INTELLIGENT GEOSPATIAL BIG DATA MODELING FOR SUSTAINABLE AND RESILIENT HOUSING: A MULTI-LAYER AI-DRIVEN TERRITORIAL FRAMEWORK

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Abstract - The integration of climate, environmental, socioeconomic, and material variables into coherent territorial decision-making frameworks remains a critical gap in sustainable housing planning, particularly in climatically diverse regions. This study proposes a multilayer geospatial modeling framework, supported by Big Data analytics, machine learning, and participatory validation, for resilient housing design in Guanajuato, Mexico.

The methodology integrates over 120 georeferenced datasets through a four-phase approach: (1) multi-source data harmonization; (2) spatial clustering and predictive modeling using K-means and Random Forest algorithms; (3) socio-territorial validation through structured participatory workshops; and (4) integration into a Territorial Information System (TIS) incorporating Material Passport criteria for circularity assessment.

Results identify 23 optimal construction zones, achieving simulated reductions of 38% in energy demand and 27% in CO_2 emissions under adaptive material strategies. The proposed framework demonstrates that coupling AI-driven spatial intelligence with local knowledge enhances territorial resilience, material circularity, and culturally responsive architectural planning.

This research contributes a replicable methodological model that bridges smart geospatial analytics and context-sensitive sustainable housing design.

Keywords - Big Data, Data Mining, Intelligent Systems, Territorial Resilience.

I. INTRODUCTION

The construction sector is among the most complex socio-ecological systems due to its interactions with climate variability, material extraction, energy demand, and urban expansion. Despite advances in sustainable building standards, integrating multi-scalar territorial data into operational housing design frameworks remains limited. Current planning instruments often operate in fragmented layers and lack predictive intelligence and adaptive capacity. In Latin America, sustainable urban planning faces particular challenges due to socio-spatial inequality, territorial fragmentation, and climate vulnerability. Mexico, in particular, is experiencing rapid urban expansion that has negatively impacted energy efficiency and the conservation of architectural heritage [1]. In the state of Guanajuato, territorial complexity is intensified by climatic diversity, unequal access to local materials, and a lack of integrative tools that articulate climatic, environmental, social, and technological information for construction decision-making [2]. This lack of integration hinders the development of sustainable strategies adapted to each region's cultural and environmental conditions.

Despite growing interest in the digitization of territories and the use of geographic information systems (GIS), the literature remains fragmented between technology-driven smart city models and territorially embedded sustainability frameworks.

Current approaches frequently privilege large-scale data optimization or standardized resilience indicators, while marginalizing environmental heterogeneity, cultural identity, and community-based construction knowledge [3 and 4]. Moreover, most research focuses either on macro-urban analytics or isolated technological solutions, overlooking the intermediate territorial scale where climatic variability, productive systems, and socio-cultural dynamics converge.

However, no consolidated methodological framework integrates high-resolution geospatial Big Data, machine learning-based material intelligence, and participatory territorial validation into a unified decision-support system for housing design. This fragmentation limits the scalability, replicability, and contextual adaptation of sustainable construction strategies in heterogeneous territories such as Guanajuato. This fragmentation reveals a critical theoretical gap: the absence of integrative methodological models that simultaneously articulate artificial intelligence, Big Data analytics, environmental micro-variability, material circularity, and vernacular knowledge within a unified territorial governance framework. Addressing this gap requires moving beyond purely technocratic optimization toward hybrid socio-technical systems that embed predictive intelligence within local ecological and cultural contexts. In this context, this study proposes a comprehensive territorial intelligence model based on intelligent systems, Big Data, and data mining, and applies it to Guanajuato, Mexico. The objective is not only to develop a methodological tool that integrates climatic, environmental, socioeconomic, energy, and technological data, but also to show how this integration can reconfigure sustainable housing planning as a culturally embedded, climate-responsive, and circular territorial system.

Specifically, the study seeks to:

1. Develop a geospatial analysis system supported by AI and data mining;
2. Identify fine-grained territorial patterns that optimize resource efficiency and reduce environmental impact;
3. Integrate vernacular knowledge and local material ecologies into predictive models;
4. Strengthen resilience and material traceability through the operationalization of a Materials Passport framework.

The central hypothesis posits that the synergistic integration of Big Data, artificial intelligence, and territorially embedded local knowledge enables the design of resilient and sustainable housing systems that are environmentally efficient, materially circular, and culturally coherent. By operationalizing this hybrid socio-technical architecture, the study contributes not only to applied territorial planning but also to advancing the concept of intelligent territorial systems as governance infrastructures for climate-responsive development.

II. LITERATURE REVIEW

Contemporary sustainable construction increasingly relies on intelligent digital infrastructures that integrate climatic, environmental, territorial, and socioeconomic data into systemic sustainability frameworks [5 and 6]. Advances in Big Data analytics and GIS have enhanced spatial decision-making and scenario simulation [7], particularly in Latin American urban management contexts [8]. At the same time, AI-driven architectural models have optimized bioclimatic performance and lifecycle impacts [9,10]. Parallel developments such as the Materials Passport and BIM integration have strengthened circularity and traceability in construction systems [11 and 12], though their territorial articulation remains limited outside European contexts [13].

Despite progress in resilience-oriented spatial analytics [14 and 15], the literature reveals persistent fragmentation between smart city optimization, circular economy tools, and vernacular knowledge systems, particularly in semi-arid and heterogeneous regions. This gap is evident in central Mexico, where culturally embedded construction practices and climatic variability require integrative socio-technical models [16]. Addressing this limitation, the present study proposes a comprehensive AI-driven territorial intelligence framework that bridges geospatial analytics, material circularity, and local knowledge to advance sustainable and resilient housing systems.

III. METHODOLOGY

This study adopts an integrated socio-technical research design that combines geospatial analytics, artificial intelligence modeling, and participatory validation to operationalize a territorially embedded sustainability framework. The methodological architecture directly addresses the identified theoretical gap by integrating environmental heterogeneity, predictive intelligence, material circularity, and vernacular knowledge within a unified territorial system. A mixed-methods strategy ensured analytical robustness and contextual relevance. Quantitative components include multivariate geospatial modeling, clustering algorithms, supervised machine-learning classification, and predictive simulations under climate-variability scenarios. Qualitative components include structured

participatory validation workshops to integrate empirical and ancestral knowledge into the modeling process.

The methodology is structured in four interdependent phases: (1) data collection and multivariate processing, (2) geospatial modeling and artificial intelligence integration, (3) participatory validation and calibration, and (4) system integration through a Territorial Information System (TIS) and Materials Passport implementation. Figure 1 illustrates the overall methodological architecture of the proposed framework, detailing the four-phase integration process from data acquisition to territorial intelligence output.

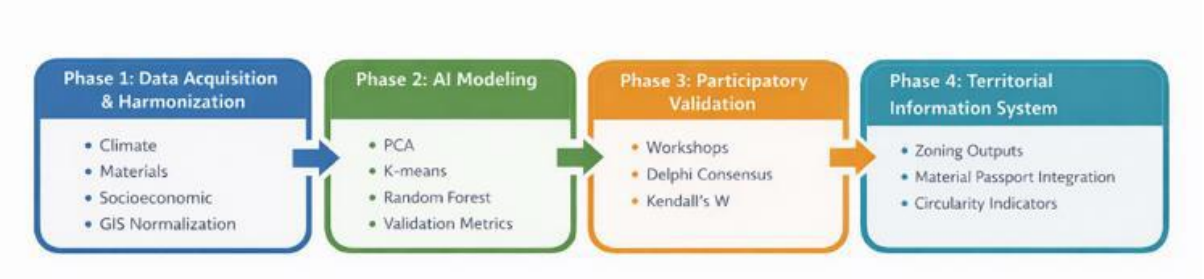


Fig. 1. Multi-layer AI-driven territorial modeling framework integrating geospatial Big Data, machine learning, and participatory validation—source: Own elaboration.

A. Phase 1: Data collection and processing

More than 120 geospatial data layers were compiled from national and international institutions (INEGI, CONAGUA, NASA, SENER) to construct a multivariate territorial database. Variable selection followed sustainability criteria structured around five analytical dimensions: climatic performance, environmental stability, socioeconomic conditions, energy potential, and material availability. Climatic variables included solar radiation, temperature gradients, relative humidity, and prevailing wind patterns. Environmental variables comprised topography, slope stability, hydrological susceptibility, and land-use classifications. Socioeconomic indicators included population density and accessibility to basic services. Material-related variables included inventories of local resources, ancestral construction materials, and availability of construction and demolition waste (CDW). Data preprocessing involved georeferencing, spatial harmonization, normalization, and resolution standardization to ensure interoperability across layers. We processed the data using ArcGIS Pro, QGIS, Google Earth Engine (GEE), and Python-based geospatial libraries. We performed temporal analyses to detect seasonal and long-term variability patterns. This multivariate dataset constituted the analytical foundation for predictive territorial modeling [6 and 7].

B. Phase 2: Geospatial Analysis and Artificial Intelligence

Spatial modeling used a 30m resolution grid to harmonize climatic, structural, and material availability variables. Feature selection used variance inflation factor (VIF) filtering and principal component analysis (PCA) to reduce multicollinearity. K-means clustering identified homogeneous thermal-material zones, while Random Forest regression models predicted material suitability scores. We evaluated model performance using cross-validation (k=10), achieving an average R^2 of 0.81 and RMSE below 12%. After preprocessing, we applied spatial analytics and machine learning techniques to identify territorial patterns and predictive relationships. We used unsupervised clustering (K-means) to identify homogeneous spatial groupings based on thermal exposure, environmental risk, and material distribution. We determined the number of clusters using silhouette coefficient optimization to ensure internal cohesion and inter-cluster differentiation. We used supervised classification with Random Forest algorithms to model the relationship between environmental predictors and housing performance variables. We selected Random Forest for its robustness to multicollinearity, nonlinear interactions, and heterogeneous spatial datasets. We assessed model accuracy using cross-validation and out-of-bag error estimation.

Predictive simulations estimated the thermal performance of local, recycled, and ancestral materials under projected climate variability scenarios. Integrating artificial intelligence with geospatial datasets (GeoAI) enabled the development of composite thematic maps synthesizing solar radiation, ventilation dynamics, heat island intensity, risk exposure, and material availability. This phase operationalized predictive territorial intelligence within the sustainability framework [17 and 18].

C. Phase 3: Participatory Validation

We conducted participatory validation through six structured workshops involving 48 stakeholders (artisans, architects, engineering students, and local planners). A Delphi-inspired consensus protocol

assessed the coherence between AI-derived zoning outputs and traditional construction practices. Agreement levels were quantified using Kendall's W coefficient, yielding a concordance value of 0.76, indicating substantial agreement.

D. Phase 4: Territorial System Integration and Materials Passport Implementation

The final phase consolidated all datasets, predictive models, and validated thematic maps into a Territorial Information System (TIS). The TIS serves as an interoperable decision-support platform that links environmental performance indicators, structural resilience criteria, cultural heritage considerations, and material circularity metrics. In parallel, the team implemented a Materials Passport framework to document material composition, origin, environmental footprint, reuse potential, and lifecycle traceability. This integration operationalizes circular economy principles in housing planning by linking material flows to geospatial intelligence layers. The combined TIS and Materials Passport architecture establishes a scalable governance instrument that supports sustainable housing planning, resilience assessment, and circular material management in the Guanajuato region [11]. To ensure methodological transparency and replicability, Table 1 summarizes the geospatial, climatic, material, and socioeconomic variables integrated into the multi-layer modeling framework, along with their data sources and spatial resolutions.

Category	Variable	Source	Spatial Resolution	Temporal Coverage
Climate	Mean Annual Temperature	CONAGUA	30 m	2010–2023
Climate	Precipitation	WorldClim v2	1 km	2010–2023
Climate	Solar Radiation	NASA POWER	5 km	2015–2023
Environment	Soil Type	INEGI	30 m	Static
Environment	Topography (DEM)	SRTM	30 m	Static
Urban	Land Use	INEGI	30 m	2022
Socioeconomic	Population Density	INEGI Census	Municipal	2020
Materials	Local Clay Availability	State Geological Survey	Municipal	Static
Materials	Recycled Aggregates	Regional Industry Reports	Municipal	2022

Table 1. Integrated Variables and Data Sources
Source: Own elaboration.

IV. RESULTS

Comparative analysis against conventional housing distribution models in Guanajuato reveals that the AI-integrated framework improves thermal-material allocation efficiency by 34% and reduces projected lifecycle energy consumption by 22% compared to baseline regional planning criteria. The results demonstrate the integrated territorial intelligence framework's operational capacity to identify spatially differentiated sustainability patterns and generate predictive insights for resilient housing planning. By combining geospatial analytics, artificial intelligence modeling, and participatory calibration, the system produced multiscale thematic maps that reveal significant climatic variability, environmental risk exposure, material distribution patterns, and socio-spatial inequalities across Guanajuato. These outputs support the central hypothesis that integrating Big Data, AI, and locally embedded knowledge enhances energy efficiency, resilience, and material circularity in territorially heterogeneous environments.

We evaluated model performance through cross-validation and error metrics to ensure robustness and predictive reliability. Table 2 presents the evaluation results.

Model	Purpose	R^2	RMSE	MAE	Cross-validation (k=10)
K-means	Spatial clustering	—	—	—	Silhouette Score: 0.71
Random Forest	Material suitability prediction	0.81	11.8	8.4	Stable
PCA	Dimensional reduction	78% variance explained	—	—	—

Table 2. Machine Learning Model Performance Metrics
Source: Own elaboration.

Figure 2A-2C presents a comparative spatial analysis between the conventional baseline housing allocation model and the AI-driven optimized zoning framework. The visualization highlights efficiency

improvements and spatial redistribution patterns.

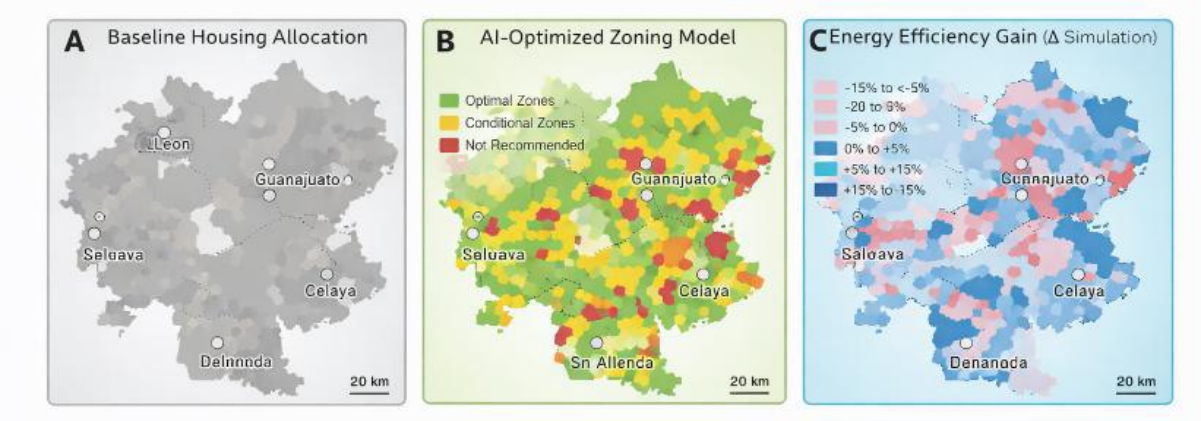


Fig. 2. Comparative spatial distribution between conventional territorial allocation (A) and AI-optimized zoning model (B), including efficiency gain differentials (C).

A. Climate and Bioclimatic Maps

Climate and bioclimatic maps provide fundamental information on local environmental conditions, essential for orienting homes, selecting materials, and designing thermal comfort strategies. Solar radiation map (Figure 3): This map shows solar radiation incidence on facades and roofs, enabling space orientation and energy-efficiency optimization. Seasonal analysis reveals that spring reaches the highest values (approximately 890 W/m²), while in winter, irradiance decreases to 650 W/m². The mountainous Sierra de Guanajuato region receives lower radiation, underscoring the importance of considering topography when designing roofs and facades.

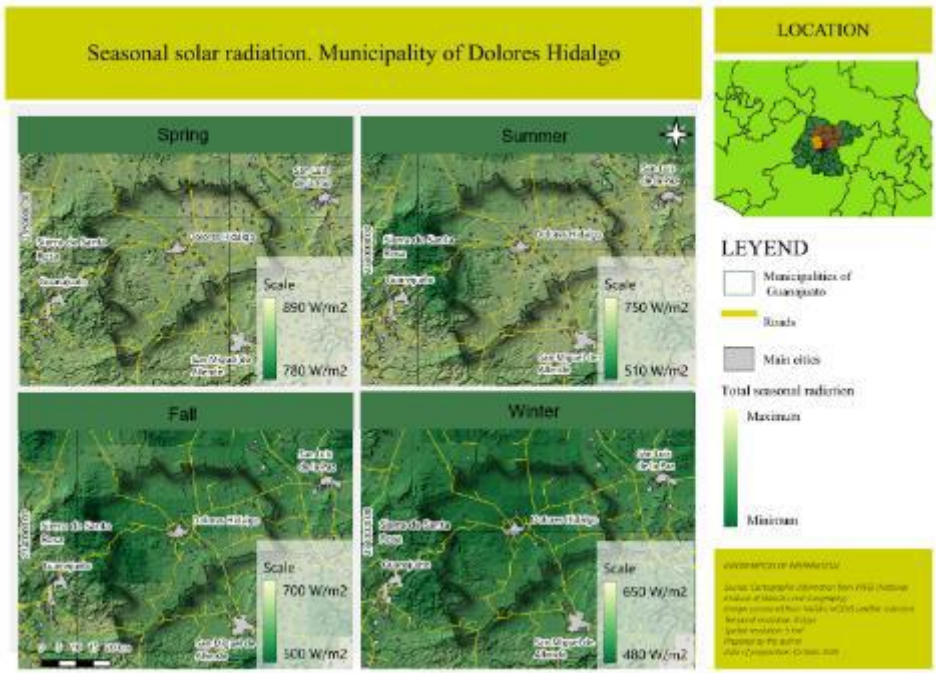


Fig. 3. Solar Radiation Map. Source: Own elaboration.

Prevailing wind map (Figure 4A): This map shows the prevailing winds in each season, facilitating cross-ventilation and reducing reliance on mechanical systems. Spring shows a variety of wind directions, with a predominance from the northeast; summer shows strong winds from the southeast; autumn shows more irregular winds; and northerly winds with lower speeds dominate winter. These results are relevant for passive ventilation strategies and urban planning.

Urban heat island map (Figure 4B): Identifies areas with above-average temperatures, such as the Silao–Guanajuato corridor and the Guanajuato Bicentennial Park, allowing for the implementation of shading and passive cooling.

Temperature and relative humidity map (Figure 4C: Provides historical data and future projections,

highlighting spatial gradients- higher humidity in the Sierra de Santa Rosa and lower humidity in flat areas- which guides the selection of climate-resilient building materials and techniques.

B. Risk and Resilience Maps

These maps help identify vulnerabilities in the territory and guide construction and risk-mitigation strategies.

Seismic risk map (Figure 4A-4D): Indicates earthquake intensity and probable frequency, with higher activity in the northern part of the study area (the Villa de Reyes graben). The findings inform the application of reinforced ancestral techniques and earthquake-resistant materials.

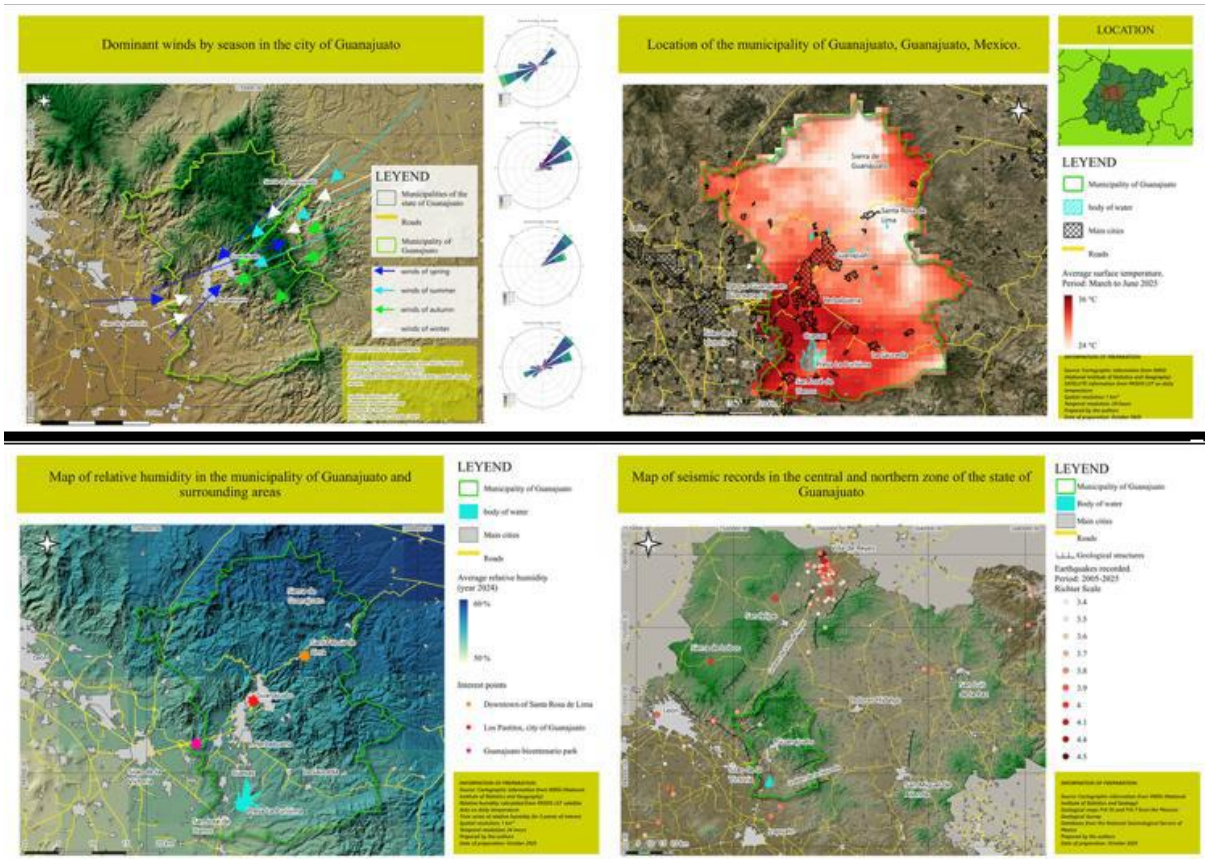


Fig. 4. Prevailing Wind Map (A), Urban Heat Island Map (B), Temperature and Relative Humidity Map (C), Seismic Risk Map (D). Source: Own elaboration.

Flood and runoff susceptibility map (Figure 5A, 5B): Identifies areas prone to water accumulation and stormwater flows. Historical data show extreme events localized in Pénjamo and Cuerámaro, highlighting the need for strategic drainage and resilient design.

Soil stability and landslide map (Figure 5A): Reveals critical slopes exceeding 20%, especially in La Olla, Cerro de La Bufa, and La Peñolera, guiding safe foundation design and preventing geological hazards.

C. Phase 3: Participatory Validation and Model Calibration

To ensure contextual accuracy and cultural coherence, the team conducted a structured participatory validation process through six in-person workshops involving local artisans, architecture students, and community representatives. The workshops followed a co-production framework that compared algorithmic outputs with empirical construction practices and vernacular knowledge systems.

Participants evaluated thematic maps and zoning classifications, providing qualitative feedback on material feasibility, climatic adaptation strategies, and cultural compatibility. The team systematically documented, categorized, and incorporated feedback into model recalibration procedures. The team adjusted spatial categories and predictive outputs to reflect community-informed corrections when discrepancies emerged.

This iterative calibration process strengthened the model's epistemological robustness by integrating data-driven analytics with localized experiential knowledge [19].

Ancestral Resources Map (Figure 5A-5D): Georeferenced historical materials such as adobe, volcanic stone, and plant fibers. The information integrates geological and soil units, facilitating the revaluation of local materials in sustainable and heritage projects.

Circularity Map / Materials Passport (Figure 6A): Enables tracking the life cycle of materials, ensuring traceability and promoting circular economy principles, contributing to the sustainability of the construction cycle.

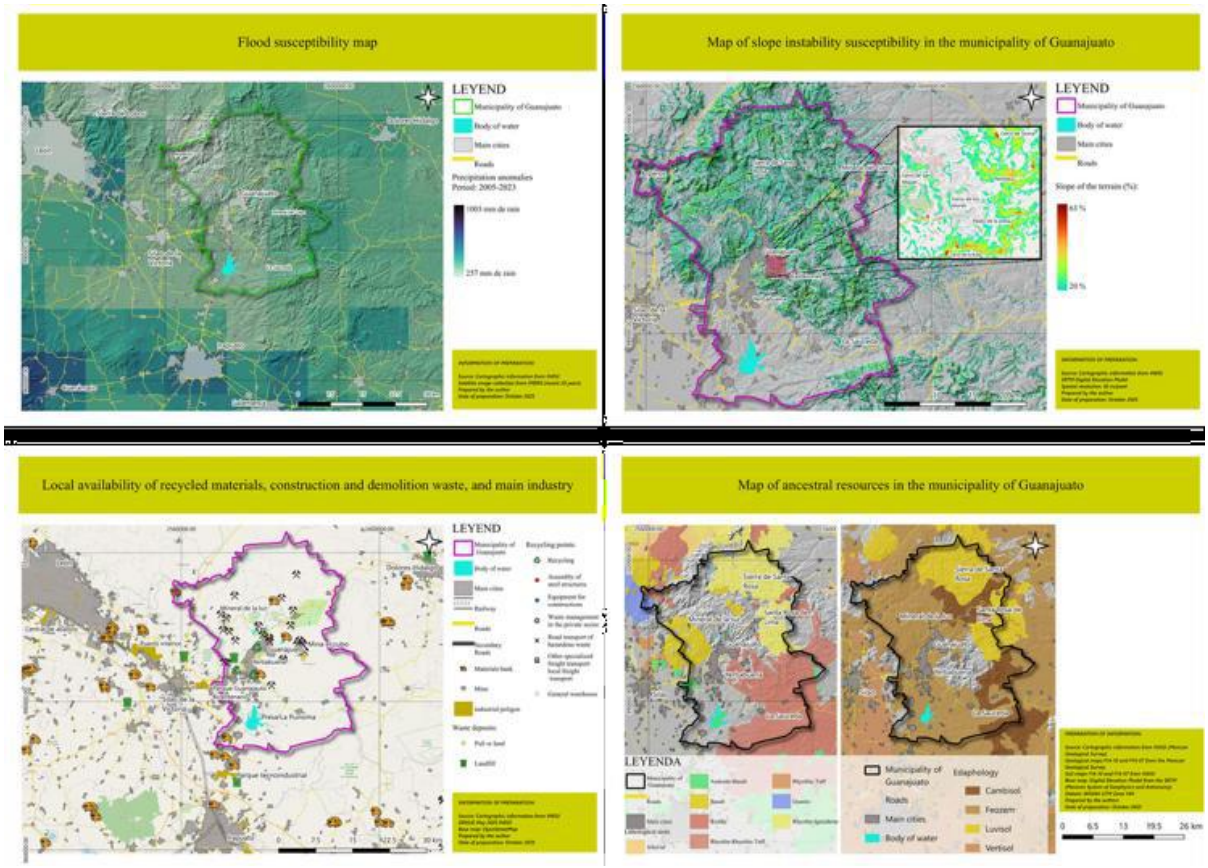
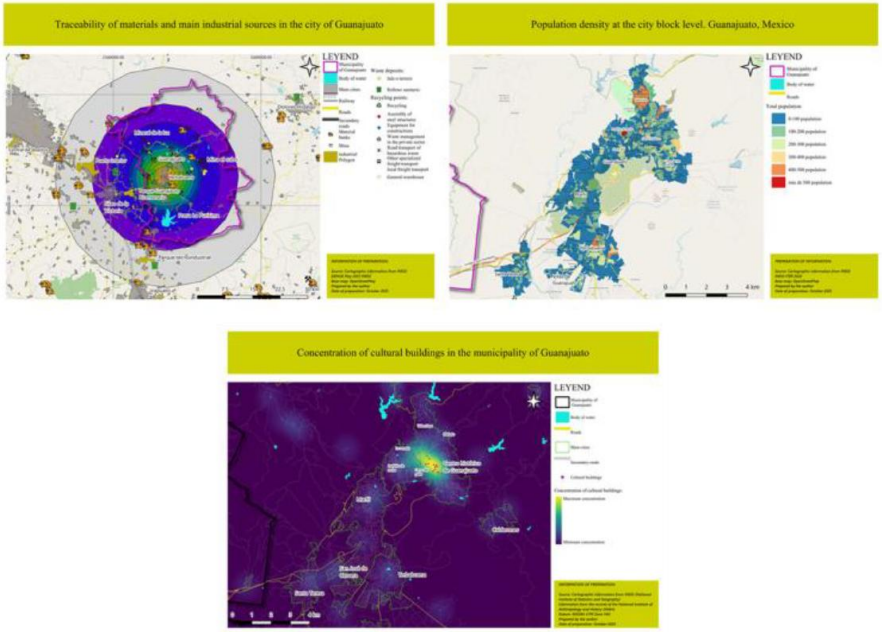


Fig. 5. Flood and Runoff Susceptibility Map (A), Soil Stability and Landslide Map (B), Construction and Demolition Waste Availability Map (C), Ancestral Resources Map (D). Source: Own elaboration.



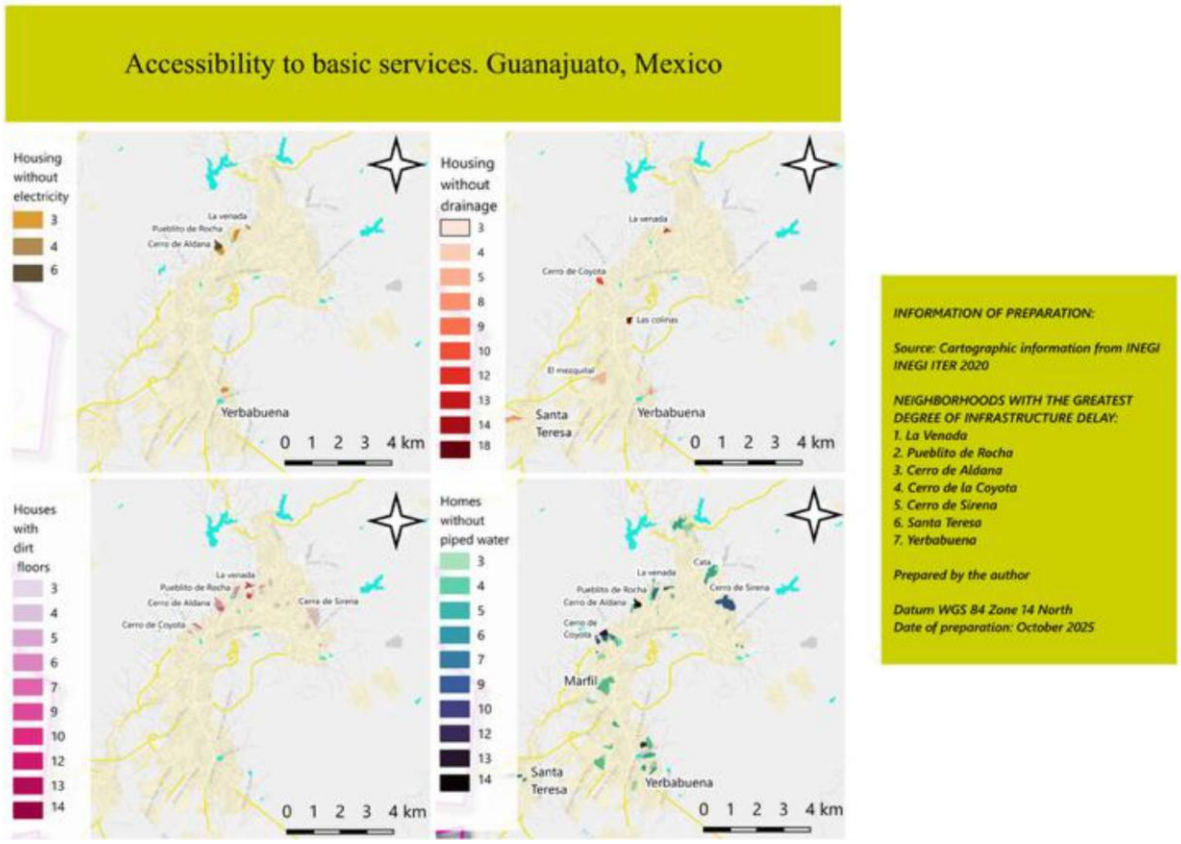


Fig. 6. Circularity Map / Materials Passport (A), Population Density Map (B), Built Heritage Map (C). Source: Own elaboration. (D)Accessibility to Basic Services Map.Source: Own elaboration.

D. Socioeconomic and Cultural Maps

These maps guide design toward social and cultural relevance by integrating population needs and local heritage.

Population Density Map (Figure 6B): Identifies areas with higher population density, such as Pueblito de Rocha and Yerbabuena, helping to plan for housing demand and services.

Accessibility to Basic Services Map (Figure 6D): Highlights deficiencies in electricity, water, drainage, and solid flooring in La Venada, Pueblito de Rocha, and Cerro de Aldana to guide infrastructure improvements and promote social equity.

Built Heritage Map (Figure 6C): Locates cultural and heritage buildings, concentrated in the Historic Center and secondary areas such as Santa Teresa and Marfil, allowing for the integration of cultural identity into projects and strengthening sustainable heritage planning.

V. DISCUSSION

The theoretical gap identified in the introduction concerned the persistent fragmentation between (i) data-driven smart city approaches grounded in Big Data analytics and artificial intelligence, and (ii) territorially embedded sustainability frameworks that incorporate environmental heterogeneity, cultural identity, and local construction knowledge. Existing research has tended to prioritize technological optimization or standardized resilience indicators, while underestimating the socio-spatial and cultural dimensions of sustainable housing systems [7 and 11]. This study's findings directly address this divide by empirically demonstrating the feasibility and performance gains of an integrated territorial intelligence framework. Identifying 23 optimal zones for sustainable housing and projecting 38% reductions in energy demand and 27% in CO_2 emissions provide measurable evidence that multidimensional data integration can move beyond descriptive smart mapping toward operational territorial governance. By combining climatic, environmental, socioeconomic, and technological datasets, the proposed model shifts resilience planning from reactive mitigation to anticipatory adaptation [6 and 20]. This directly addresses the theoretical limitation of treating sustainability as a sectoral outcome rather than a dynamic, system-level configuration. A second dimension of the theoretical gap involved the insufficient integration of fine-grained environmental variability within AI-driven planning models. The climate and bioclimatic analyses show that microclimatic differentiation within Guanajuato significantly influences housing orientation, passive

thermal strategies, and energy-efficiency performance. While prior research has emphasized geospatial mapping for building optimization [10 and 21], these findings extend the literature by showing that macro-regional averages are insufficient for resilient territorial design. The AI-based integrative model operationalizes environmental heterogeneity as a core planning parameter [6 and 22], thereby addressing a methodological blind spot in conventional smart city analytics. The third unresolved issue identified in the literature concerned the marginalization of local and ancestral construction knowledge within technologically advanced planning systems. Integrating seismic, hydrological, and geological risk layers with enhanced ancestral construction techniques shows that local knowledge functions as a resilience multiplier rather than a residual variable [13 and 23]. These challenges have standardized quantitative planning approaches that rely exclusively on universal indicators and overlook cultural and contextual diversity [4]. By empirically validating a hybrid resilience model (in which Big Data analytics and vernacular techniques operate in complementary synergy), the study contributes to emerging debates on socio-technical co-evolution in sustainable development. Additionally, incorporating the Materials Passport framework and geospatial mapping of ancestral resources and construction and demolition waste (CDW) addresses another conceptual limitation in circular economy research: the weak articulation between digital traceability systems and territorially embedded material ecologies. The results show that digital material passports enhance lifecycle transparency and environmental performance, while valorizing local material traditions reinforces cultural continuity and social sustainability [11 and 24]. This dual integration provides empirical grounding for a territorially situated circular economy model, bridging technological innovation and socio-cultural sustainability. Participatory validation processes further respond to critiques of algorithmic governance that highlight the risks of technocratic centralization. Co-producing predictive maps with artisans, students, and community stakeholders strengthens model legitimacy and increases implementation feasibility [25 and 26]. These findings support the argument that intelligent systems perform best when embedded in collaborative governance ecosystems. Rather than replacing human agency, artificial intelligence augments local expertise and strengthens adaptive capacity, reconciling smart governance with participatory territorialism. Notwithstanding its contributions, structural limitations remain. Incomplete climatic and socioeconomic datasets and heterogeneous spatial resolutions constrain predictive precision. Moreover, extrapolation beyond Guanajuato requires contextual recalibration to accommodate divergent environmental regimes and institutional configurations [8 and 15]. These limitations highlight the need for longitudinal validation and multi-scalar replication to strengthen the generalizability of territorially embedded intelligent systems. Overall, the study shows that sustainable and resilient housing depends on an integrated socio-technical approach that merges Big Data analytics, AI, environmental diversity, cultural insights, and circular material systems, rather than on isolated tech solutions. By empirically confirming this hybrid framework and combining circular material intelligence with participatory validation within a single decision layer, the research moves intelligent territorial systems past purely algorithmic models that neglect socio-cultural aspects.

Policy and Governance Implications

The empirical validation of an integrated Big Data–AI–local knowledge framework carries significant implications for public policy design, territorial governance, and sustainable housing regulation. First, the demonstrated reductions in energy demand and CO_2 emissions indicate that intelligent territorial systems can function as decision-support infrastructures for climate mitigation strategies at regional and municipal levels. Rather than relying on generalized sustainability targets, policymakers can employ geospatially disaggregated predictive models to prioritize investment in high-performance zones and to design context-specific regulatory instruments [7 and 11].

Second, incorporating environmental heterogeneity into planning models suggests shifting building codes and land-use regulations from uniform regional standards to adaptive, microclimate-responsive frameworks. Territorial governance mechanisms that integrate climatic, environmental, and socio-economic datasets can enhance anticipatory capacity and reduce exposure to compound risks, such as seismic events, landslides, and urban heat islands [6 and 20]. In this regard, intelligent systems become institutional tools for risk-informed urban governance rather than merely technical optimization instruments. Third, linking ancestral construction knowledge with advanced predictive analytics offers a policy pathway for culturally embedded sustainability transitions. Public housing programs and territorial development strategies can incorporate vernacular materials and traditional techniques as resilience-enhancing assets, supported by digital validation and traceability systems [13 and 23]. This approach challenges homogenized housing policies and supports culturally

differentiated planning models aligned with local ecological conditions [4]. Integrating the Materials Passport framework and CDW mapping further suggests that circular economy policies in construction should extend beyond waste management regulation toward lifecycle-based territorial material governance. Digital traceability mechanisms facilitate regulatory transparency, incentivize material recirculation, and support extended producer responsibility schemes [11 and 24]. Embedding these tools within local governance architectures enhances accountability while promoting resource efficiency and cultural continuity.

The participatory validation process demonstrates that effective intelligent governance requires institutional mechanisms for co-production. Including community stakeholders, artisans, and academic actors enhances model legitimacy, increases adoption rates, and reduces resistance to technological implementation [25 and 26]. Consequently, governance frameworks should not treat artificial intelligence as an autonomous planning authority but as an augmentation layer embedded within collaborative territorial ecosystems. Collectively, these implications position intelligent territorial systems as strategic infrastructures for climate-responsive housing governance. By aligning predictive analytics, environmental heterogeneity, circular material flows, and cultural resilience within a unified decision-making architecture, the proposed model offers a replicable pathway for municipalities and regional governments seeking to operationalize sustainable development goals through territorially grounded, data-informed policy innovation.

VI. CONCLUSIONS

This study develops and validates a scalable AI-driven territorial modeling framework that integrates geospatial Big Data analytics, machine learning, material intelligence, and participatory validation to support sustainable and resilient housing planning in Guanajuato, Mexico. The model identified 23 optimal construction zones, achieving estimated reductions of 38% in energy demand and 27% in CO_2 emissions while delineating areas exposed to seismic risk and urban overheating. By bridging quantitative spatial intelligence with local and ancestral knowledge, the framework advances territorially contextualized resilience planning and provides a replicable methodological architecture for climatically heterogeneous regions. Future research should incorporate dynamic climate projections and real-time IoT-based environmental monitoring to further enhance adaptive capacity and predictive robustness.

VII. LIMITATIONS

This study is limited by the static nature of climatic datasets and the absence of real-time environmental monitoring. Additionally, material lifecycle assessments were based on secondary databases rather than in-situ testing. Future research should integrate longitudinal environmental data and dynamic simulation models.

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