Kenya--three developing countries that have made notable progress in deploying technology-enabled land governance systems. Four dimensions were used to structure the comparison: (i) the use of AI and GIS tools; (ii) institutional and legal frameworks; (iii) mechanisms for community participation; and (iv) results for tenure security and transparency in governance. In order to determine applicable lessons and necessary context-specific adjustments, Nepal's context was evaluated in relation to these dimensions.

3. RESULTS AND FINDINGS

This section presents the results and findings of the study.

3.1. Current Status of Land Tenure in Nepal

Nepal's land tenure system is characterised by significant complexity, inequality, and informality. According to the Ministry of Land Management, Cooperatives and Poverty Alleviation (MoLMCPA, 2019), approximately 5.1 million hectares, representing about 35% of the total land area, remain outside formal cadastral registration. Of the registered land, a 2021 assessment by Land Alliance Nepal found that women hold formal ownership rights in only 20.4% of land parcels (Raj Joshi et al., 2021), despite comprising approximately 51% of the population (CBS, 2021). Among Nepal's landless population, Dalits are severely overrepresented, with 41.4% of Madhesi Dalits and 36.7% of Hill Dalits having no land, reflecting systematic exclusion of marginalised groups from formal land rights(IDSN,2015).

The cadastral system suffers from significant spatial inaccuracies and outdated records. According to a study conducted by the Department of Land Management and Archives (DoLMA) in 2020, a technical investigation, about 40% of cadastral sheets in hilly districts were last updated between 1970 and 1990, making them insufficient for the demands of modern land administration. In the Kathmandu Valley, rapid urbanisation has produced an estimated 350,000 informal or unregistered structures, creating acute tenure insecurity for urban migrants and low-income communities. The Terai region similarly shows approximately 1.2 million disputed or informally occupied parcels, frequently generating land conflicts that burden the judicial system (Land Conflicts in Nepal, 2017). The 2015 Gorkha earthquake destroyed over 600,000 homes, leaving a massive backlog of unresolved property rights claims that manual systems have been unable to adequately handle (National Reconstruction Authority, 2020).

Ansari & Ghimire (2024) empirically documented the institutional fragmentation, lack of transparency, and inefficiency that continue to threaten land governance processes in their study of land acquisition and compensation for the Kathmandu–Terai Madhesh Fast Track Road Project (KTFTRP). Their results showed that 64% of impacted landowners thought compensation procedures were very opaque, 90% thought the process was very complicated and time-consuming, and 64% of participants thought compensation rates were less than 25% of market replacement cost (Ansari & Ghimire,2024).These results highlight systemic shortcomings in participation, transparency, rule of law, efficiency, and effectiveness, the fundamentals of good land governance.

3.2. AI and GIS Applications for Land Tenure Mapping in Nepal

The results of the secondary data synthesis demonstrate that AI and GIS technologies hold significant and largely untapped potential for addressing Nepal's land tenure mapping challenges. The results are presented in the following subsections.

3.2.1 Machine Learning for Boundary Detection and Land Classification

Mishra et al. (2025) show that the application of ML algorithms to Sentinel-2 and Landsat-8 imagery across Nepal's diverse terrain demonstrates that automated LULC classification can achieve overall accuracies of 85–92%, with Random Forest models consistently outperforming traditional maximum likelihood classification, particularly in mixed-use terrain. Similarly, Li et al. (2021) report comparable performance in diverse landscape settings. CNN-based semantic segmentation models applied to very high-resolution imagery (sub-meter UAV data) have demonstrated strong performance in parcel boundary delineation in peri-urban contexts, significantly reducing manual digitisation effort and associated costs(Zhu et al., 2017).

In the context of Nepal's specific terrain, ML-based classification of Sentinel-2 imagery at 10m resolution has been validated for mapping agricultural land parcels, forest cover, and water bodies in the Gandaki and Koshi river basins. However, the complex topography of Nepal's high mountain zones, combined with persistent cloud cover limiting optical satellite imagery availability to approximately 40–60% of the year in affected regions, presents significant challenges for consistent ML-based mapping (Robinson et al., 2019)

3.2.2. GIS-Based MCDA as a Complementary Decision Support Tool

While GIS-based Multi-Criteria Decision Analysis (MCDA) is not completely an AI method, it functions as a critical spatial decision-support tool that complements AI-driven mapping by informing where tenure formalisation interventions should be prioritised. In practice, AI outputs such as land-use classifications and parcel boundary maps are most actionable when integrated with a structured prioritisation framework, which MCDA provides. Applying GIS-based MCDA to Nepal's cadastral and socioeconomic data layers enables the systematic identification of areas in greatest need of immediate tenure formalisation, taking into account factors such as infrastructure accessibility, conflict frequency, degree of informality, and ecological sensitivity (Malczewski, 2006).In this way, MCDA bridges the gap between AI- generated spatial data and evidence-based policy decisions. Three priority zones have been identified through such analysis. First, the Terai plains (including Bara, Parsa, and Rautahat districts), where informal occupation is most concentrated. Second, the mid-hill belt(including Sindhupalchok, Kavrepalanchok, and Ramechhap districts), where earthquake-damaged properties remain officially unresolved following the 2015 Gorkha earthquake. Third, the urban fringe zones surrounding Kathmandu, Pokhara, and Biratnagar, where unregistered settlements have increased as a result of rapid in-migration (UN-Habitat, 2018; World Bank, 2020).

3.3 Barriers to AI Implementation for Land Tenure Mapping in Nepal

The barriers that currently constrain the systematic adoption of AI-driven land tenure mapping in Nepal are:

1. Digital infrastructure and data availability: Broadband connectivity in rural areas is still limited, and only about 43% of Nepal's population has internet access (**NTA,2021**). Most of Nepal's 753 local governments lack reliable connectivity, which is necessary for cloud-based AI processing platforms. In order to enable contemporary AI applications, current national spatial datasets, such as the 1:25,000 topographic series maintained by the Survey Department, must be significantly updated. High-resolution satellite and UAV imagery, although critical for accurate land-tenure mapping, are also expensive and therefore limit the scalability of AI-driven approaches in Nepal.
2. Institutional fragmentation: The various organisations in Nepal that perform activities related to land administration include the Department of Land Management and Archives (DoLMA), the Survey Department, the Department of Urban Development and Building Construction (DUDBC), and provincial and local governments. The development of integrated AI-GIS platforms is hampered by coordination problems and data interoperability barriers (Ansari & Ghimire, 2024).
3. Existing legal framework: The existing legal framework, including Nepal's Civil Code (2017) and Land Act (2021), does not recognise AI-generated cadastral data as legally permissible inputs for land registration or dispute resolution. Consequently, the absence of legal recognition for AI-generated cadastral outputs creates significant uncertainty around the validity of AI-assisted tenure documentation and discourages institutional adoption of these approaches.
4. Algorithmic Bias and Inequitable Data Representation: AI models learn patterns from the data on which they are trained. When training datasets are composed predominantly of imagery and records from well-documented, formally registered land areas- typically lowland urban zones or accessible rural areas-the model develops a systematic bias towards recognising those landscape types and tenure arrangements. Inequitable data representation refers to this condition: the underrepresentation of informal settlements, indigenous communal territories, and remote mountainous regions in training datasets relative to their actual prevalence on the ground. In Nepal's context, where the areas of greatest tenure insecurity are precisely those that are most remote and least formally documented, this means AI models are likely to perform worst in the communities that need accurate mapping the most. Consequently, uncritical deployment of such models risks producing outputs that reinforce and deepen existing disparities in land administration rather than correcting them(Ndiema, 2024).
5. Capacity Constraints: Nepal lacks qualified GIS and data science experts, especially outside of Kathmandu. While the Survey Department has been exploring geospatial technologies, national and land administration organisations still lack AI-specific expertise, limiting their ability to develop, deploy and maintain AI- driven land mapping systems.

4. DISCUSSION

The findings of the study are discussed in this section.

4.1 Nepal's AI Land Governance in the International Context

The results from Nepal's case can be effectively compared with those from Rwanda, India, and Kenya, three nations that have made significant progress in implementing AI and digital technologies for land governance, to find both attainable benchmarks and lessons that apply to Nepal's situation.

Rwanda exemplifies a prominent, rapid, technologically enabled land formalisation, through a systematic demarcation process that involved community involvement, aerial photography, and analysis of recent satellite imagery. Rwanda registered about 10.4 million land parcels between 2009 and 2013(Ali et al., 2014). This resulted in nearly universal coverage at a cost of about USD 6–8 per parcel, compared to the global average of USD 20–50 per parcel for conventional methods (World Bank, 2020; UN-Habitat, 2018). AI-generated suitability maps, GIS-based zoning tools, and public dashboards available to both citizens and planners are now features of Rwanda's National Land Use Planning Portal (Ali et al., 2014).

India's experience offers important lessons for a federal and institutionally complex context closer to Nepal. India's Digital India Land Records Modernisation Programme (DILRMP), which aims to digitise all land ownership records and integrate them with GIS platforms, has advanced significantly in states like Karnataka, Andhra Pradesh, and Telangana (Mishra et al., 2025). Even in complex settlement environments, rapid, accurate parcel mapping is achievable, as demonstrated by the SVAMITVA program's use of UAV-based drone surveying, which has mapped over 50,000 villages with sub-decimeter accuracy (Government of India, 2022).

In Nepal's struggle for community and indigenous land rights, Kenya's experience is especially helpful. More than 120 community land parcels totalling 2.3 million hectares in Laikipia County, Kenya (Ali et al., 2014), that had not previously been recorded in official cadastral records were formally registered through a three stage workflow: (i) UAV aerial surveys were conducted to capture high resolution imagery of community land boundaries; (ii) community members participated in ground-truthing and validation of boundary demarcation to ensure local tenure arrangements were accurately reflected; (iii) validated boundaries were digitised and integrated into GIS-based cadastral database for formal registration.

A similar dual legal-technical approach that combines legislative recognition of community tenure with participatory AI-GIS mapping would be beneficial for Nepal's diverse customary tenure landscape, which includes Limbu Kipat, Newari Guthi, and Adivasi Janajati communal territories (Nepal & Marasini, 2018).

4.2. Opportunities for Nepal

Several specific opportunities for Nepal to use AI-driven land tenure mapping within a stronger governance framework are revealed by the comparative analysis. First, with 753 local governments granted authority by the 2015 Constitution, Nepal's federal structure offers a decentralised platform that facilitates the testing and expansion of community-anchored participatory mapping processes that are integrated with the country's AI-GIS infrastructure.

Second, the Survey Department's national topographic database and the ongoing modernisation of DoLMA's Land Information System provide a fundamental spatial data infrastructure that can be enhanced to support AI-driven cadastral applications at relatively low incremental cost (MoLMCPA, 2019). Third, international organisations like UN-Habitat, the World Bank, FAO, and the International Land Coalition are actively supporting land governance reform in Nepal and have demonstrated a willingness to invest in technology-enabled approaches through ongoing projects like the Land Pooling in Urban Areas Project and the Participatory Land Use Management initiative. Fourth, Nepal's growing network of engineering and geomatics graduates trained at Kathmandu University, Tribhuvan University, and Pokhara University offers an emerging human capital base for developing domestic AI-GIS expertise if appropriate training and institutional development investments are made.

4.3. Policy Implications

Based on the analysis, six priority policy actions are recommended for Nepal.

First, legal framework reform is needed. The Land Act (2021) and related regulations should be amended to specifically acknowledge AI-assisted cadastral mapping outputs as legally acceptable inputs for land registration, subject to established community validation and quality assurance standards.

Second, the National AI-GIS land platform should be created. A single, cloud-based National Land Information System under the Survey Department-Nepal's legally designated national mapping agency and primary custodian of spatial data, should incorporate socioeconomic, satellite, cadastral, and participatory data layers and be made available to all 753 local governments.

Third, systematic tenure formalisation using the Fit for Purpose Land Administration (FFPLA) approach (Enemark et al., 2014) represents another alternative. The FFPLA approach should be adopted for the systematic registration of customary and informal tenure, combining community-validated boundary demarcation with AI-assisted imagery interpretation to lower costs and improve coverage.

Fourth, inclusive design and community ownership. All AI-driven mapping programs should require gender-disaggregated data collection, joint titling by default, and indigenous community participation, with clear protocols for capturing women's secondary rights and communal tenure (FAO, 2012).

Fifth, an independent National Geospatial Governance Board should be established with an extensive role to monitor equity outcomes of digital land administration programs, enforce data privacy standards, audit AI systems for algorithmic bias, and guarantee that communities maintain meaningful access to mapping outputs. This ethical governance framework is essential for ensuring that AI- driven approaches serve the public interest.

Sixth, targeted capacity-building programs at national and subnational levels should be established to train GIS and AI professionals, particularly in underserved areas, to enable sustainable implementations of AI-driven land tenure mapping systems.

5. CONCLUSION

This study has examined the potential of AI-driven land tenure mapping and GIS-based Multi Criteria Decision Analysis (MCDA) – as a complementary spatial decision support tool for prioritising tenure formalisation interventions - to strengthen sustainable land governance in Nepal, using secondary data from Nepal's national land administration, international comparative evidence, and the body of research on AI applications in land management.

The analysis shows that AI approaches- specifically, machine learning and deep learning for parcel boundary detection and LULC classification supported by complementary GIS-based tools, for informal tenure documentation, provide technically feasible and economical solutions for Nepal's land tenure challenges. Drawing on international evidence, technology-enabled land formalisation is achievable at scale in developing country contexts as long as community involvement, legal recognition, and institutional capacity are suitably developed alongside technical systems. These comparisons also show how Nepal's federal structure, expanding geospatial human capital, and active international development partnerships offer significant enabling foundations for a national AI land mapping program that can be progressively expanded across the country's diverse terrain and tenure landscape.

However, the study also makes it clear that technology alone cannot solve Nepal's land governance issues. Algorithmic bias, gaps in digital infrastructure, the lack of coordination among multiple land administration institutions, the absence of legal recognition for AI-generated cadastral outputs, and the potential for poorly designed digital systems to replicate existing inequalities all require immediate policy attention.

Realising equitable tenure security outcomes requires integrating AI-driven mapping within an inclusive governance framework grounded in principles of participation, transparency, accountability, and the rule of law. Primary data collection through field-based AI-assisted mapping pilots in particular Nepalese districts, detailed evaluation of algorithmic performance across different terrain and tenure types, and co-design procedures with marginalised communities should be the top priorities for future research. When used responsibly and inclusively, AI-driven land tenure mapping is a truly promising path toward sustainable, equitable, and transparent land governance in Nepal.

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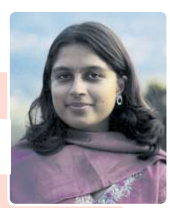

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