



LEGAL AND SPATIAL PERSPECTIVES ON SUSTAINABLE BUILT-UP LAND CONVERSION CONTROL IN PEKANBARU

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ABSTRACT

The rapid expansion of built-up land, measured as Impervious Surface Area (ISA), in Pekanbaru City has raised concerns about urban sustainability and regulatory compliance. This study develops a sustainable control model for built-up land growth integrating normative-legal and empirical-spatial perspectives. Using the Spatial Sustainability Assessment Model (SSAM) and GIS, 702,556 raster pixels of spatial data were analyzed, and systematic sampling generated 76 sample points for logistic regression analysis. Sixty-seven independent variables were examined, comprising biophysical (12), social (31), and economic (24) factors. Ensemble machine learning models, particularly CatBoost with GoldenFeatures, were applied to predict ISA growth and identify key drivers, including urban land values, population density, and the location of health and education facilities. Findings indicate that weak enforcement of relevant laws and regional regulations exacerbates unregulated land conversion. The study provides actionable insights for local governments, recommending stricter zoning enforcement, alignment with environmental laws, and targeted monitoring of high-risk areas to achieve sustainable urban growth. It recommends using the model for risk-based monitoring, enabling a shift from reactive penalties to proactive zoning enforcement to achieve sustainable urban growth.

1. Introduction

Climate change and biodiversity loss are among the most urgent ecological challenges confronting the world today, with approximately 25% of their causes originating from land use change.¹ Land, as a physical environment encompassing climate, topography, soil, water, and vegetation, performs essential ecological functions as a habitat and socio-economic functions as a means of production and a commodity of economic value.² Its utilization is influenced by a combination of physical and biological factors such as soil suitability, water availability, climate, and biodiversity, as well as economic factors including profitability, market access, and transportation.

Humans are the main actors behind the change in land use from rural to urban environments in an effort to achieve better welfare.³ According to Rustiadi and Panuju,⁴ land conversion is an inevitable consequence of socio-economic transformation, often resulting in inefficient allocation. This process generally begins with changes in land ownership, which are frequently accompanied by the weakening of land resource control structures.⁵ A major driver of land conversion is road development, which facilitates the movement of goods and people through inter-regional and toll networks. While such infrastructure improves connectivity, reduces travel time, and alleviates congestion, it simultaneously contributes to forest loss, declining agricultural productivity, and ecological degradation.⁶

In regional development theory, Friedmann and Chile⁷ argue that growth

¹ Corinne Le Quéré, Robbie M. Andrew, Pierre Friedlingstein, Stephen Sitch, Julia Pongratz, Andrew C. Manning, Jan Ivar Korsbakken et al., "Global carbon budget 2017," *Earth System Science Data*, Vol.10, no.1, 2018, page.412.

² Chun-Chang Lee, Li-Yun Huang, and Shu-Man You., "The changes and trends in urban land prices: an application of hierarchical growth modelling," *Asian Economic and Financial Review* Vol.3, no.5, 2013, page.579. See too, Ketil Skogen, Håvard Helland, and Bjørn Kaltenborn., "Concern about climate change, biodiversity loss, habitat degradation and landscape change: Embedded in different packages of environmental concern?" *Journal for Nature Conservation*, Vol.44, no.12, 2018, page.18.

³ Jing Gao, and Brian C. O'Neill., "Mapping global urban land for the 21st century with data-driven simulations and Shared Socioeconomic Pathways," *Nature communications*, Vol.11, no.1, 2020, page.2302.

⁴ Ernan Rustiadi, and Dyah Retno Panaju., "Spatial pattern of suburbanization and land-use change process: case study in Jakarta suburb," In *Land Use Changes in Comparative Perspective*, New York, CRC Press, 2002, page.35.

⁵ Janthy Trilusianthy Hidajat, S. R. P. Sitorus, and E. Rustiadi., "Urban sprawl effects on settlement areas in urban fringe of Jakarta Metropolitan Area," *J Environ Earth Sci*, Vol.3, no.12, 2013, page.175.

⁶ Jafar Mukhlis, and Sugiono Soetomo., "Analisis pengaruh exit toll terhadap tata guna lahan di Kabupaten Brebes," *Jurnal Pembangunan Wilayah & Kota*, Vol.13, no.3, 2017, page.329. See too, JDIH Marves., "Permen PUPR 6/2023: Badan Pengaturan Jalan Tol," *Kementerian Koordinator Infrastruktur dan Pembangunan Kewilayahan*, May 30, 2023. <https://jdih.kemenkoinfra.go.id/en/permen-pupr-62023-badan-pengaturan-jalan-tol>.

⁷ J. Friedmann., "A general theory of polarized development. Ford Foundation, Urban and Regional Development Advisory Program in Chile," *Santiago*, Vol.81, no.11, 1967, page.112.

originates in core areas through cumulative innovation, diffusing outward to peripheral zones with lower interaction potential.⁸ Pekanbaru, as the capital of Riau Province, exemplifies this pattern, having undergone rapid transformation driven by infrastructure expansion, socio-cultural shifts, and evolving economic structures. Developments such as toll roads, airports, and shopping centers stimulate growth yet also create spatial and environmental challenges. Dijkstra et al.⁹ define urban agglomeration as the concentration of populations in neighboring zones forming a continuous built-up area, encompassing cities and suburban regions. This spatial configuration facilitates the analysis of urbanization dynamics and land use change.¹⁰ Furthermore, Zhang et al.¹¹ categorize three centrality measures, namely degree, betweenness, and closeness, building on Freeman,¹² who suggested their use to assess interaction, importance, and efficiency within urban networks. These metrics remain interrelated under specific spatial conditions.

Land use change, particularly the conversion of rural land into urban areas, must be effectively regulated through coherent legal and spatial governance instruments, as its impacts contribute directly to environmental degradation and climate instability.¹³ Two important components in urban areas are impervious surfaces and green open spaces, which are crucial to creating livable and sustainable cities.¹⁴ The urban sprawl of Pekanbaru City illustrates a clear gap between regulatory objectives and their implementation. Since the early 2000s, suburban areas such as Panam (Tuah Madani District) and Parit Indah (Bukit Raya District) have undergone rapid conversion into built-up areas.¹⁵ Pekanbaru, which has pursued a vision of becoming a Civil Metropolitan City since 2001, expanded administratively from eight to twelve districts following the enactment of spatial planning regulations aimed at promoting sustainable and well-managed growth

⁸ Chong Peng, and Hongwei Xu., "Universities and cities: The impact of higher education on urban innovation, entrepreneurship, and economic growth," *Asian Economic Papers* Vol.23, no.2, 2024, page.36.

⁹ Lewis Dijkstra, Aneta J. Florczyk, Sergio Freire, Thomas Kemper, Michele Melchiorri, Martino Pesaresi, and Marcello Schiavina., "Applying the degree of urbanisation to the globe: A new harmonised definition reveals a different picture of global urbanisation," *Journal of Urban Economics*, Vol.125, no.11, 2021, page.112.

¹⁰ Fangqu Niu, Xinyu Yang, and Fang Wang., "Urban agglomeration formation and its spatiotemporal expansion process in China: From the perspective of industrial evolution," *Chinese Geographical Science*, Vol.30, no.3, 2020, page.537.

¹¹ Shuyan Zhang, Yong Ma, Erping Shang, Wutao Yao, Ke Qiao, Jian Peng, Jin Yang, and Chun Feng., "Production of Annual Nighttime Light Based on De-Difference Smoothing Algorithm," *Remote Sensing*, Vol.16, no.16, 2024, page.3015.

¹² Linton C. Freeman., "Centrality in social networks conceptual clarification," *Social networks*, Vol.1, no.3, 1978, page.223.

¹³ Belinda Arunarwati Margono, Peter V. Potapov, Svetlana Turubanova, Fred Stolle, and Matthew C. Hansen., "Primary Forest cover loss in Indonesia over 2000–2012," *Nature climate change*, Vol.4, no.8, 2014, page.732.

¹⁴ Xiaoping Liu, Yinghuai Huang, Xiacong Xu, Xuecao Li, Xia Li, Philippe Ciais, Peirong Lin et al., "High-spatiotemporal-resolution mapping of global urban change from 1985 to 2015," *Nature Sustainability*, Vol.3, no.7, 2020, page.567.

¹⁵ Yusra Aulia Sari, and D. Dewanti., "Perubahan Penggunaan Lahan Dan Faktor-Faktor Yang Mempengaruhi Di Sekitar Area Panam Kota Pekanbaru," In *Seminar Nasional Geomatika*, Vol.3, no.751, 2019, page.2018.

(*das sollen*).¹⁶ However, actual development (*das sein*) often proceeds without strict adherence to zoning requirements, resulting in uncontrolled increases in impervious surface area, environmental degradation, and inefficient land use. This problem is closely related to ongoing land conversion in the suburbs, further accelerated by key policy decisions such as the relocation of government office complexes and the development of the Tenayan Industrial Estate under Regional Regulation Number 4 of 2016.

To address this challenge, Pekanbaru has enacted Regional Regulation Number 7 of 2020 concerning the 2020–2040 Regional Spatial Plan (*Rencana Tata Ruang Wilayah/RTRW*), which aims to balance growth with environmental sustainability. However, law enforcement remains weak, and development often ignores zoning mechanisms and environmental assessments. In this context, previous studies have explored that forecasting approaches when combined with artificial intelligence, offer significant potential to improve predictive planning and support more accountable urban management.¹⁷

At the national level, Law Number 26/2007 on Spatial Planning remains the foundation for sustainable land use governance, but core provisions on zoning control and environmental protection have been significantly weakened by Omnibus Law Number 11/2020 on Job Creation and its replacement, Law Number 6/2023. These reforms prioritize investment facilitation by centralizing licensing authority and reducing oversight by local governments, thereby weakening enforcement of spatial plans and increasing vulnerability to uncontrolled urban expansion. Meanwhile, Law Number 32/2009 on Environmental Protection and Management still suffers from overlapping jurisdictions, fragmented coordination, and weak sanctions, further exacerbating regulatory failures in rapidly growing cities like Pekanbaru. The combination of deregulatory changes and implementation gaps has systematically weakened spatial and environmental control across Indonesia.¹⁸

¹⁶ Yudin Wan Rahmah, and Zaili Rusli., "Tata Kelola Kota Pekanbaru Menuju Smart City Madani," *Jurusan Ilmu Administrasi* Vol.7, no.1, 2020, page.22;

¹⁷ Terence Mushore, John Odindi, Onesimo Mutanga, and Timothy Dube., "Predicting urban growth and implication on urban thermal characteristics in Harare, Zimbabwe," In *IGARSS 2018-2018 IEEE International Geoscience and Remote Sensing Symposium*, IEEE, 2018, page.847.

¹⁸ Haris Budiman, Anis Mashdurohatun, and Eman Suparman., "A Comparative Study of Spatial Policy in Indonesia and the Netherlands," *Jurnal Dinamika Hukum*, Vol.18, no.3, 2018, page.296. See too, Sri Wahyu Handayani, Suparjo Sujadi, and Arie Sukanti Sumantri., "A critical review of the discrepancy between the spatial planning map and the spatial planning regulation of agricultural lands in Indonesia: Kulon Progo Regency case study," *World Review of Science, Technology and Sustainable Development*, Vol.16, no.4, 2020, page.353; Agung Indrajit, Bastiaan Van Loenen, Virgo Eresta Jaya, Hendrik Ploeger, Christiaan Lemmen, and Peter van Oosterom., "Implementation of the spatial plan information package for improving ease of doing business in Indonesian cities," *Land use policy*, Vol.105 no.8, 2021, page.10338; Maret Priyanta, and Cut Sabina Anasya Zulkarnain., "Urban green open space in developing countries: Indonesia regulations, problems and alternative solutions," *Journal of Property, Planning and Environmental Law*, Vol.16, no.2, 2024, page.137; Deden Rukmana., "The change and transformation of Indonesian spatial planning after Suharto's new order regime: The case of the Jakarta

This regulatory inconsistency is further compounded by structural changes introduced by Law Number 11 of 2020 on Job Creation (*Cipta Kerja*). By replacing the traditional 'Location Permit' (*Izin Lokasi*), which required a local assessment, with the 'Suitability of Spatial Utilization Activities' (*Persetujuan Kesesuaian Kegiatan Pemanfaatan Ruang*/PKKPR), the law has centralized and streamlined investment procedures. While intended to simplify bureaucracy, this shift has inadvertently weakened the 'upstream' control mechanisms of local governments like Pekanbaru. Consequently, while the city's own spatial plan in the form of regional regulations (*Peraturan Daerah*/PERDA Number 7/2020) remains normatively valid, its practical enforcement instruments have been fragmented, creating a governance gap where national economic priorities can more easily override local spatial and environmental controls.

Urban land expansion and growth in rapidly urbanizing areas have been extensively studied, focusing on biophysical and socioeconomic factors and their environmental consequences, including urban heat islands, flood risk, and loss of ecosystem services.¹⁹ In Indonesia, the integration of legal and governance frameworks with spatial dynamics remains underexplored in secondary cities outside Java, such as Pekanbaru. Most studies focus on national regulations, rural areas, coastal zones, or larger urban centers.²⁰

metropolitan area," *International Planning Studies*, Vol.20, no.4, 2015, page.355; Christopher Silver., "Rapid urbanization: the challenges and opportunities for planning in Indonesian cities," *The Indonesian economy and the surrounding regions in the 21st century: essays in honor of Iwan Jaya Azis*, Vol.7, no.21, 2024, page.38; Jieming Zhu, and Hendricus Andy Simarmata., "Formal land rights versus informal land rights: Governance for sustainable urbanization in the Jakarta metropolitan region, Indonesia," *Land use policy*, Vol.43, no.7, 2015, page.67.

¹⁹ Levan Alpaidze, and Joseph Salukvadze., "Green in the city: estimating the ecosystem services provided by urban and peri-urban forests of Tbilisi municipality, Georgia," *Forests*, Vol.14, no.1, 2023, page.121. See too, Wiwandari Handayani, Uchendu Eugene Chigbu, Iwan Rudiarto, and Intan Hapsari Surya Putri., "Urbanization and Increasing flood risk in the Northern Coast of Central Java Indonesia: An assessment towards better land use policy and flood management," *Land*, Vol.9, no.10, 2020, page.343; Terence Mushore, John Odindi, Onesimo Mutanga, and Timothy Dube., "Predicting urban growth and implication on urban thermal characteristics in Harare, Zimbabwe," In *IGARSS 2018-2018 IEEE International Geoscience and Remote Sensing Symposium*, IEEE, 2018, page.848; Ilknur Zeren Cetin, Tugrul Varol, Halil Baris Ozel, and Hakan Sevik., "The effects of climate on land use/cover: a case study in Turkey by using remote sensing data," *Environmental Science and Pollution Research*, Vol.30, no.3, 2023, page.5686.

²⁰ Haris Budiman, Anis Mashdurohatun, and Eman Suparman., "A Comparative Study of Spatial Policy In Indonesia and the Netherlands," *Jurnal Dinamika Hukum*, Vol.18, no.3, 2018, page.297. See too, Sri Wahyu Handayani, Suparjo Sujadi, and Arie Sukanti Sumantri., "A critical review of the discrepancy between the spatial planning map and the spatial planning regulation of agricultural lands in Indonesia: Kulon Progo Regency case study," *World Review of Science, Technology and Sustainable Development*, Vol.16, no.4, 2020, page.354; Agung Indrajit, Bastiaan Van Loenen, Virgo Eresta Jaya, Hendrik Ploeger, Christiaan Lemmen, and Peter van Oosterom., "Implementation of the spatial plan information package for improving ease of doing business in Indonesian cities," *Land use policy*, Vol.105 no.8, 2021, page.10339; Edy Lisdiyono., "Land Procurement for Public Interest and Spatial Planning: Legal and Juridical Implications," *Lex Publica*, Vol.4, no.2, 2017, page.770; Maret Priyanta, and Cut Sabina Anasya Zulkarnain., "Urban green open space in developing countries: Indonesia regulations, problems and alternative solutions," *Journal of Property, Planning and Environmental Law*, Vol.16, no.2, 2024, page.138;

Despite a growing body of research on urban land conversion, previous studies have primarily provided descriptive analyses of urban growth trends and land use changes without examining the legal and governance dimensions that underpin these processes.²¹ Few studies have explored how national and local laws have failed to curb ISA expansion due to weak enforcement, regulatory overlaps, and lack of adaptive spatial control mechanisms.²² Research has also shown that the transition from the centralized Spatial Planning Law Number 24/1992 to the more participatory Law Number 26/2007, and subsequent amendments through the Job Creation Law Number 11/2020 and Law Number 6/2023, has democratized planning but reduced regional law enforcement and environmental protection powers.²³ National economic priorities, centralized licensing, overlapping jurisdictions, limited sanctions, and weak ultimum remedium enforcement have collectively fragmented regulatory control, exacerbating unplanned suburban sprawl.²⁴

Wen, Krishna Samudera, Luky Adrianto, Gabrielle L. Johnson, Mary Sue Brancato, and Alan White., "Towards Marine spatial planning implementation in Indonesia: progress and hindering factors," *Coastal Management*, Vol.50, no.6, 2022, page.474; I. Gusti Ngurah Parikesit Widiatedja, Ida Bagus Erwin Ranawijaya, Sagung Putri ME Purwani, and Bima Kumara Dwi Atmaja., "Developing Effective Procedures for Public Participation in Spatial Planning Regulation in Indonesia: Lesson Learned from Australia," *Padjadjaran Jurnal Ilmu Hukum*, Vol.10, no.3, 2023, page.390; I. Gusti Ngurah Parikesit Widiatedja, Nadirsyah Hosen, Putu Gede Arya Sumerta Yasa, I. Made Budi Arsika, and Made Cinthya Puspita Shara., "Reforming Digital Mapping Regulations for Preventing Spatial Planning Violations in Indonesia: A Lesson from Australia," *Journal of Indonesian Legal Studies*, Vol.9, no.2, 2024, page.640.

²¹ Yusra Aulia Sari, and D. Dewanti., "Perubahan Penggunaan Lahan Dan Faktor-Faktor Yang Mempengaruhi Di Sekitar Area Panam Kota Pekanbaru," In *Seminar Nasional Geomatika*, Vol.3, no.751, page.2018-3. 2019.

²² Deden Rukmana., "The change and transformation of Indonesian spatial planning after Suharto's new order regime: The case of the Jakarta metropolitan area," *International Planning Studies*, Vol.20, no.4, 2015, page.356. See too, Wilmar Salim, and Delik Hudalah., "Urban governance challenges and reforms in Indonesia: towards a new Urban Agenda," In *New urban agenda in Asia-Pacific: Governance for sustainable and inclusive cities*, Singapore, Springer Singapore, 2019, page.167; Jieming Zhu, and Hendricus Andy Simarmata., "Formal land rights versus informal land rights: Governance for sustainable urbanization in the Jakarta metropolitan region, Indonesia," *Land use policy*, Vol.43, no.7, 2015, page.68.

²³ Agung Indrajit, Bastiaan Van Loenen, Virgo Eresta Jaya, Hendrik Ploeger, Christiaan Lemmen, and Peter van Oosterom., "Implementation of the spatial plan information package for improving ease of doing business in Indonesian cities," *Land use policy*, Vol.105 no.8, 2021, page.10340. See too, Fajar Hari Mardiansjah, Paramita Rahayu, and Deden Rukmana., "New patterns of urbanization in Indonesia: emergence of non-statutory towns and new extended urban regions," *Environment and Urbanization ASIA*, Vol.12, no.1, 2021, page.16; Rini Rachmawati., "Urban development, land use, and spatial planning for settlements: lessons learned from Yogyakarta City, Indonesia," *American Journal of Economics and Sociology*, Vol.80, no.2, 2021, page.761; Christopher Silver., "Rapid urbanization: the challenges and opportunities for planning in Indonesian cities," *The Indonesian economy and the surrounding regions in the 21st century: essays in honor of Iwan Jaya Azis*, Vol.7, no.21, 2024, page.39.

²⁴ Hamidah Abdurrahman, Achmad Irwan Hamzani, and Joko Mariyono., "Environmental crime and law enforcement in Indonesia: some reflections on counterproductive approaches," *Environmental Policy and Law* Vol.51, no.6, 2021, page.413. See too, Kateryna

This study addresses these gaps by linking legal frameworks to dynamic urban growth through predictive spatial modeling, incorporating multivariate legal, social, economic, and biophysical analyses. Its novelty lies in conceptualizing spatial governance as an adaptive legal instrument that leverages predictive modeling and dynamic spatial data. Theoretically, this advances environmental law and spatial planning scholarship by framing law enforcement as a responsive, data-driven mechanism.²⁵ Accordingly, this study aims to formulate a sustainable built-up land growth control model (urban sprawl) in Pekanbaru City by analyzing the dynamics of spatial development, identifying its environmental consequences, and examining the legal, social, and economic drivers of rapid urban expansion. The findings are expected to advance the understanding of urban land governance in Indonesia and to contribute practically to the development of legal and policy mechanisms that ensure sustainable spatial management at both local and national levels.

2. Research Methods

This study employs a quantitative approach combined with a normative-empirical legal analysis within a case study framework to develop a sustainable urban sprawl control model in Pekanbaru City. The quantitative component uses the Spatial Sustainability Assessment Model (SSAM) and Geographic Information Systems (GIS) to analyze spatial dynamics, while the normative-empirical component evaluates the alignment between empirical land conversion patterns and the applicable legal framework. The quantitative method is comparative-associative, analyzing the influence of environmental, social, economic, and legal variables over a 20-year period to obtain objective and measurable results. The study area covers the entire territory of Pekanbaru City, with a total area of 632.3 km². Spatial data were converted into raster format with a 30×30-meter resolution, generating 702,556 pixels. Sampling was conducted using systematic sampling with a 1×1 km

Kravchenko., "Urban agglomeration: human-geographical concept in the sustainable development perspective," *Visnyk of VN Karazin Kharkiv National University, Series Geology, Geography, Ecology*, Vol.62, no.12, 2025, page.242; Punam Parikh, Michael A. Taylor, Theresa Hoagland, Hale Thurston, and William Shuster., "Application of market mechanisms and incentives to reduce stormwater runoff: An integrated hydrologic, economic and legal approach," *Environmental Science & Policy*, Vol.8, no.2, 2005, page.140; L. Siebritz, and S. Coetzee., "Evaluating stakeholder influences on the land use application process in South Africa—Results from an analysis of the legal framework," *Land Use Policy*, Vol.120, no.12, 2022, page.106238; Gregorius Widiartana, Vincentius Patria Setyawan, and Ariesta Wibisono Anditya., "Ecocide as an Environmental Crime: Urgency for Legal Reform in Indonesia," *Journal of Law, Environmental and Justice*, Vol.3, no.2, 2025, page.270; Ismu Gunadi Widodo, J. Andy Hartanto, Eddy Pranjoto W, and Jonaedi Efendi., "Constraints on enforcement of environmental law against corporate defendants," *Environmental Policy and Law*, Vol.49, no.1, 2019, page.79; Rochmani, Wenny Megawati, Adi Suliantoro, and Muhammet Ebuzer Ersoy., "An Effective Environmental Dispute Resolution Model That Supports Environmental Sustainability," *Jurnal Hukum* Vol.41, no.2, 2025, page.284.

²⁵ Claudio Ricky Adhitya, Kezia Elvira Nainggolan, Emi Juliana Sinaga, Ester Susanti, and Vincentia Cordialia Halan., "Environment Destruction in Indonesia: The Effectiveness of Indonesia's Environment Law (Legal Sociology Perspective)," *Equality: Journal of Law and Justice*, Vol.2, no.1, 2025; page.113. See too, Paul Jones., "Formalizing the informal: Understanding the position of informal settlements and slums in sustainable urbanization policies and strategies in Bandung, Indonesia," *Sustainability*, Vol.9, no.8, 2017, page.1436.

grid, resulting in a minimum of 76 sample points or 32,400 m² for logistic regression analysis. The research variables consist of 67 independent variables, which include biophysical (12), social (31), economic (24), and legal (5) factors, and one dependent variable, namely the level of built-up land growth.

The inclusion of legal variables responds to the need to operationalize the normative-empirical framework. These legal variables represent spatial governance and compliance indicators, such as: Zoning compliance index based on Regional Regulation (Perda) of Pekanbaru City Number 7 of 2020 on the City Spatial Plan (RTRW) 2020–2040; Land use conformity with spatial allocation under Law Number 26 of 2007 on Spatial Planning; Environmental compliance variable referring to Law Number 32 of 2009 on Environmental Protection and Management; Permit conformity variable related to building and land use licenses; and law enforcement variable, measured through records of zoning violations or unlicensed developments.

These legal indicators were spatially overlaid with land use data in GIS to evaluate whether areas of built-up expansion comply with established zoning and environmental norms. Through this method, the study tests the legal hypothesis that areas with high legal non-compliance (e.g., a low Zoning Compliance Index) are not merely a result of urban sprawl, but are, in fact, significant predictive drivers of unsustainable land conversion. This transforms legal status from a passive descriptor into an active variable within the spatial model. The results were then integrated into the SSAM to assess sustainability levels under both ecological and legal compliance dimensions. In the normative-empirical dimension, the study uses a deductive legal reasoning approach, starting from general legal norms and sustainability principles to derive implications for urban land governance.

Finally, ground validation (ground checking) was conducted at selected points to confirm the accuracy of land use classification and zoning compliance observations. This validation strengthens the empirical reliability of the spatial and legal integration results. The combined use of SSAM, GIS, and normative-empirical legal analysis thus provides a comprehensive methodological framework that bridges spatial modeling and environmental law to formulate a sustainable urban sprawl control model.

3. Results and Discussion

3.1. Dynamics of Spatial Development and Built-Up Land Growth

The development of Pekanbaru City as the capital of Riau Province has experienced rapid growth in recent decades, in line with the theory of development centrality that requires an adequate environment to support city sustainability.²⁶ To understand the dynamics of this change, this study uses JavaScript-based programming on the Google Earth Engine (GEE) platform with the multitemporal Global Artificial Impervious Areas (GAIA) dataset from Tsinghua University.

²⁶ Jean Gottmann, and Robert Alexander Harper., *Since Megalopolis: the urban writings of Jean Gottmann*, Baltimore, Johns Hopkins University Press, 1990, page.211.

Landsat imagery data with a spatial resolution of 30 meters was analyzed in five-year intervals to capture built-up land growth patterns. The results of the analysis show that the area of Impervious Surface Area (ISA) in Pekanbaru City has increased significantly. During the period 1990–2018, built-up land growth reached 17.02%, with a total area increasing by around 2,774.74 hectares. The highest spikes occurred in the periods 2010–2015 and 2013–2018. To support the analysis of built-up land development / ISA, a comparison was made with the analysis of population and population density in 2018 from BPS data. 2 displays the distribution of population in Pekanbaru City using black dots whose sizes reflect the population in each region and a colored grid that depicts population density.

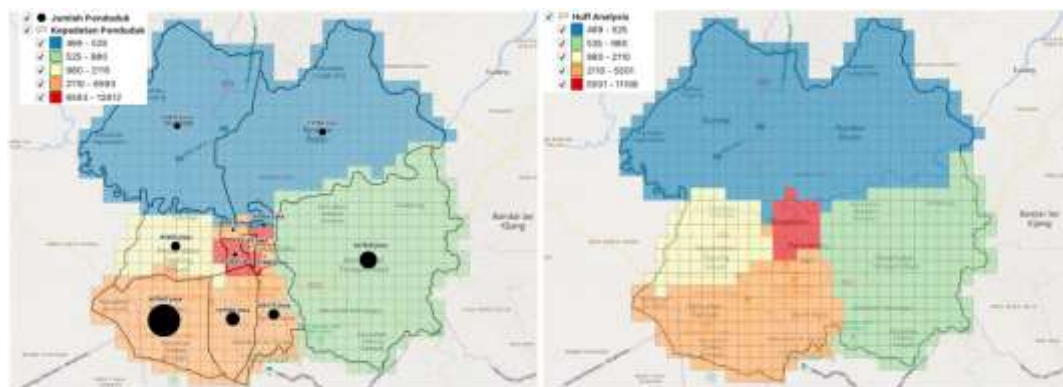


Figure 1. Population Density Distribution and Regional Attractiveness Analysis in Pekanbaru City

The red color reflects the greatest appeal for urban development due to the high concentration of economic activity, established infrastructure, and the availability of supporting public facilities. Meanwhile, the orange to blue areas illustrate a gradual decline in preference towards the outskirts, such as Rumbai and Rumbai Pesisir Districts. The analysis for Pekanbaru focuses on urban area development preferences based on population density and the potential of the location as an attractive area for growth. This data is relevant to understanding urbanization patterns and city area development.

Putra et al.²⁷ using a digital mapping approach to monitor residential areas over a six-year span (2006–2012), recorded an increase of 2,158.84 hectares, from 11,302.87 hectares to 13,461.17 hectares. Similarly, Schneider et al.²⁸ found that urban land across Southeast Asia has been expanding rapidly at an average rate of 2.2% per year. On a broader scale, Seto et al.²⁹ reported that urban land growth in low elevation coastal zones is significantly higher than in non-coastal urban regions. In Pekanbaru, the rate of urban expansion exceeds the regional average,

²⁷ Rizki Rianda Putra., "Analisis Perubahan Tata Guna Lahan Terhadap Koefisien Limpasan Kota Pekanbaru Berbasis Sistem Informasi Geografis (SIG)," (PhD diss., Riau University, 2016), page.24.

²⁸ Annemarie Schneider, Carly M. Mertes, A. J. Tatem, B. Tan, Damien Sulla-Menashe, Sarah J. Graves, Nirav Nikunj Patel et al., "A new urban landscape in East-Southeast Asia, 2000–2010," *Environmental Research Letters*, Vol.10, no.3, 2015, page.4002.

²⁹ Karen C. Seto, Michail Fragkias, Burak Güneralp, and Michael K. Reilly., "A meta-analysis of global urban land expansion," *PloS one*, Vol.6, no.8, 2011, page.237.

underscoring the city's accelerated growth during the study period. Gao and O'Neill³⁰ further attribute this trend to the pressures of rapid urban population growth.

When compared with the economic activity data in BPS data (cooperatives, banks and hotels) in Table 1, it can be seen that the two economic centers based on BPS data are in line with the commercial data obtained from big data processing. Based on BPS population and economic activity data in 2022, it was found that Marpoyan Damai District and Pekanbaru Kota District are the 2 districts with the largest number of economic activities. The 2 points that are suspected as the economic centers of Pekanbaru City from the results of big data processing are in Pekanbaru Kota District (Pekanbaru Mall Area - Sukaramai Market) and Marpoyan Damai District (Jalan Nangka Area).

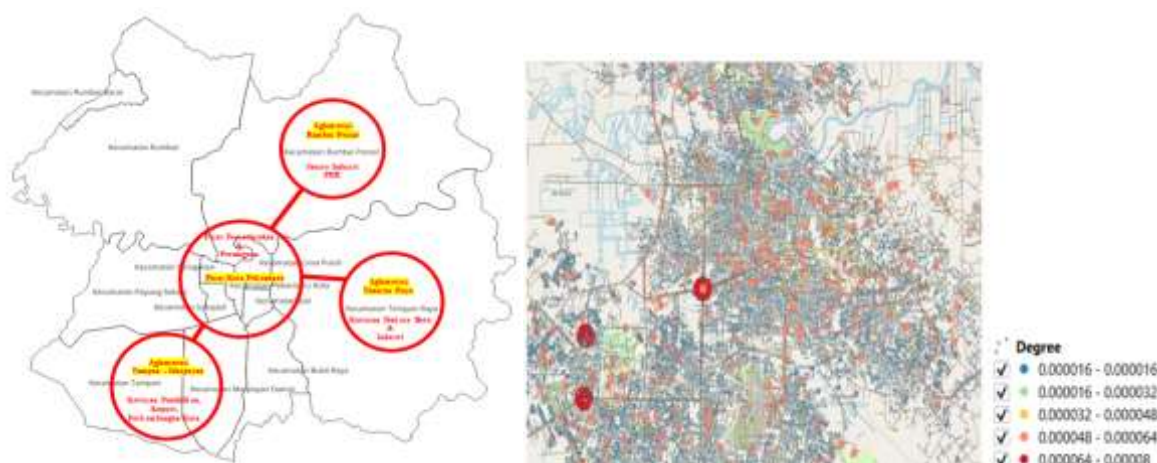


Figure 2. Integration of Pekanbaru's Four Agglomeration Areas and Key Nodes

The four agglomeration areas are interconnected and form an integrated urban unit as shown in Figure 2. Based on the analysis of development patterns, Pekanbaru City shows a growth trend towards the Northeast from the city center (1 o'clock direction), Southwest from the city center (6 o'clock direction), and East from the city center (3 o'clock direction), as seen in Figure 2. However, to achieve equitable development, new development is needed in the Northwest area of the city center (11 o'clock direction). It is planned that in the future the Jakarta metropolitan area (*Jabodetabekjur*/ Jakarta–Bogor–Depok–Tangerang–Bekasi–Cianjur) will be coordinated under the vice president. With more integrated management, economic growth driven by integrated government policies can be

³⁰ Jing Gao, and Brian C. O'Neill., "Mapping global urban land for the 21st century with data-driven simulations and Shared Socioeconomic Pathways," *Nature communications*, Vol.11, no.1, 2020, page.2303. See too, Shuyan Zhang, Yong Ma, Erping Shang, Wutao Yao, Ke Qiao, Jian Peng, Jin Yang, and Chun Feng., "Production of Annual Nighttime Light Based on De-Difference Smoothing Algorithm," *Remote Sensing*, Vol.16, no.16, 2024, page.3014.

carried out as stated by Hapsari et al.³¹

The notion of centrality strongly influences urban road development, particularly in relation to economic growth and social integration. Centrality within an urban road network is a key indicator for analyzing structural characteristics that shape human activities.³² Research indicates that road nodes exhibit a negative correlation between area size and centrality, with larger regions experiencing reduced centrality. In such expansive areas, points of interaction become more dispersed, leading to higher transportation costs.³³ The results of the analysis show that the degree value at the SKA Intersection at point 4 (the meeting of Jalan Soekarno-Hatta and Jalan Nangka) and 2 Garuda Sakti Intersections is higher than other areas. This indicates that the node has a higher level of connectivity, making it more frequently passed by human movement than other areas. This condition reflects the presence of a significant flow of activity, both in the form of human movement and social interaction, because the intersection is connected to many main movement routes that connect various areas. These points not only function as transportation nodes, but also as centers of active commercial, social, and cultural activities.³⁴

The Simpang SKA area is a strategic route connecting the city center with the Panam area, which is known as one of the important areas in Pekanbaru. To overcome congestion, the Pekanbaru City Government has planned to build a flyover at Simpang Garuda Sakti, following in the footsteps of the flyover at Simpang SKA. This shows that in the context of secondary cities in Indonesia such as Pekanbaru, high centrality values at major intersections tend to encourage the proliferation of commercial facilities, offices, housing, and other economic activities, which in turn accelerates the expansion of impervious surfaces and

³¹ Ambar Tri Hapsari, Sidik Priadana, Sugiyanto Sugiyanto., "Factor Affecting Local Own Revenue and Their Impact on Impact on Fiscal Autonomy and Economic Growth in Jabodetabekjur," In *Proceedings of the 2nd International Conference on Law, Social Science, Economics, and Education, ICLSSEE 2022, 16 April 2022, Semarang, Indonesia*.

³² Fatemeh Noori, Hamid Kamangir, Scott A. King, Alaa Sheta, Mohammad Pashaei, and Abbas Sheikh Mohammad Zadeh., "A deep learning approach to urban street functionality prediction based on centrality measures and stacked denoising autoencoder," *ISPRS International Journal of Geo-Information*, Vol.9, no.7, 2020, page.457. See too, Ilknur Zeren Cetin, Tugrul Varol, Halil Baris Ozel, and Hakan Sevik., "The effects of climate on land use/cover: a case study in Turkey by using remote sensing data," *Environmental Science and Pollution Research*, Vol.30, no.3, 2023, page.5688.

³³ Mark Altaweel, Jack Hanson, and Andrea Squitieri., "The structure, centrality, and scale of urban street networks: Cases from Pre-Industrial Afro-Eurasia," *PLoS one*, Vol.16, no.11, 2021; 2385. See too, Deltri Dikwardi Eisenring., "Pertumbuhan Area Perkotaan 2 Di Sekitar Kampus Perguruan Tinggi Universitas Tadulako Palu," *Ruang: Jurnal Arsitektur*, Vol.16, no.1, 2022, page.42.

³⁴ Kateryna Kravchenko., "Urban agglomeration: human-geographical concept in the sustainable development perspective," *Visnyk of VN Karazin Kharkiv National University, Series Geology, Geography, Ecology*, Vol.62, no.12, 2025, page.244. See too, Fadjar Hari Mardiansjah, Paramita Rahayu, and Deden Rukmana., "New patterns of urbanization in Indonesia: emergence of non-statutory towns and new extended urban regions," *Environment and Urbanization ASIA*, Vol.12, no.1, 2021, page.17; Christopher Silver., "Rapid urbanization: the challenges and opportunities for planning in Indonesian cities," *The Indonesian economy and the surrounding regions in the 21st century: essays in honor of Iwan Jaya Azis*, Vol.7, no.21, 2024, page.40.

reduces green open space.³⁵ Centrality values in Copenhagen, Denmark, for comparison, show that areas close to the city center tend to be more centralized, providing benefits for pedestrians and cyclists due to the close proximity of buildings/facilities to each other.³⁶ In contrast, high centrality in Indonesian cities tends to trigger development that relies on motorized vehicles and uncontrolled land conversion, thereby increasing the risk of flooding, the urban heat island effect, and pressure on urban infrastructure.³⁷

3.2. Environmental Consequences of Urban Expansion

Estimation of impervious surface is a useful method for evaluating urbanization, and the increase in impervious surface area is related to population growth and economic development.³⁸ By viewing the VIS configuration in a multi-temporal manner, urban growth can be observed. VIS analysis is performed using python programming on Google Colab Cloud.

³⁵ Levan Alpaidze, and Joseph Salukvadze., "Green in the city: estimating the ecosystem services provided by urban and peri-urban forests of Tbilisi municipality, Georgia," *Forests*, Vol.14, no.1, 2023, page.122. See too, Wiwandari Handayani, Uchendu Eugene Chigbu, Iwan Rudiarto, and Intan Hapsari Surya Putri., "Urbanization and Increasing flood risk in the Northern Coast of Central Java Indonesia: An assessment towards better land use policy and flood management," *Land*, Vol.9, no.10, 2020, page.345; Paul Jones., "Formalizing the informal: Understanding the position of informal settlements and slums in sustainable urbanization policies and strategies in Bandung, Indonesia," *Sustainability*, Vol.9, no.8, 2017, page.1437; Fadjar Hari Mardiansjah, Paramita Rahayu, and Deden Rukmana., "New patterns of urbanization in Indonesia: emergence of non-statutory towns and new extended urban regions," *Environment and Urbanization ASIA*, Vol.12, no.1, 2021, page.18; Punam Parikh, Michael A. Taylor, Theresa Hoagland, Hale Thurston, and William Shuster., "Application of market mechanisms and incentives to reduce stormwater runoff: An integrated hydrologic, economic and legal approach," *Environmental Science & Policy*, Vol.8, no.2, 2005, page.141; Rini Rachmawati., "Urban development, land use, and spatial planning for settlements: lessons learned from Yogyakarta City, Indonesia," *American Journal of Economics and Sociology*, Vol.80, no.2, 2021, page.763; Christopher Silver., "Rapid urbanization: the challenges and opportunities for planning in Indonesian cities," *The Indonesian economy and the surrounding regions in the 21st century: essays in honor of Iwan Jaya Azis*, Vol.7, no.21, 2024, page.41; Jieming Zhu, and Hendricus Andy Simarmata., "Formal land rights versus informal land rights: Governance for sustainable urbanization in the Jakarta metropolitan region, Indonesia," *Land use policy*, Vol.43, no.7, 2015, page.69.

³⁶ Maria Andrakakou, and Carsten Keßler., "Investigating configurational and active centralities: The example of metropolitan Copenhagen," *Environment and Planning B: Urban Analytics and City Science* Vol.49, no.7, 2022, page.1953.

³⁷ Sri Wahyu Handayani, Suparjo Sujadi, and Arie Sukanti Sumantri., "A critical review of the discrepancy between the spatial planning map and the spatial planning regulation of agricultural lands in Indonesia: Kulon Progo Regency case study," *World Review of Science, Technology and Sustainable Development*, Vol.16, no.4, 2020, page.356. See too, Christopher Silver., "Rapid urbanization: the challenges and opportunities for planning in Indonesian cities," *The Indonesian economy and the surrounding regions in the 21st century: essays in honor of Iwan Jaya Azis*, Vol.7, no.21, 2024, page.42.

³⁸ Kapo Wong, Yuanzhi Zhang, Qiuming Cheng, Ming Chun Chao, and Jin Yeu Tsou., "Comparison of Impervious Surface Dynamics through Vegetation/High-Albedo/Low-Albedo/Soil Model and Socio-Economic Factors," *Land*, Vol.11, no.3, 2022, page.431.

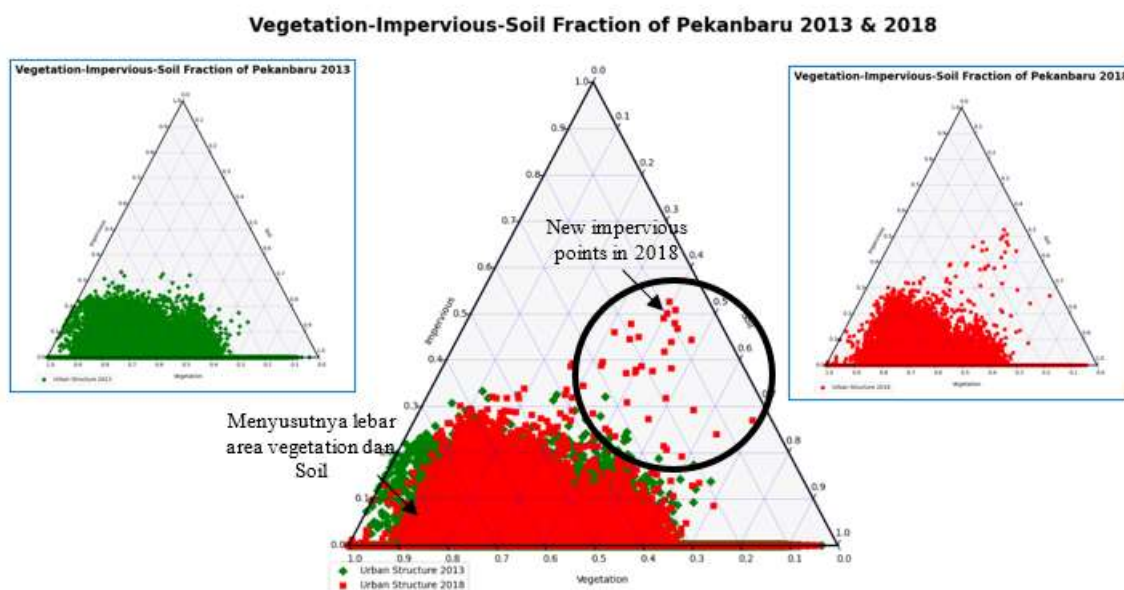


Figure 3. Pekanbaru VIS Configuration in 2013 (Green) and 2018 (Red).

The calculation results of the VIS Model of the Pekanbaru city area in 2013 and 2018 can be shown by the diagram in Figure 3, showing the distribution of points from NDVI, NDBI and BSI from the results of big data processing of satellite imagery as a whole in 2013 (green) and in 2018 (red). From the VIS ternary diagram, we can see that in 2018 (red) there was a significant change compared to 2013 (green). In 2018, the impervious and soil fractions increased significantly as indicated by the appearance of other red dots in the upper-middle part of the graph that were not previously visible in 2013. This data provides a clear picture of changes in land that have turned into built-up areas, which generally include buildings, roads, and other infrastructure that cannot absorb rainwater. The analysis results in Figure 4 show that Tenayan Raya District is the area with the highest development of built-up land during this period. Other sub-districts that also showed significant growth were Rumbai, Tampan, Rumbai Pesisir, Payung Sekaki, Marpoyan Damai, and Bukit Raya.



Figure 4. Development of Built-up Land Per District 2013 – 2018

Tenayan Raya District shows the highest population in Pekanbaru, driving built-up land expansion. Rapid urbanization increases impermeable surfaces, affecting runoff and rainwater management, making the area vulnerable to flooding. Road network analysis using Python and rose diagrams reveals an average entropy value of 3.5013, indicating high structural irregularity and complexity. Understanding these patterns is crucial for urban planning, as irregular networks impact accessibility, mobility efficiency, and equality. Areas near Pekanbaru's agglomeration center, including Limapuluh, Payung Sekaki, and Senapelan, exhibit more regular road networks with entropy values between 3.0 and 3.4, reflecting better-planned connectivity.

The calculation of regional temperatures enabled the determination of the Urban Thermal Field Variance Index (UTFVI), which illustrates thermal comfort levels and ecological conditions across 13 sub-districts in Pekanbaru City. The analysis was visualized in a map (Figure 5), revealing that areas with higher UTFVI values are predominantly concentrated in built-up zones, particularly in the city center. This pattern suggests that densely developed urban areas face greater ecological degradation compared to suburban regions. Elevated surface temperatures in the city core are largely attributed to the scarcity of green open spaces (RTH) and limited vegetation capable of absorbing and mitigating heat. These conditions highlight the environmental consequences of rapid urbanization, where extensive construction and infrastructure growth, without sufficient ecological balance, intensify the Urban Heat Island (UHI) effect in Pekanbaru.

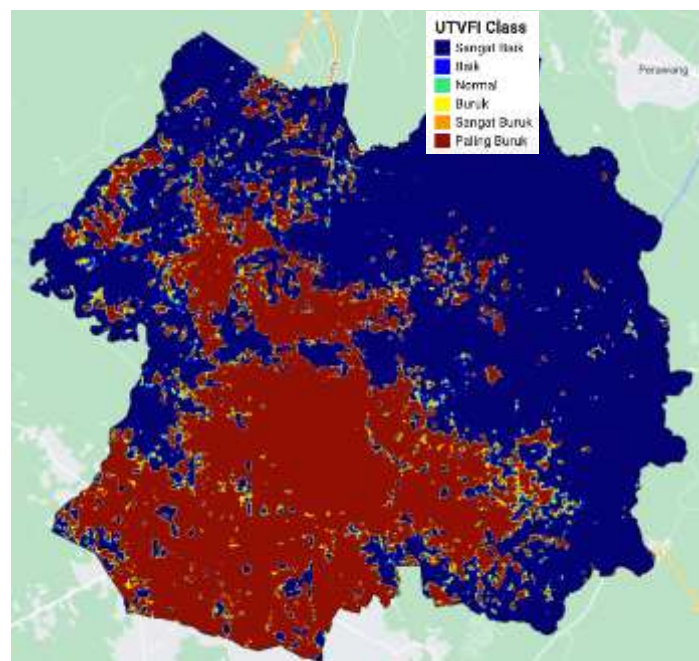


Figure 5. Map of UTFVI Calculation Results for Pekanbaru City

On the other hand, lower UTFVI values tend to be found in areas with more vegetation, such as green areas, city parks, and residential areas that still have

large open spaces. The presence of abundant vegetation plays an important role in maintaining the balance of environmental temperatures. Trees and plants function to absorb heat, provide shade, and improve air quality in the environment. From the Table 1, it can be seen that most sub-districts in Pekanbaru City have areas with fairly good ecological conditions. Areas with good ecological values are generally areas that have dense vegetation and green open spaces. However, if we look at the maximum UTFVI value of each sub-district, there is a sub-district with the highest value, namely Rumbai Pesisir Sub-district. The area with the highest UTFVI value is Perumnas Rumbai, which is also recorded as having a high surface temperature intensity.

Table 1. Minimum and Maximum UTFVI Values for Each District

Subdistrict	Max	Min
Bukit Raya	0.18307	-0.1748
Lima Puluh	0.14619	-0.1769
Marpoyan Damai	0.18557	-0.1344
Payung Sekaki	0.16517	-0.1996
Pekanbaru Kota	0.10282	-0.1057
Rumbai	0.24796	-0.1897
Rumbai Pesisir	0.33798	-0.3158
Sail	0.11302	-0.1199
Senapelan	0.11178	-0.1404
Sukajadi	0.07671	-0.085
Tampan	0.16199	-0.1507
Tenayan Raya	0.24065	-0.2215

This is because the UTFVI value describes the urban ecological condition index derived from LST. In addition, UTFVI can be used as an indicator to determine the intensity of UHI and the level of thermal comfort in an area.³⁹ The UTFVI value can be used as a basis for determining priorities on how to address urban areas with degraded ecological conditions and determine whether to require mitigation of the adverse impacts of UHI or not. This is done so that environmental engineers or other stakeholders can carry out targeted ecological restoration efforts. Greenhouse gas (GHG) emissions in urban areas are of great concern because of their adverse impacts on climate change and the urban environment. Urbanization, gas emissions and industrial development contribute to increasing GHG emissions in urban areas. Greenhouse gases and air pollutants such as NO₂, CO and HCHO (formaldehyde) are significant contributors to urban air quality and climate change.⁴⁰ Greenhouse gases and air pollutants such as NO₂, CO and HCHO have been studied extensively

³⁹ Prafull Singh, Noyingbeni Kikon, and Pradipika Verma., "Impact of land use change and urbanization on urban heat island in Lucknow city, Central India. A remote sensing based estimate," *Sustainable cities and society*, Vol.32 no.6, 2017, page.107. See too, Ilknur Zeren Cetin, Tugrul Varol, Halil Baris Ozel, and Hakan Sevik., "The effects of climate on land use/cover: a case study in Turkey by using remote sensing data," *Environmental Science and Pollution Research*, Vol.30, no.3, 2023, page.5685.

⁴⁰ Xin Tian, Pinhua Xie, Jin Xu, Ang Li, Yang Wang, Min Qin, and Zhaokun Hu., "Long-term observations of tropospheric NO₂, SO₂ and HCHO by MAX-DOAS in Yangtze River Delta area, China," *Journal of Environmental Sciences*, Vol.71, no.21, 2018, page.213.

in urban environments. Understanding the sources and dynamics of these gases is critical for effective pollution control and climate change mitigation efforts in cities around the world.

The analysis was conducted using Javascript on the Google Earth Engine (GEE) platform. The results of the big data analysis of satellite imagery in Figure 6 show that NO_2 levels in the air in Pekanbaru City are in the range of 0.068 to 0.124 $\mu\text{gr}/\text{m}^3$. This figure has mostly exceeded the quality standard set by BMKG, which is 0.08 $\mu\text{gr}/\text{m}^3$, which is a safe threshold for human health. High NO_2 levels have the potential to cause various health problems, such as respiratory disorders, cardiovascular disease, and the risk of premature death.

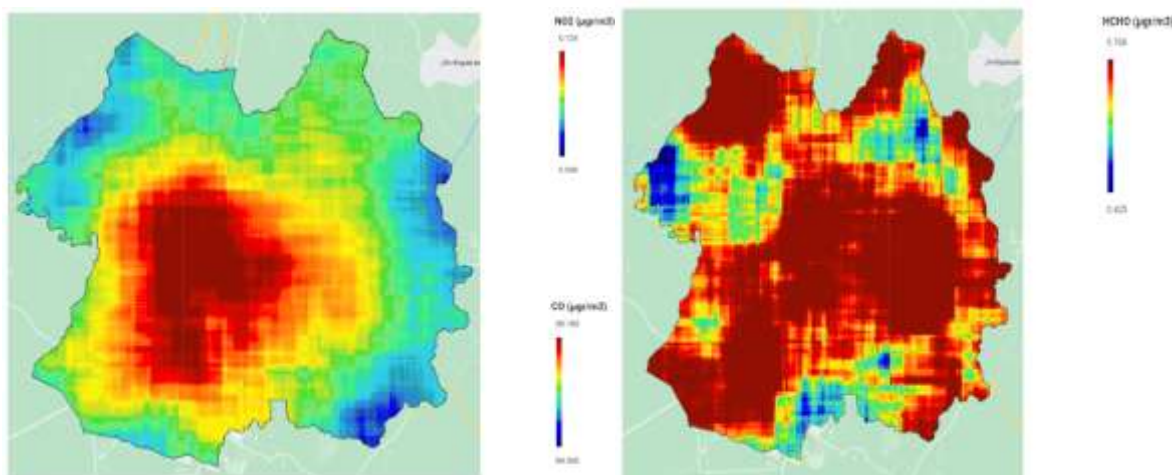


Figure 6. GHG Emissions (NO_2 and HCHO) in Pekanbaru City Areas, 2018 (by Zones)

In densely trafficked urban areas like Pekanbaru City, carbon monoxide (CO) concentrations frequently exceed safe limits, resulting in health impacts such as headaches, dizziness, and respiratory complications (Figure 6). Image processing results indicate that nearly all areas of Pekanbaru show elevated CO levels, averaging 84.36 $\mu\text{g}/\text{m}^3$, surpassing the mild exposure threshold of 35 $\mu\text{g}/\text{m}^3$ established by the Mound Fire Department, USA. The highest exposure areas are concentrated along north-south and west-east corridors in the city center, reflecting dense vehicle mobility. Formaldehyde (HCHO) mapping identified five major clusters, including the city center, Tenayan Raya Industrial Area, and surrounding construction and power plant zones, highlighting industrial and transport-related emission sources. Statistical t-tests revealed significant differences in Greenhouse Gas (GHG) concentrations between built-up and non-built-up areas. NO_2 emissions in urban zones averaged 0.1 ppm, significantly higher than 0.09 ppm in non-built-up land ($P < 0.05$), with both exceeding the 0.08 ppm air quality standard. HCHO concentrations also exceeded the 0.1 ppm threshold in both groups, indicating unsafe levels of air pollutants (Figure 7).

Comparative studies show that cities in developing countries, including locations in

China and India, face similar increases in GHG emissions.⁴¹ Vertical column measurements of HCHO and NO₂ in Mexico highlighted these gases as key urban pollutants.⁴² Vehicle emissions in Lahore demonstrated strong correlations among CO, NO₂, and HCHO as shared sources.⁴³ Additional research in Dalian, Qingdao, and Shanghai detailed spatio-temporal distributions and transport of aerosols, CO, NO₂, and HCHO from industrial areas.⁴⁴ Findings indicate that industrial emissions, fossil fuel combustion, and urban energy use are primary HCHO sources, consistent with Pekanbaru data. GHG emissions in 2018 were higher than in 2021 ("new normal"), suggesting mitigation strategies, including reducing vehicle emissions through light-duty electric vehicles and increasing urban vegetation, can help decrease overall emissions.⁴⁵

This pattern is reinforced by the rapid expansion of impervious surface area (ISA) and loss of vegetative cover in many secondary cities in the Global South, which directly exacerbate air pollution, urban heat island effects, and greenhouse gas emissions through increased energy demand for cooling and higher vehicle dependency.⁴⁶ GHG emissions in 2018 were higher than in 2021 ("new normal"),

⁴¹ Mriganka Sekhar Biswas, and D. C. Ayantika., "Impact of COVID-19 Control Measures on Trace Gases (NO₂, HCHO and SO₂) and Aerosols over India during Pre-monsoon of 2020," *Aerosol and Air Quality Research*, Vol.21, no.1, 2021, page.221.

⁴² M. Johansson, Claudia Rivera, Benjamin de Foy, Wenfang Lei, Jihee Song, Yan Zhang, Bo Galle, and L. Molina., "Mobile mini-DOAS measurement of the outflow of NO₂ and HCHO from Mexico City," *Atmospheric Chemistry and Physics*, Vol.9, no.15, 2009, page.5650.

⁴³ Maria Razi, Steffen Dörner, Sebastian Donner, Noor Ahmad, Fahim Khokhar, and Thomas Wagner., "Study of the interrelationships between NO₂, SO₂, HCHO and CHOCHO vertical column densities derived by car MAX-DOAS observations in and around the megacity of Lahore, Pakistan," In *EGU General Assembly Conference Abstracts*, 2022, page.10254.

⁴⁴ Wang S. Mi X, Shao C, Zhang P, Chen M., "Resident travel mode prediction model in Beijing metropolitan area," *PLoS ONE*, Vol.16, no.11, 2021, page.793. See too, Man-hua Wang, Pin-hua Xie, Min Qin, Ke Dou, Jie Wang, Ang Li, Jin Xu, Peng Shi, and Feng-cheng Wu., "Atmospheric HCHO gradient monitoring and analysis in Beijing city with a scanning DOAS system," *Spectroscopy and Spectral Analysis*, Vol.31, no.3, 2011, page.790.

⁴⁵ Daniel E. Horton, Jordan L. Schnell, Daniel R. Peters, David C. Wong, Xi Lu, Hao Gao, Hongliang Zhang, and Patrick L. Kinney., "Effect of adoption of electric vehicles on public health and air pollution in China: a modelling study," *The Lancet Planetary Health*, Vol.5, no.2, 2021, page.8. See too, Ilknur Zeren Cetin, Tugrul Varol, Halil Baris Ozel, and Hakan Sevik., "The effects of climate on land use/cover: a case study in Turkey by using remote sensing data," *Environmental Science and Pollution Research*, Vol.30, no.3, 2023, page.5689.

⁴⁶ Levan Alpaidze, and Joseph Salukvadze., "Green in the city: estimating the ecosystem services provided by urban and peri-urban forests of Tbilisi municipality, Georgia," *Forests*, Vol.14, no.1, 2023, page.123. See too, Wiwandari Handayani, Uchendu Eugene Chigbu, Iwan Rudiarto, and Intan Hapsari Surya Putri., "Urbanization and Increasing flood risk in the Northern Coast of Central Java Indonesia: An assessment towards better land use policy and flood management," *Land*, Vol.9, no.10, 2020, page.347; Paul Jones., "Formalizing the informal: Understanding the position of informal settlements and slums in sustainable urbanization policies and strategies in Bandung, Indonesia," *Sustainability*, Vol.9, no.8, 2017, page.1438; Kateryna Kravchenko., "Urban agglomeration: human-geographical concept in the sustainable development perspective," *Visnyk of VN Karazin Kharkiv National University, Series Geology, Geography, Ecology*, Vol.62, no.12, 2025, page.247; Fadjar Hari Mardiansjah, Paramita Rahayu, and Deden Rukmana., "New patterns of urbanization in Indonesia: emergence of non-statutory towns and new extended urban regions," *Environment and Urbanization ASIA*, Vol.12, no.1, 2021, page.19; Punam Parikh, Michael A. Taylor, Theresa Hoagland, Hale Thurston, and William Shuster., "Application of market mechanisms and incentives to reduce stormwater runoff: An

suggesting mitigation strategies, including reducing vehicle emissions through light-duty electric vehicles, promoting compact mixed-use development, and massively increasing urban vegetation and green infrastructure, can help decrease overall emissions and improve urban air quality.⁴⁷

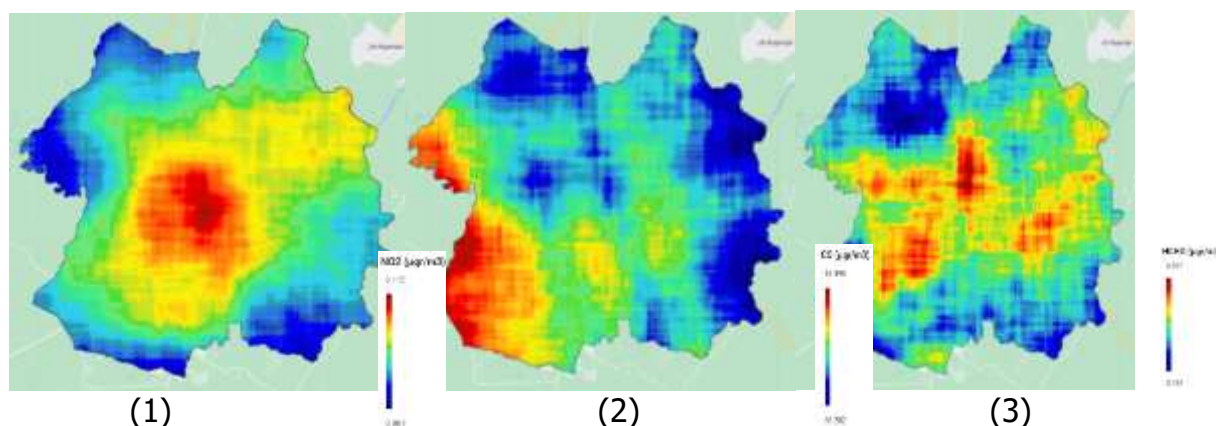


Figure 7. Post-New Normal GHG Levels in Pekanbaru: NO₂, CO, HCHO

3.3. Legal, Social, and Economic Drivers of Urban Sprawl

The expansion of built-up land in Pekanbaru City is driven by a complex interplay of legal, social, and economic factors. While biophysical variables such as proximity to urban areas, urban density, access to roads, and soil type have been shown to influence spatial and temporal dynamics of urban growth, the present study

integrated hydrologic, economic and legal approach," *Environmental Science & Policy*, Vol.8, no.2, 2005, page.143; Rini Rachmawati., "Urban development, land use, and spatial planning for settlements: lessons learned from Yogyakarta City, Indonesia," *American Journal of Economics and Sociology*, Vol.80, no.2, 2021, page.765; Christopher Silver., "Rapid urbanization: the challenges and opportunities for planning in Indonesian cities," *The Indonesian economy and the surrounding regions in the 21st century: essays in honor of Iwan Jaya Azis*, Vol.7, no.21, 2024, page.43; Jieming Zhu, and Hendricus Andy Simarmata., "Formal land rights versus informal land rights: Governance for sustainable urbanization in the Jakarta metropolitan region, Indonesia," *Land use policy*, Vol.43, no.7, 2015, page.70.

⁴⁷ Sri Wahyu Handayani, Suparjo Sujadi, and Arie Sukanti Sumantri., "A critical review of the discrepancy between the spatial planning map and the spatial planning regulation of agricultural lands in Indonesia: Kulon Progo Regency case study," *World Review of Science, Technology and Sustainable Development*, Vol.16, no.4, 2020, page.357. See too, Punam Parikh, Michael A. Taylor, Theresa Hoagland, Hale Thurston, and William Shuster., "Application of market mechanisms and incentives to reduce stormwater runoff: An integrated hydrologic, economic and legal approach," *Environmental Science & Policy*, Vol.8, no.2, 2005, page.144; Maret Priyanta, and Cut Sabina Anasya Zulkarnain., "Urban green open space in developing countries: Indonesia regulations, problems and alternative solutions," *Journal of Property, Planning and Environmental Law*, Vol.16, no.2, 2024, page.139; Christopher Silver., "Rapid urbanization: the challenges and opportunities for planning in Indonesian cities," *The Indonesian economy and the surrounding regions in the 21st century: essays in honor of Iwan Jaya Azis*, Vol.7, no.21, 2024, page.43.

demonstrates that human and institutional factors are equally decisive.⁴⁸ Using spatial logistic regression and ensemble machine learning models, this study identifies significant predictors of built-up land development and interprets their implications for governance, social demand, and market-driven incentives.

In this study, the dependent variable Y was converted into a binary format for logistic regression, with built-up land coded as 1 and non-built-up land as 0. The independent variables X included spatial variables labeled 'DIST' derived from raster GIS analysis at pixel level and nominal or quantitative variables labeled 'JML' obtained from sub-district data. A total of 63,745 sample points were collected using grid systematic sampling with 100-meter spacing. The initial dataset was highly imbalanced, with 61,063 non-built land samples and 2,682 built-up land samples, representing 95.78% and 4.22% respectively. To address this imbalance and prevent biased classification, the SMOTE technique was applied, creating a balanced dataset for logistic regression modeling. The analysis was conducted using Python and the statsmodels library, incorporating 67 variables comprising 12 biophysical, 31 social, and 24 economic factors. The resulting model was statistically significant at a 5% confidence level, with a P value less than 0.05, indicating that these variables collectively explain the probability of land being developed.

Table 2. Logistic Regression Results

Model:	Logit	Method:	MLE
Dependent Variable:	y	Pseudo R-squared:	0.45
Date:	6/3/2024 3:02	AIC:	74547.3229
No. Observations:	97670	BIC:	75192.5987
Df Model:	67	Log-Likelihood:	-37206
Df Residuals:	97602	LL-Null:	-67700
Converged:	1	LLR p-value:	0
No. Iterations:	475	Scale:	1

The logistic regression analysis of 67 independent variables revealed that only 34 variables, about half, were initially significant in explaining built-up land development (Table 2). Most spatial variables marked 'DIST' were significant, while several quantitative variables marked 'JML' were not. Rainfall showed no effect on land development, likely due to swampy conditions in parts of Pekanbaru. After further iteration, the total number of significant variables increased to 41, including seven previously insignificant variables such as number of sub-districts, area, crimes, population growth, agricultural workers, and fishermen. Biophysical variables like sub-district number and area naturally influence urban growth.

Eighty percent of the data was used for training the logistic regression model, while the remaining twenty percent served as test data, a standard approach to balance model training and evaluation. The model was trained on 44,211 samples using 41 independent variables to predict built-up land as the dependent variable. Model

⁴⁸ Mauricio I. Aguayo, Thorsten Wiegand, Gerardo D. Azócar, Kerstin Wiegand, and Claudia E. Vega., "Revealing the driving forces of mid-cities urban growth patterns using spatial modeling: a case study of Los Angeles, Chile," *Ecology and Society*, Vol.12, no.1, 2007, page.249.

performance was assessed using confusion matrix accuracy, Count R^2 , and the ROC curve. The confusion matrix showed that the model accurately classified both non-built-up and built-up land, achieving an overall accuracy of 82 percent. The F1-scores were 0.81 for non-built-up and 0.83 for built-up land, indicating slightly better performance in predicting built-up areas, with only a minor difference of two percent (Table 3).

Table 3. Results of the Confusion Matrix of the Logistic Regression Model

Category Y	Precision	Recall	f1-score	Support
0 (non-Awakened)	0.86	0.77	0.81	9782
1 (Awakened)	0.79	0.87	0.83	9752
accuracy			0.82	19534
macro avg	0.82	0.82	0.82	19534
weighted avg	0.82	0.82	0.82	19534

In this study, the traditional R^2 used in ordinary least squares regression is not suitable because the dependent variable is binary. Instead, Count R^2 , or Pseudo R^2 , is used to measure the model's goodness of fit in classifying non-built-up and built-up land. The model achieved a Pseudo R^2 of 0.8215, indicating a strong ability of the 41 independent variables to explain built-up land development. Typically, a minimum value of 0.2 is considered acceptable for goodness of fit. For model validation, 75 percent of the data was used for training and 25 percent for testing. This adjustment, slightly higher than the common 20 percent test proportion, was chosen to enhance model comparison and validation, ensuring that the machine learning model's predictive performance is thoroughly evaluated and reliable.

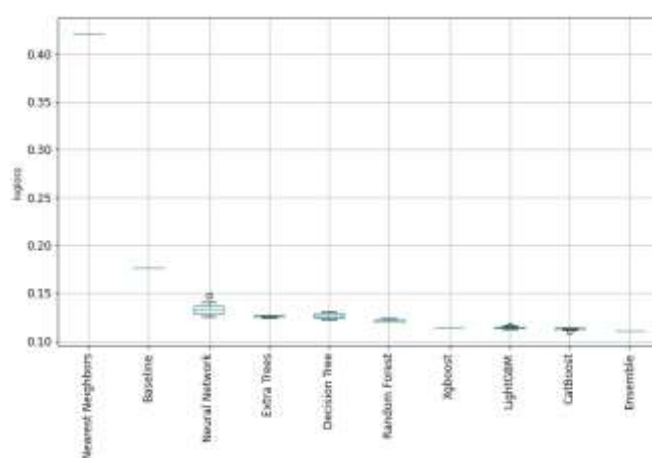


Figure 8. Logloss Metric Graph Results from Each AutoML Method

Out of 80 AutoML experiments, the CatBoost method achieved the best performance among nine tested methods, including ensemble approaches. Boosting and bagging techniques generally produced lower Logloss values, indicating higher classification accuracy (Figure 8). Methods such as CatBoost, LightGBM, XGBoost, and Random

Forest outperformed ensemble stacking, while Extra Trees performed similarly to Decision Trees but with lower variance. These results align with ensemble theory, which combines multiple base models to reduce variance and enhance predictive accuracy. Additionally, incorporating GoldenFeatures significantly improved model performance, with the top nine models in the classification ranking including these features, demonstrating their strong contribution to prediction accuracy and quality (Table 4).

Table 4. CatBoost Classification Results (16 Trials Sorted by Lowest Logloss)

Classifier	Model Type	Metric Type	Metric Value	Train Time
45_CatBoost_GoldenFeatures	CatBoost	logloss	0.110999	22.05
13_CatBoost_GoldenFeatures	CatBoost	logloss	0.112142	17.92
12_CatBoost_GoldenFeatures	CatBoost	logloss	0.11237	15.57
14_CatBoost_GoldenFeatures_SelectedFeatures	CatBoost	logloss	0.112602	13.8
43_CatBoost_GoldenFeatures	CatBoost	logloss	0.112614	24.54
47_CatBoost_GoldenFeatures_SelectedFeatures	CatBoost	logloss	0.112733	19.94
15_CatBoost_GoldenFeatures_SelectedFeatures	CatBoost	logloss	0.112782	14.73
5_Default_CatBoost_GoldenFeatures_RandomFeature	CatBoost	logloss	0.112842	16.1
5_Default_CatBoost_GoldenFeatures	CatBoost	logloss	0.112949	14.27
22_CatBoost	CatBoost	logloss	0.113395	13.58
5_Default_CatBoost_GoldenFeatures_SelectedFeatures	CatBoost	logloss	0.113469	13.15
48_CatBoost_GoldenFeatures_SelectedFeatures	CatBoost	logloss	0.113505	16.42
44_CatBoost_GoldenFeatures	CatBoost	logloss	0.113553	15.17
23_CatBoost	CatBoost	logloss	0.113645	16.94
46_CatBoost_GoldenFeatures	CatBoost	logloss	0.113739	14.35
5_Default_CatBoost	CatBoost	logloss	0.113873	13.19

The classification result for the model ID "45 CatBoost_GoldenFeatures" achieved an accuracy of 92%, demonstrating excellent predictive performance compared to classical logistic regression, which reached only 82%. The ROC curve shows that both classes, $Y = 0$ (non-Built-up) and $Y = 1$ (Built-up), as reflected in the macro-average ROC value. Urban land value is closely linked to urban growth, as increasing land prices tend to attract construction and investment. Factors such as population density, migration, and existing built-up areas influence these trends. Logistic regression studies in cities like Dhaka, Kunshan, Beijing, Tianjin, Shijiazhuang, and Bogor reveal similar patterns in urban development.⁴⁹ In

⁴⁹ Wenjia Wu, Shuqing Zhao, and Geoffrey M. Henebry., "Drivers of urban expansion over the past three decades: A comparative study of Beijing, Tianjin, and Shijiazhuang," *Environmental*

Pekanbaru, rising population and land values contribute to surrounding land expansion. Comparable trends were observed in Abomey-Calavi, Benin, where new settlements and increasing land prices led to uncontrolled urban sprawl, reflecting similar dynamics of urban growth and development pressures.⁵⁰ Moreover, comparable trends of rapid conversion of peri-urban and agricultural land driven by rising land values and weak regulatory enforcement have been widely documented in secondary and intermediate cities across developing countries, leading to uncontrolled urban sprawl and significant increases in impervious surface area.⁵¹

The statistical findings from the logistic regression and ensemble machine learning models provide a strong foundation to interpret the drivers of urban sprawl in Pekanbaru City from legal, social, and economic perspectives. The high predictive accuracy of the CatBoost_GoldenFeatures model, achieving 92 percent, emphasizes the reliability of the identified significant variables, making them suitable for evaluating how institutional frameworks, social dynamics, and market pressures contribute to built-up land expansion. These results align with a large body of research on Indonesian cities that consistently identifies weak spatial planning enforcement, fragmented governance structures, private-sector dominance in land development, and inadequate integration of social and environmental considerations as the primary institutional and socio-economic drivers behind uncontrolled built-up expansion.⁵²

Monitoring and Assessment, Vol.191, no.1, 2019, page.34. See too, Ilknur Zeren Cetin, Tugrul Varol, Halil Baris Ozel, and Hakan Sevik., "The effects of climate on land use/cover: a case study in Turkey by using remote sensing data," *Environmental Science and Pollution Research*, Vol.30, no.3, 2023, page.5690.

⁵⁰ Boukari Wadjidou., "Why the 11th Sustainable Development Goal should be updated: The impact of land prices on immigrant settlement," *Authorea Preprints*, Vol.11, no.4, 2022, page.241.

⁵¹ Wiwandari Handayani, Uchendu Eugene Chigbu, Iwan Rudiarto, and Intan Hapsari Surya Putri., "Urbanization and Increasing flood risk in the Northern Coast of Central Java Indonesia: An assessment towards better land use policy and flood management," *Land*, Vol.9, no.10, 2020, page.350. See too, Agung Indrajit, Bastiaan Van Loenen, Virgo Eresta Jaya, Hendrik Ploeger, Christiaan Lemmen, and Peter van Oosterom., "Implementation of the spatial plan information package for improving ease of doing business in Indonesian cities," *Land use policy*, Vol.105 no.8, 2021, page.10341; Paul Jones., "Formalizing the informal: Understanding the position of informal settlements and slums in sustainable urbanization policies and strategies in Bandung, Indonesia," *Sustainability*, Vol.9, no.8, 2017, page.1439; Fadjar Hari Mardiansjah, Paramita Rahayu, and Deden Rukmana., "New patterns of urbanization in Indonesia: emergence of non-statutory towns and new extended urban regions," *Environment and Urbanization ASIA*, Vol.12, no.1, 2021, page.20; Rini Rachmawati., "Urban development, land use, and spatial planning for settlements: lessons learned from Yogyakarta City, Indonesia," *American Journal of Economics and Sociology*, Vol.80, no.2, 2021, page.767; Wilmar Salim, and Delik Hudalah., "Urban governance challenges and reforms in Indonesia: towards a new Urban Agenda," In *New urban agenda in Asia-Pacific: Governance for sustainable and inclusive cities*, Singapore, Springer Singapore, 2019, page.168; Jieming Zhu, and Hendricus Andy Simarmata., "Formal land rights versus informal land rights: Governance for sustainable urbanization in the Jakarta metropolitan region, Indonesia," *Land use policy*, Vol.43, no.7, 2015, page.71.

⁵² Wiwandari Handayani, Uchendu Eugene Chigbu, Iwan Rudiarto, and Intan Hapsari Surya Putri., "Urbanization and Increasing flood risk in the Northern Coast of Central Java Indonesia: An assessment towards better land use policy and flood management," *Land*, Vol.9, no.10, 2020,

From a legal standpoint, the spatial distribution of built-up land highlighted by the models can be directly linked to existing regulatory frameworks. Areas identified as high-risk for future development, particularly zones exhibiting rapid land conversion, may reflect gaps in enforcement of land use and zoning laws. Pekanbaru's regulatory landscape, including Perda 7/2020 on local spatial planning and Law 26/2007 on national spatial planning, sets clear guidelines for permissible land use. However, the concentration of built-up land growth in certain districts suggests that enforcement may be inconsistent or that regulations are not fully aligned with emerging development pressures. The model's spatial variables, marked as 'DIST', illustrate that proximity to urban cores, main roads, and existing built-up areas significantly drives land development. When interpreted legally, this suggests that areas near urban infrastructure may be subject to unauthorized or unlicensed construction if regulatory oversight is weak. By mapping high-probability built-up areas against legal zoning boundaries, policymakers can identify gaps where zoning revisions, stricter enforcement, or permit audits are required. For example, districts with high population density and land value, where new settlements appear disproportionately, may indicate unpermitted construction activities.

These findings are strongly corroborated by numerous studies across Indonesian cities, which consistently demonstrate that proximity-driven development regularly overrides statutory zoning due to weak enforcement mechanisms, overlapping authorities, inadequate digital land-administration systems, and private-sector dominance in permitting processes.⁵³ By mapping high-probability built-up areas

page.351. See too, Agung Indrajit, Bastiaan Van Loenen, Virgo Eresta Jaya, Hendrik Ploeger, Christiaan Lemmen, and Peter van Oosterom., "Implementation of the spatial plan information package for improving ease of doing business in Indonesian cities," *Land use policy*, Vol.105 no.8, 2021, page.10342; Fadjar Hari Mardiansjah, Paramita Rahayu, and Deden Rukmana., "New patterns of urbanization in Indonesia: emergence of non-statutory towns and new extended urban regions," *Environment and Urbanization ASIA*, Vol.12, no.1, 2021, page.21; Deden Rukmana., "The change and transformation of Indonesian spatial planning after Suharto's new order regime: The case of the Jakarta metropolitan area," *International Planning Studies*, Vol.20, no.4, 2015, page.358; Wilmar Salim, and Delik Hudalah., "Urban governance challenges and reforms in Indonesia: towards a new Urban Agenda," In *New urban agenda in Asia-Pacific: Governance for sustainable and inclusive cities*, Singapore, Springer Singapore, 2019, page.170; L. Siebritz, and S. Coetzee., "Evaluating stakeholder influences on the land use application process in South Africa—Results from an analysis of the legal framework," *Land Use Policy*, Vol.120, no.12, 2022, page.106239.

⁵³ Sri Wahyu Handayani, Suparjo Sujadi, and Arie Sukanti Sumantri., "A critical review of the discrepancy between the spatial planning map and the spatial planning regulation of agricultural lands in Indonesia: Kulon Progo Regency case study," *World Review of Science, Technology and Sustainable Development*, Vol.16, no.4, 2020, page.359; Agung Indrajit, Bastiaan Van Loenen, Virgo Eresta Jaya, Hendrik Ploeger, Christiaan Lemmen, and Peter van Oosterom., "Implementation of the spatial plan information package for improving ease of doing business in Indonesian cities," *Land use policy*, Vol.105 no.8, 2021, page.10344; Paul Jones., "Formalizing the informal: Understanding the position of informal settlements and slums in sustainable urbanization policies and strategies in Bandung, Indonesia," *Sustainability*, Vol.9, no.8, 2017, page.1440; Fadjar Hari Mardiansjah, Paramita Rahayu, and Deden Rukmana., "New patterns of urbanization in Indonesia: emergence of non-statutory towns and new extended urban regions," *Environment and Urbanization ASIA*, Vol.12, no.1, 2021, page.22; Rini Rachmawati., "Urban development, land use, and spatial planning for settlements: lessons learned from

against legal zoning boundaries, policymakers can identify gaps where zoning revisions, stricter enforcement, or permit audits are required. For example, districts with high population density and land value, where new settlements appear disproportionately, may indicate unpermitted construction activities. These insights support the use of predictive modeling as a tool for legal monitoring and proactive planning, enabling authorities to anticipate sprawl and enforce regulations before uncontrolled expansion occurs, a strategy already advocated for improving ease-of-doing-business indicators while curbing illegal conversion in Indonesian urban regions.⁵⁴

Analyzed through a legal-empirical lens, the model's high predictive weight of proximity and land value reveals regulatory failure in Pekanbaru. Despite zoning and permitting laws, development follows market and infrastructure cues, indicating weak legal intervention. Economic incentives, unclear land titles, and delayed permits further accelerate unplanned urban expansion. Incorporating machine learning predictions into governance can help authorities prioritize inspections, enforce zoning, and target high-risk areas, mitigating informal settlements and uncontrolled sprawl. These findings underscore the critical need to strengthen legal frameworks and adaptive urban management mechanisms.⁵⁵

Yogyakarta City, Indonesia," *American Journal of Economics and Sociology*, Vol.80, no.2, 2021, page.768; Wilmar Salim, and Delik Hudalah., "Urban governance challenges and reforms in Indonesia: towards a new Urban Agenda," In *New urban agenda in Asia-Pacific: Governance for sustainable and inclusive cities*, Singapore, Springer Singapore, 2019, page.172; L. Siebritz, and S. Coetzee., "Evaluating stakeholder influences on the land use application process in South Africa—Results from an analysis of the legal framework," *Land Use Policy*, Vol.120, no.12, 2022, page.106240; Christopher Silver., "Rapid urbanization: the challenges and opportunities for planning in Indonesian cities," *The Indonesian economy and the surrounding regions in the 21st century: essays in honor of Iwan Jaya Azis*, Vol.7, no.21, 2024, page.44; I. Gusti Ngurah Parikesit Widiatedja, Nadirsyah Hosen, Putu Gede Arya Sumerta Yasa, I. Made Budi Arsika, and Made Cinthya Puspita Shara., "Reforming Digital Mapping Regulations for Preventing Spatial Planning Violations in Indonesia: A Lesson from Australia," *Journal of Indonesian Legal Studies*, Vol.9, no.2, 2024, page.642; Jieming Zhu, and Hendricus Andy Simarmata., "Formal land rights versus informal land rights: Governance for sustainable urbanization in the Jakarta metropolitan region, Indonesia," *Land use policy*, Vol.43, no.7, 2015, page.72.

⁵⁴ Agung Indrajit, Bastiaan Van Loenen, Virgo Eresta Jaya, Hendrik Ploeger, Christiaan Lemmen, and Peter van Oosterom., "Implementation of the spatial plan information package for improving ease of doing business in Indonesian cities," *Land use policy*, Vol.105 no.8, 2021, page.10345. See too, Christopher Silver., "Rapid urbanization: the challenges and opportunities for planning in Indonesian cities," *The Indonesian economy and the surrounding regions in the 21st century: essays in honor of Iwan Jaya Azis*, Vol.7, no.21, 2024, page.45.

⁵⁵ Haris Budiman, Anis Mashdurohatun, and Eman Suparman., "A Comparative Study of Spatial Policy in Indonesia and the Netherlands," *Jurnal Dinamika Hukum*, Vol.18, no.3, 2018, page.298. See too, Wiwandari Handayani, Uchendu Eugene Chigbu, Iwan Rudiarto, and Intan Hapsari Surya Putri., "Urbanization and Increasing flood risk in the Northern Coast of Central Java Indonesia: An assessment towards better land use policy and flood management," *Land*, Vol.9, no.10, 2020, page.352; Agung Indrajit, Bastiaan Van Loenen, Virgo Eresta Jaya, Hendrik Ploeger, Christiaan Lemmen, and Peter van Oosterom., "Implementation of the spatial plan information package for improving ease of doing business in Indonesian cities," *Land use policy*, Vol.105 no.8, 2021, page.10347; Edy Lisdiyono., "Land Procurement for Public Interest and Spatial Planning: Legal

This pattern of market-led, proximity-driven expansion overriding statutory planning is a recurrent finding across Indonesian cities, where weak enforcement capacity, fragmented governance, private-sector dominance, unclear land rights, and outdated or poorly integrated land-administration systems consistently allow speculative development to outpace regulatory control.⁵⁶ Furthermore, legal frameworks interact with economic incentives, as landowners and developers respond to market opportunities. Weak legal enforcement, unclear land titles, or delays in permit issuance can accelerate unplanned urban growth, highlighting the need for stronger governance mechanisms. Incorporating machine learning predictions into regulatory planning can assist urban authorities in prioritizing inspections and targeting areas where built-up land development conflicts with statutory zoning, thereby reducing the risk of informal settlements and uncontrolled sprawl a strategy already demonstrated to improve transparency, reduce information asymmetry, and support evidence-based enforcement in Indonesian urban contexts.⁵⁷

The weak law enforcement that has enabled uncontrolled urban expansion in Pekanbaru can be systematically analyzed through a triad: legal substance, structure, and culture. First, the legal substance fails because the sanctions in Law Number 26/2007 concerning Spatial Planning and regional regulations, such as Pekanbaru Regional Regulation Number 7/2020, are inadequate and economically

and Juridical Implications," *Lex Publica*, Vol.4, no.2, 2017, page.771; Maret Priyanta, and Cut Sabina Anasya Zulkarnain., "Urban green open space in developing countries: Indonesia regulations, problems and alternative solutions," *Journal of Property, Planning and Environmental Law*, Vol.16, no.2, 2024, page.140; I. Gusti Ngurah Parikesit Widiatedja, Ida Bagus Erwin Ranawijaya, Sagung Putri ME Purwani, and Bima Kumara Dwi Atmaja., "Developing Effective Procedures for Public Participation in Spatial Planning Regulation in Indonesia: Lesson Learned from Australia," *Padjadjaran Jurnal Ilmu Hukum*, Vol.10, no.3, 2023, page.391.

⁵⁶ Wiwandari Handayani, Uchendu Eugene Chigbu, Iwan Rudiarto, and Intan Hapsari Surya Putri., "Urbanization and Increasing flood risk in the Northern Coast of Central Java Indonesia: An assessment towards better land use policy and flood management," *Land*, Vol.9, no.10, 2020, page.353. See too, Fatih Taktak., "Comparative building amnesty and land use policies: Insights from ten countries with a focus on Turkey," *Land Use Policy*, Vol.158, no.12, 2025, page.1063; Wen, Krishna Samudera, Luky Adrianto, Gabrielle L. Johnson, Mary Sue Brancato, and Alan White., "Towards Marine spatial planning implementation in Indonesia: progress and hindering factors," *Coastal Management*, Vol.50, no.6, 2022, page.475; I. Gusti Ngurah Parikesit Widiatedja, Ida Bagus Erwin Ranawijaya, Sagung Putri ME Purwani, and Bima Kumara Dwi Atmaja., "Developing Effective Procedures for Public Participation in Spatial Planning Regulation in Indonesia: Lesson Learned from Australia," *Padjadjaran Jurnal Ilmu Hukum*, Vol.10, no.3, 2023, page.393.

⁵⁷ Hamidah Abdurrachman, Achmad Irwan Hamzani, and Joko Mariyono., "Environmental crime and law enforcement in Indonesia: some reflections on counterproductive approaches," *Environmental Policy and Law*, Vol.51, no.6, 2021, page.414. See too, Claudio Ricky Adhitya, Kezia Elvira Nainggolan, Emi Juliana Sinaga, Ester Susanti, and Vincentia Cordialia Halan., "Environment Destruction in Indonesia: The Effectiveness of Indonesia's Environment Law (Legal Sociology Perspective)," *Equality: Journal of Law and Justice*, Vol.2, no.1, 2025; page.114; Edy Lisdiyono., "Land Procurement for Public Interest and Spatial Planning: Legal and Juridical Implications," *Lex Publica*, Vol.4, no.2, 2017, page.773; I. Gusti Ngurah Parikesit Widiatedja, Nadirsyah Hosen, Putu Gede Arya Sumerta Yasa, I. Made Budi Arsika, and Made Cinthya Puspita Shara., "Reforming Digital Mapping Regulations for Preventing Spatial Planning Violations in Indonesia: A Lesson from Australia," *Journal of Indonesian Legal Studies*, Vol.9, no.2, 2024, page.644.

irrational. The financial benefits from illegal land conversion exceed potential fines, thus encouraging violations.⁵⁸ Second, the legal structure is weak due to fragmented institutional authority at the national, provincial, and city levels, limited monitoring capacity, overlapping mandates, and inadequate staffing. This makes systematic inspections practically impossible and allows speculative development to continue unchecked.⁵⁹ Third, the legal culture perpetuates non-compliance as socially normalized; developers, elites, and some members of the public perceive violations as routine, while practices of regulatory manipulation and collusion further weaken law enforcement.⁶⁰

Machine learning model analysis in Pekanbaru shows that the expansion of built-up land (impervious surface area) is not solely driven by biophysical factors, but primarily by a complex interaction between social and economic dynamics, and the failure of spatial planning laws. Social factors such as population growth, household density, and rural-urban migration are the primary drivers of the conversion of agricultural land and wetlands into residential and commercial areas.⁶¹ The insignificance of rainfall as a predictor confirms that settlement

⁵⁸ Hamidah Abdurrachman, Achmad Irwan Hamzani, and Joko Mariyono., "Environmental crime and law enforcement in Indonesia: some reflections on counterproductive approaches," *Environmental Policy and Law*, Vol.51, no.6, 2021, page.415. See too, Terry G. McGee., "The emergence of desakota regions in Asia: expanding a hypothesis." *The extended metropolis: Settlement transition in Asia*, Vol.2, no.3, 1991, page.23; Ismu Gunadi Widodo, J. Andy Hartanto, Eddy Pranjoto W, and Jonaedi Efendi., "Constraints on enforcement of environmental law against corporate defendants," *Environmental Policy and Law*, Vol.49, no.1, 2019, page.80.

⁵⁹ Hamidah Abdurrachman, Achmad Irwan Hamzani, and Joko Mariyono., "Environmental crime and law enforcement in Indonesia: some reflections on counterproductive approaches," *Environmental Policy and Law*, Vol.51, no.6, 2021, page.416. See too, Hartiwingsih, Seno Wibowo Gumbira, and Jaco Barkhuizen., "Dysfunctional Factors of Environmental Law on Strategic Lawsuit Against Public Participation and Developing Remedial Strategies Through Reconstruction Criminal Law System Model in Indonesia," *PADJADJARAN Jurnal Ilmu Hukum*, Vol.10, no.3, 2023, page.2; Baginda Khalid Hidayat Jati, Esmi Warassih Pujirahayu, Teddy Asmara, and Ridwan Arifin., "Legal Culture, Environmental Non-Compliance, and the Persistence of Illegal Mining in Paningkaban," *Indonesian Journal of Criminal Law Studies*, Vol.10, no.1, 2025, page.150; Fatih Taktak., "Comparative building amnesty and land use policies: Insights from ten countries with a focus on Turkey," *Land Use Policy*, Vol.158, no.12, 2025, page.1064.

⁶⁰ Claudio Ricky Adhitya, Kezia Elvira Nainggolan, Emi Juliana Sinaga, Ester Susanti, and Vincentia Cordialia Halan., "Environment Destruction in Indonesia: The Effectiveness of Indonesia's Environment Law (Legal Sociology Perspective)," *Equality: Journal of Law and Justice*, Vol.2, no.1, 2025; page.115. See too, Arifin Maruf., "Legal aspects of environment in Indonesia: An efforts to prevent environmental damage and pollution," *Journal of Human Rights, Culture and Legal System*, Vol.1, no.1, 2021, page.5; Derita Prapti Rahayu, Faisal Faisal, Rafiq Sari, and Ndaru Satrio., "Law enforcement in the context of legal culture in society," *Law Reform*, Vol.16, no.2, 2020, page.278; Gregorius Widiartana, Vincentius Patria Setyawan, and Ariesta Wibisono Anditya., "Ecocide as an Environmental Crime: Urgency for Legal Reform in Indonesia," *Journal of Law, Environmental and Justice*, Vol.3, no.2, 2025, page.271.

⁶¹ Wiwandari Handayani, Uchendu Eugene Chigbu, Iwan Rudiarto, and Intan Hapsari Surya Putri., "Urbanization and Increasing flood risk in the Northern Coast of Central Java Indonesia: An

decisions are driven more by accessibility to social services (schools, hospitals, markets) than environmental constraints, resulting in sprawl even in flood-prone areas.

Economically, high land values, proximity to main roads, and infrastructure accessibility create a positive feedback loop that accelerates property investment and speculation.⁶² From a spatial planning perspective, these findings reflect a systemic failure of regulatory enforcement in Indonesia: weak coordination between levels of government, overlapping authority, and low oversight capacity often lead to development that ignores spatial plans.⁶³ Integrating predictive models into policymaking enables local governments to prioritize inspections, evidence-based zoning revisions, and implement economic instruments such as progressive land value taxes or vertical development incentives.⁶⁴

A multidimensional approach that combines social insights (providing public infrastructure in high-risk districts), economic insights (controlling speculation through market instruments), and legal insights (enforcement based on machine learning predictions) is key to shifting from a reactive to a proactive approach to controlling urban sprawl. Without integrating these three dimensions, Pekanbaru

assessment towards better land use policy and flood management," *Land*, Vol.9, no.10, 2020, page.354. See too, Paul Jones., "Formalizing the informal: Understanding the position of informal settlements and slums in sustainable urbanization policies and strategies in Bandung, Indonesia," *Sustainability*, Vol.9, no.8, 2017, page.1441.

⁶² Haris Budiman, Anis Mashdurohatun, and Eman Suparman., "A Comparative Study of Spatial Policy in Indonesia and the Netherlands," *Jurnal Dinamika Hukum*, Vol.18, no.3, 2018, page.299. See too, Punam Parikh, Michael A. Taylor, Theresa Hoagland, Hale Thurston, and William Shuster., "Application of market mechanisms and incentives to reduce stormwater runoff: An integrated hydrologic, economic and legal approach," *Environmental Science & Policy*, Vol.8, no.2, 2005, page.146; Maret Priyanta, and Cut Sabina Anasya Zulkarnain., "Urban green open space in developing countries: Indonesia regulations, problems and alternative solutions," *Journal of Property, Planning and Environmental Law*, Vol.16, no.2, 2024, page.142.

⁶³ Claudio Ricky Adhitya, Kezia Elvira Nainggolan, Emi Juliana Sinaga, Ester Susanti, and Vincentia Cordialia Halan., "Environment Destruction in Indonesia: The Effectiveness of Indonesia's Environment Law (Legal Sociology Perspective)," *Equality: Journal of Law and Justice*, Vol.2, no.1, 2025; page.116. See too, Edy Lisdiyono., "Land Procurement for Public Interest and Spatial Planning: Legal and Juridical Implications," *Lex Publica*, Vol.4, no.2, 2017, page.775; Deden Rukmana., "The change and transformation of Indonesian spatial planning after Suharto's new order regime: The case of the Jakarta metropolitan area," *International Planning Studies*, Vol.20, no.4, 2015, page.359; Fatih Taktak., "Comparative building amnesty and land use policies: Insights from ten countries with a focus on Turkey," *Land Use Policy*, Vol.158, no.12, 2025, page.1065; Wen, Krishna Samudera, Luky Adrianto, Gabrielle L. Johnson, Mary Sue Brancato, and Alan White., "Towards Marine spatial planning implementation in Indonesia: progress and hindering factors," *Coastal Management*, Vol.50, no.6, 2022, page.477; I. Gusti Ngurah Parikesit Widiatedja, Ida Bagus Erwin Ranawijaya, Sagung Putri ME Purwani, and Bima Kumara Dwi Atmaja., "Developing Effective Procedures for Public Participation in Spatial Planning Regulation in Indonesia: Lesson Learned from Australia," *Padjadjaran Jurnal Ilmu Hukum*, Vol.10, no.3, 2023, page.392.

⁶⁴ Agung Indrajit, Bastiaan Van Loenen, Virgo Eresta Jaya, Hendrik Ploeger, Christiaan Lemmen, and Peter van Oosterom., "Implementation of the spatial plan information package for improving ease of doing business in Indonesian cities," *Land use policy*, Vol.105 no.8, 2021, page.10348. See too, L. Siebritz, and S. Coetzee., "Evaluating stakeholder influences on the land use application process in South Africa—Results from an analysis of the legal framework," *Land Use Policy*, Vol.120, no.12, 2022, page.106241.

and other mid-sized Indonesian cities, will continue to experience uncontrolled growth, increasing flood vulnerability, social inequality, and the loss of productive land.⁶⁵

4. Conclusion

Pekanbaru City has experienced significant urban expansion over the past few decades, as evidenced by the increasing growth of Impervious Surface Area (ISR) and the emergence of new agglomeration zones. This rapid development has created major sustainability challenges, including uncontrolled land use, a strengthened Urban Heat Island effect, and higher greenhouse gas emissions. Using classical logistic regression in combination with a sophisticated AutoML model, this study identifies key drivers of ISR growth, particularly spatial proximity, population density, land value, and infrastructure accessibility.

From a legal perspective, the findings indicate that existing spatial planning and zoning regulations are insufficiently enforced to manage the pace of urban growth. To address this gap, the study argues for moving beyond generic calls for “stricter enforcement” and proposes three concrete measures. First, integrate predictive models as adaptive legal instruments. The Pekanbaru City Government should adopt predictive tools (such as the CatBoost_GoldenFeatures model) as proactive monitoring systems. Instead of reactive compliance checks, such tools enable early detection of high-risk districts and targeted inspections before illegal land conversion occurs. Second, implement risk-based permitting. Model outputs should be incorporated into the development approval process. Areas classified as high probability for urban sprawl would be subject to tighter oversight, higher development fees, or fiscal disincentives to redirect growth toward designated zones. Third, strengthen legal data as a continuous feedback loop. Cities should improve spatial databases of legal violations. By systematically mapping zoning breaches and unauthorized construction, this data can be fed back into the predictive model, improving accuracy and helping planners understand not only where urban sprawl is occurring but also why certain regulatory instruments are failing. The implementation requires addressing institutional and data limitations, improving coordination, and integrating law enforcement with social infrastructure planning and sustainable development incentives. By aligning predictive modeling with proactive legal and socio-economic strategies, Pekanbaru can better manage ISA growth and promote balanced urban sustainability.

⁶⁵ Wiwandari Handayani, Uchendu Eugene Chigbu, Iwan Rudiarto, and Intan Hapsari Surya Putri., “Urbanization and Increasing flood risk in the Northern Coast of Central Java Indonesia: An assessment towards better land use policy and flood management,” *Land*, Vol.9, no.10, 2020, page.355. See too, Fadjar Hari Mardiansjah, Paramita Rahayu, and Deden Rukmana., “New patterns of urbanization in Indonesia: emergence of non-statutory towns and new extended urban regions,” *Environment and Urbanization ASIA*, Vol.12, no.1, 2021, page.24.

References

Books:

- Gottmann, Jean, and Robert Alexander Harper., *Since Megalopolis: the urban writings of Jean Gottmann*. Baltimore, Johns Hopkins University Press, 1990;
- Rustiadi, Ernan, and Dyah Retno Panaju., "Spatial pattern of suburbanization and land-use change process: case study in Jakarta suburb." In *Land Use Changes in Comparative Perspective*, New York, CRC Press, 2002;
- Salim, Wilmar, and Delik Hudalah., "Urban governance challenges and reforms in Indonesia: towards a new Urban Agenda." In *New urban agenda in Asia-Pacific: Governance for sustainable and inclusive cities*, Singapore: Springer Singapore, 2019;

Journals:

- Abdurrachman, Hamidah, Achmad Irwan Hamzani, and Joko Mariyono., "Environmental crime and law enforcement in Indonesia: some reflections on counterproductive approaches." *Environmental Policy and Law* Vol.51, no.6, 2021; <https://doi.org/10.3233/EPL-210024>;
- Adhitya, Claudio Ricky, Kezia Elvira Nainggolan, Emi Juliana Sinaga, Ester Susanti, and Vincentia Cordialia Halan., "Environment Destruction in Indonesia: The Effectiveness of Indonesia's Environment Law (Legal Sociology Perspective)." *Equality: Journal of Law and Justice* Vol.2, no.1, 2025; <https://doi.org/10.69836/equality-jlj.v2i1.285>;
- Aguayo, Mauricio I., Thorsten Wiegand, Gerardo D. Azócar, Kerstin Wiegand, and Claudia E. Vega., "Revealing the driving forces of mid-cities urban growth patterns using spatial modeling: a case study of Los Ángeles, Chile." *Ecology and Society* Vol.12, no.1, 2007;
- Alpaidze, Levan, and Joseph Salukvadze., "Green in the city: estimating the ecosystem services provided by urban and peri-urban forests of Tbilisi municipality, Georgia." *Forests* Vol.14, no.1, 2023; <https://doi.org/10.3390/f14010121>;
- Altaweel, Mark, Jack Hanson, and Andrea Squitieri., "The structure, centrality, and scale of urban street networks: Cases from Pre-Industrial Afro-Eurasia." *PLoS one* Vol.16, no.11, 2021; <https://doi.org/10.1371/journal.pone.0259680>;
- Andrakakou, Maria, and Carsten Keßler., "Investigating configurational and active centralities: The example of metropolitan Copenhagen." *Environment and Planning B: Urban Analytics and City Science* Vol.49, no.7, 2022; <https://doi.org/10.1177/23998083211072861>;
- Biswas, Mriganka Sekhar, and D. C. Ayantika., "Impact of COVID-19 Control Measures on Trace Gases (NO₂, HCHO and SO₂) and Aerosols over India during Pre-monsoon of 2020." *Aerosol and Air Quality Research* Vol.21, no.1, 2021; <https://doi.org/10.4209/aaqr.2020.06.0306>;

- Budiman, Haris, Anis Mashdurohatun, and Eman Suparman., "A Comparative Study of Spatial Policy in Indonesia and the Netherlands." *Jurnal Dinamika Hukum* Vol.18, no.3, 2018;
- Dijkstra, Lewis, Aneta J. Florczyk, Sergio Freire, Thomas Kemper, Michele Melchiorri, Martino Pesaresi, and Marcello Schiavina., "Applying the degree of urbanisation to the globe: A new harmonised definition reveals a different picture of global urbanisation." *Journal of Urban Economics* Vol.125, no.11, 2021; <http://dx.doi.org/10.20884/1.jdh.2018.18.3.2154>;
- Eisenring, Deltri Dikwardi., "Pertumbuhan Area Perkotaan 2 Di Sekitar Kampus Perguruan Tinggi Universitas Tadulako Palu." *Ruang: Jurnal Arsitektur* Vol.16, no.1, 2022;
- Freeman, Linton C., "Centrality in social networks conceptual clarification." *Social networks* Vol.1, no.3, 1978;
- Friedmann, J., "A general theory of polarized development. Ford Foundation, Urban and Regional Development Advisory Program in Chile." *Santiago* Vol.81, no.11, 1967;
- Gao, Jing, and Brian C. O'Neill., "Mapping global urban land for the 21st century with data-driven simulations and Shared Socioeconomic Pathways." *Nature communications* Vol.11, no.1, 2020; <https://doi.org/10.1038/s41467-020-15788-7>;
- Handayani, Sri Wahyu, Suparjo Sujadi, and Arie Sukanti Sumantri. "A critical review of the discrepancy between the spatial planning map and the spatial planning regulation of agricultural lands in Indonesia: Kulon Progo Regency case study." *World Review of Science, Technology and Sustainable Development* Vol.16, no.4, 2020; <https://doi.org/10.1504/WRSTSD.2020.113489>;
- Handayani, Wiwandari, Uchendu Eugene Chigbu, Iwan Rudiarto, and Intan Hapsari Surya Putri., "Urbanization and Increasing flood risk in the Northern Coast of Central Java Indonesia: An assessment towards better land use policy and flood management." *Land* Vol.9, no.10, 2020; <https://doi.org/10.3390/land9100343>;
- Hartiwiningsih, Hartiwiningsih, Seno Wibowo Gumbira, and Jaco Barkhuizen., "Dysfunctional Factors of Environmental Law on Strategic Lawsuit Against Public Participation and Developing Remedial Strategies Through Reconstruction Criminal Law System Model in Indonesia." *PADJADJARAN Jurnal Ilmu Hukum* Vol.10, no.3, 2023; <https://doi.org/10.22304/pjih.v10n3.a6>;
- Hidajat, Janthy Trilusianthy, S. R. P. Sitorus, and E. Rustiadi., "Urban sprawl effects on settlement areas in urban fringe of Jakarta Metropolitan Area." *J Environ Earth Sci* Vol.3, no.12, 2013;

- Horton, Daniel E., Jordan L. Schnell, Daniel R. Peters, David C. Wong, Xi Lu, Hao Gao, Hongliang Zhang, and Patrick L. Kinney. "Effect of adoption of electric vehicles on public health and air pollution in China: a modelling study." *The Lancet Planetary Health* Vol.5, no.2, 2021;
- Indrajit, Agung, Bastiaan Van Loenen, Virgo Eresta Jaya, Hendrik Ploeger, Christiaan Lemmen, and Peter van Oosterom., "Implementation of the spatial plan information package for improving ease of doing business in Indonesian cities." *Land use policy* Vol.105 no.8, 2021; <https://doi.org/10.1016/j.landusepol.2021.105338>;
- Jati, Baginda Khalid Hidayat, Esmi Warassih Pujirahayu, Teddy Asmara, and Ridwan Arifin., "Legal Culture, Environmental Non-Compliance, and the Persistence of Illegal Mining in Paningkaban." *Indonesian Journal of Criminal Law Studies* Vol.10, no.1, 2025;
- Johansson, M., Claudia Rivera, Benjamin de Foy, Wenfang Lei, Jihee Song, Yan Zhang, Bo Galle, and L. Molina., "Mobile mini-DOAS measurement of the outflow of NO₂ and HCHO from Mexico City." *Atmospheric Chemistry and Physics* Vol.9, no.15, 2009;
- Jones, Paul., "Formalizing the informal: Understanding the position of informal settlements and slums in sustainable urbanization policies and strategies in Bandung, Indonesia." *Sustainability* Vol.9, no.8, 2017;
- Kravchenko, Kateryna., "Urban agglomeration: human-geographical concept in the sustainable development perspective." *Visnyk of VN Karazin Kharkiv National University. Series Geology. Geography. Ecology* Vol.62, no.12, 2025; <https://doi.org/10.26565/2410-7360-2025-62-18>;
- Le Quéré, Corinne, Robbie M. Andrew, Pierre Friedlingstein, Stephen Sitch, Julia Pongratz, Andrew C. Manning, Jan Ivar Korsbakken et al., "Global carbon budget 2017." *Earth System Science Data* Vol.10, no.1, 2018;
- Lee, Chun-Chang, Li-Yun Huang, and Shu-Man You., "The changes and trends in urban land prices: an application of hierarchical growth modelling." *Asian Economic and Financial Review* Vol.3, no.5, 2013;
- Lisdiyono, Edy. "Land Procurement for Public Interest and Spatial Planning: Legal and Juridical Implications." *Lex Publica* Vol.4, no.2, 2017;
- Liu, Xiaoping, Yinghuai Huang, Xiaocong Xu, Xuecao Li, Xia Li, Philippe Ciais, Peirong Lin et al., "High-spatiotemporal-resolution mapping of global urban change from 1985 to 2015." *Nature Sustainability* Vol.3, no.7, 2020; <https://doi.org/10.1038/s41893-020-0521-x>;
- Mardiansjah, Fadjar Hari, Paramita Rahayu, and Deden Rukmana., "New patterns of urbanization in Indonesia: emergence of non-statutory towns and new extended urban regions." *Environment and Urbanization ASIA* Vol.12, no.1, 2021, <https://doi.org/10.1177/0975425321990384>;
- Maruf, Arifin., "Legal aspects of environment in Indonesia: An efforts to prevent environmental damage and pollution." *Journal of Human Rights, Culture and Legal System* Vol.1, no.1, 2021; <https://doi.org/10.53955/jhcls.v1i1.4>;

- McGee, Terry G. "The emergence of desakota regions in Asia: expanding a hypothesis." *The extended metropolis: Settlement transition in Asia* Vol.2, no.3, 1991;
- Mi X, Wang S, Shao C, Zhang P, Chen M., "Resident travel mode prediction model in Beijing metropolitan area." *PLoS ONE* 16, 11, 2021; <https://doi.org/10.1371/journal.pone.0259793>;
- Mukhlis, Jafar, and Sugiono Soetomo., "Analisis pengaruh exit toll terhadap tata guna lahan di Kabupaten Brebes." *Jurnal Pembangunan Wilayah & Kota* Vol.13, no.3, 2017;
- Niu, Fangqu, Xinyu Yang, and Fang Wang., "Urban agglomeration formation and its spatiotemporal expansion process in China: From the perspective of industrial evolution." *Chinese Geographical Science* Vol.30, no.3, 2020; <https://doi.org/10.1007/s11769-020-1094-3>;
- Noori, Fatemeh, Hamid Kamangir, Scott A. King, Alaa Sheta, Mohammad Pashaei, and Abbas Sheikh Mohammad Zadeh., "A deep learning approach to urban street functionality prediction based on centrality measures and stacked denoising autoencoder." *ISPRS International Journal of Geo-Information* Vol.9, no.7, 2020; <https://doi.org/10.3390/ijgi9070456>;
- Parikh, Punam, Michael A. Taylor, Theresa Hoagland, Hale Thurston, and William Shuster., "Application of market mechanisms and incentives to reduce stormwater runoff: An integrated hydrologic, economic and legal approach." *Environmental Science & Policy* Vol.8, no.2, 2005; <https://doi.org/10.1016/j.envsci.2005.01.002>;
- Peng, Chong, and Hongwei Xu., "Universities and cities: The impact of higher education on urban innovation, entrepreneurship, and economic growth." *Asian Economic Papers* Vol.23, no.2, 2024; https://doi.org/10.1162/asep_a_00890;
- Margono, Belinda Arunarwati, Peter V. Potapov, Svetlana Turubanova, Fred Stolle, and Matthew C. Hansen., "Primary Forest cover loss in Indonesia over 2000–2012." *Nature climate change* Vol.4, no.8, 2014, <https://doi.org/10.1038/nclimate2277>.
- Priyanta, Maret, and Cut Sabina Anasya Zulkarnain., "Urban green open space in developing countries: Indonesia regulations, problems and alternative solutions." *Journal of Property, Planning and Environmental Law* Vol.16, no.2, 2024; <https://doi.org/10.1108/JPEL-01-2024-0002>;
- Rachmawati, Rini., "Urban development, land use, and spatial planning for settlements: lessons learned from Yogyakarta City, Indonesia." *American Journal of Economics and Sociology* Vol.80, no.2, 2021; <https://doi.org/10.1111/ajes.12393>;
- Rahayu, Derita Prapti, Faisal Faisal, Rafiqah Sari, and Ndaru Satrio., "Law enforcement in the context of legal culture in society." *Law Reform* Vol.16,

- no.2, 2020; <https://doi.org/10.14710/lr.v16i2.33780>;
- Rukmana, Deden., "The change and transformation of Indonesian spatial planning after Suharto's new order regime: The case of the Jakarta metropolitan area." *International Planning Studies* Vol.20, no.4, 2015; <https://doi.org/10.1080/13563475.2015.1008723>;
- Sari, Yusra Aulia, and D. Dewanti., "Perubahan Penggunaan Lahan Dan Faktor-Faktor Yang Mempengaruhi Di Sekitar Area Panam Kota Pekanbaru." In *Seminar Nasional Geomatika*, Vol.3, no.751, 2019;
- Schneider, Annemarie, Carly M. Mertes, A. J. Tatem, B. Tan, Damien Sulla-Menashe, Sarah J. Graves, Nirav Nikunj Patel et al., "A new urban landscape in East-Southeast Asia, 2000–2010." *Environmental Research Letters* Vol.10, no.3, 2015;
- Seto, Karen C., Michail Fragkias, Burak Güneralp, and Michael K. Reilly., "A meta-analysis of global urban land expansion." *PloS one* Vol.6, no.8, 2011; <https://doi.org/10.1371/journal.pone.0023777>;
- Siebritz, L., and S. Coetzee., "Evaluating stakeholder influences on the land use application process in South Africa—Results from an analysis of the legal framework." *Land Use Policy* Vol.120, no.12, 2022, <https://doi.org/10.1016/j.landusepol.2022.106238>;
- Silver, Christopher., "Rapid urbanization: the challenges and opportunities for planning in Indonesian cities." *The Indonesian economy and the surrounding regions in the 21st century: essays in honor of Iwan Jaya Azis* Vol.7, no.21, 2024; https://doi.org/10.1007/978-981-97-0122-3_3;
- Singh, Prafull, Noyingbeni Kikon, and Pradipika Verma., "Impact of land use change and urbanization on urban heat island in Lucknow city, Central India. A remote sensing-based estimate." *Sustainable cities and society* Vol.32, no.6, 2017; <https://doi.org/10.1016/j.scs.2017.02.018>;
- Skogen, Ketil, Håvard Helland, and Bjørn Kaltenborn., "Concern about climate change, biodiversity loss, habitat degradation and landscape change: Embedded in different packages of environmental concern." *Journal for Nature Conservation* Vol.44, no.12, 2018; <https://doi.org/10.1016/j.jnc.2018.06.001>;
- Taktak, Fatih., "Comparative building amnesty and land use policies: Insights from ten countries with a focus on Turkey." *Land Use Policy* Vol.158, no.12, 2025; <https://doi.org/10.1016/j.landusepol.2025.107763>;
- Tian, Xin, Pinhua Xie, Jin Xu, Ang Li, Yang Wang, Min Qin, and Zhaokun Hu., "Long-term observations of tropospheric NO₂, SO₂ and HCHO by MAX-DOAS in Yangtze River Delta area, China." *Journal of Environmental Sciences*, Vol.71, no.21, 2018; <https://doi.org/10.1016/j.jes.2018.03.006>;
- Wadjidou, Boukari., "Why the 11th Sustainable Development Goal should be updated: The impact of land prices on immigrant settlement." *Authorea Preprints* Vol.11, no.4, 2022; DOI: 10.22541/au.164778652.22896495/v1;
- Wan Rahmah, Yudin, and Zaili Rusli., "Tata Kelola Kota Pekanbaru Menuju Smart

- City Madani." *Jurusan Ilmu Administrasi* Vol.7, no.1, 2020;
- Wang, Man-hua, Pin-hua Xie, Min Qin, Ke Dou, Jie Wang, Ang Li, Jin Xu, Peng Shi, and Feng-cheng Wu., "Atmospheric HCHO gradient monitoring and analysis in Beijing city with a scanning DOAS system." *Spectroscopy and Spectral Analysis* Vol.31, no.3, 2011; [https://doi.org/10.3964/j.issn.1000-0593\(2011\)03-0789-04](https://doi.org/10.3964/j.issn.1000-0593(2011)03-0789-04);
- Wen, Wen, Krishna Samudera, Luky Adrianto, Gabrielle L. Johnson, Mary Sue Brancato, and Alan White., "Towards Marine spatial planning implementation in Indonesia: progress and hindering factors." *Coastal Management* Vol.50, no.6, 2022; <https://doi.org/10.1080/08920753.2022.2126262>;
- Widiartana, Gregorius, Vincentius Patria Setyawan, and Ariesta Wibisono Anditya., "Ecocide as an Environmental Crime: Urgency for Legal Reform in Indonesia." *Journal of Law, Environmental and Justice* Vol.3, no.2, 2025; <https://doi.org/10.62264/jlej.v3i2.129>;
- Widiatedja, I. Gusti Ngurah Parikesit, Ida Bagus Erwin Ranawijaya, Sagung Putri ME Purwani, and Bima Kumara Dwi Atmaja., "Developing Effective Procedures for Public Participation in Spatial Planning Regulation in Indonesia: Lesson Learned from Australia." *Padjadjaran Jurnal Ilmu Hukum (Journal of Law)* Vol.10, no.3, 2023; <https://doi.org/10.22304/pjih.v10n3.a5>;
- Widiatedja, I. Gusti Ngurah Parikesit, Nadirsyah Hosen, Putu Gede Arya Sumerta Yasa, I. Made Budi Arsika, and Made Cinthya Puspita Shara., "Reforming Digital Mapping Regulations for Preventing Spatial Planning Violations in Indonesia: A Lesson from Australia." *Journal of Indonesian Legal Studies* Vol.9, no.2, 2024;
- Widodo, Ismu Gunadi, J. Andy Hartanto, Eddy Pranjoto W, and Jonaedi Efendi., "Constraints on enforcement of environmental law against corporate defendants." *Environmental Policy and Law* Vol.49, no.1, 2019; <https://doi.org/10.3233/EPL-190134>;
- Wong, Kapo, Yuanzhi Zhang, Qiuming Cheng, Ming Chun Chao, and Jin Yeu Tsou., "Comparison of Impervious Surface Dynamics through Vegetation/High-Albedo/Low-Albedo/Soil Model and Socio-Economic Factors." *Land* Vol.11, no.3, 2022; <https://doi.org/10.3390/land11030430>;
- Wu, Wenjia, Shuqing Zhao, and Geoffrey M. Henebry., "Drivers of urban expansion over the past three decades: A comparative study of Beijing, Tianjin, and Shijiazhuang." *Environmental Monitoring and Assessment* Vol.191, no.1, 2019; <https://doi.org/10.1007/s10661-018-7151-z>;
- Zeren Cetin, Ilknur, Tugrul Varol, Halil Baris Ozel, and Hakan Sevik., "The effects of climate on land use/cover: a case study in Turkey by using remote sensing data." *Environmental Science and Pollution Research* Vol.30, no.3, 2023; <https://doi.org/10.1007/s11356-022-22566-z>;

Zhang, Shuyan, Yong Ma, Erping Shang, Wutao Yao, Ke Qiao, Jian Peng, Jin Yang, and Chun Feng., "Production of Annual Nighttime Light Based on De-Difference Smoothing Algorithm." *Remote Sensing* Vol.16, no.16, 2024; <https://doi.org/10.3390/rs16163013>;

Zhu, Jieming, and Hendricus Andy Simarmata., "Formal land rights versus informal land rights: Governance for sustainable urbanization in the Jakarta metropolitan region, Indonesia." *Land use policy* Vol.43, no.7, 2015; <https://doi.org/10.1016/j.landusepol.2014.10.016>;

Conference:

Tri Hapsari, Ambar, Sidik Priadana, Sugiyanto Sugiyanto., "Factor Affecting Local Own Revenue and Their Impact on Impact on Fiscal Autonomy and Economic Growth in Jabodetabekjur." In *Proceedings of the 2nd International Conference on Law, Social Science, Economics, and Education, ICLSSEE 2022, 16 April 2022, Semarang, Indonesia*. <https://doi.org/10.4108/eai.16-4-2022.2319758>;

Mushore, Terence, John Odindi, Onesimo Mutanga, and Timothy Dube. "Predicting urban growth and implication on urban thermal characteristics in Harare, Zimbabwe." In *IGARSS 2018-2018 IEEE International Geoscience and Remote Sensing Symposium*, IEEE, 2018;

Razi, Maria, Steffen Dörner, Sebastian Donner, Noor Ahmad, Fahim Khokhar, and Thomas Wagner., "Study of the interrelationships between NO₂, SO₂, HCHO and CHOCHO vertical column densities derived by car MAX-DOAS observations in and around the megacity of Lahore, Pakistan." In *EGU General Assembly Conference Abstracts*, 2022;

Dissertation:

Putra, Rizki Rianda., "Analisis Perubahan Tata Guna Lahan Terhadap Koefisien Limpasan Kota Pekanbaru Berbasis Sistem Informasi Geografis (SIG)." PhD diss., Riau University, 2016;

Website:

JDIH Marves., "Permen PUPR 6/2023: Badan Pengaturan Jalan Tol." *Kementerian Koordinator Infrastruktur dan Pembangunan Kewilayahan*, May 30, 2023. <https://jdih.kemenkoinfra.go.id/en/permen-pupr-62023-badan-pengaturan-jalan-tol>. Accessed on October 23, 2025.