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Urban Inequalities

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The deprivations and inequalities based on settlement typologies and urban form: the case of Addis Ababa, Ethiopia

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Abstract
The study differentiated formal and informal settlements based on the slum ontology concept and space syntax analysis, which in turn revealed the pattern of spatial inequalities and deprivations for sustainable planning interventions. The delineated settlement revealed that the informal areas constituted 61% in 2010 and 59% in 2022, while the population living in the informal settlements was 68% and 54% in 2010 and 2020, respectively. The space syntax analysis of the road network for five case study areas revealed that formal settlements have a higher score, indicating a sustainable urban form relative to informal settlement typologies in the inner, intermediate, and periphery. Comparing the three informal settlement typologies, the peri-urban informal settlements are the most unconnected, isolated, and segregated, and they are not resilient to climatic change. The study contributes to monitoring the SDG-11 status regarding the proportion of the population living in informal settlements in Addis Ababa. The study showed that the slum ontology concept and space syntax disaggregate settlement dichotomies and informal settlement typologies based on sustainable urban form and deprivations. The study suggests considering the local contexts of informal settlement typologies and the trends of land consumption per population for smart city planning and climatic change implications.

Keywords
Deprivations; Slum ontology concept; Sustainable urban form; Informal settlement; Space syntax; Spatial inequalities

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1. Introduction

The challenges to sustainable urbanization policy are the growth of informal settlements and poverty (Jones, 2017; Liddle, 2017), which trigger multidimensional deprivations and spatial inequality. Spatial inequalities in urban areas are based on the development over time of distinct areas of urban deprivation (Grant, 2010) with increasing urbanization. World urbanization surpassed 50% in 2009 (Liddle, 2017), 54% in 2015 (UN-Habitat, 2016), and will be 68% in 2050 (Parikh et al., 2020). The absolute number of poor people in developing countries has increased from 689 million in 1990 to 807 million in 2000, 881 million in 2014, 883 million in 2015, and 682 million in 2022 (Development Initiatives, 2023; UN-Habitat & ISDP, 2020; UN-Habitat, 2016, 2017; UNICEF & UN-Habitat, 2020). A significant proportion of the poor live in rapidly urbanized areas (UN, 2018). Yet, the proportion of the population living in slums declined from 46% in 1990 to 25.4% in 2014 and 24.2% in 2020 (UN-Habitat & Global Urban Observatory, 2019; UNSD, 2023). Poverty is increasingly urbanized, with features of high living costs, limited services, and social marginalization (UNDG, 2012). Properly planned and managed urbanization contributes to a reduction in poverty (UN-Habitat, 2016). Unplanned rapid urbanization is associated with the proliferation of informal settlements (deprived areas) in low- and middle-income countries (Tjia & Coetzee, 2022). The informal (deprived areas) and formal (less deprived areas) settlement dichotomy generated housing inequality and the spatial exclusion of certain categories of urban residents from access to land, housing, and infrastructure (Anierobi et al., 2023). The urbanization of poverty, combined with unequal resource distribution and anti-poor policies, leads to rising urban poverty (UNDP, 2012). In 2035, most of the world's extremely poor will live in urban areas. Therefore, urban centers have become the focal point of multidimensional poverty (UNDP, 2016) and socio-spatial inequality. Moreover, the disproportional higher physical growth of urban areas than population growth impacts the environment, increasing spatial inequalities and lessening economies of agglomeration (UN-Habitat, 2015a). One of the major globally transformational forces of the twenty-first century is sustainable urbanization, which requires structural change to avert the urbanization challenges faced by cities (McCormick, et al., 2012). Structural transformation in turn requires consistent, comprehensive, and reliable geospatial data on informal settlement areas (Tjia & Coetzee, 2022). For monitoring informal settlements, SDG uses geospatial technology for slum identification (UN, 2018), backed by ground verification and statistical information. Thus, mapping the deprived area is the basis for estimating the progress towards SDG 11—the proportion of people living in slums and informal settlements (Kuffer et al., 2020).

Informal settlement definitions are crucial for deriving indicators of deprived areas based on the context of a country. The definition of informal settlements is based on the breach of statutory regulations (ECE, 2008; UN-Habitat & ISDP, 2020). On the other hand, informal settlements are not always defined in accordance with violations of binding laws (Arif et al., 2022; Drakakis-Smith, 1981; Mahiteme, 2014). In Ethiopia, for instance, de jure tenure rights do not necessarily guarantee formal buildings; rather, informal housing refers to dwellings that do not comply with legally enforced building laws and regulations (Mahiteme, 2014). Since the agreed-upon criteria distinguish settlement typologies, the ontology of being gives a philosophical lens for identifying reality through clearly formed entities and identifiable properties (Crotty, 1998). Accordingly, the slum ontology identified slums at three levels: environment, settlement, and object levels (Kohli et al., 2012). The manual delineation from VHR (Very High-Resolution Image) differentiates morphology at the settlement level, despite being labor- and time-intensive (Lilford et al., 2012). If the human judgment of an array of criteria is conjugated with ground verifications, there is a possibility to distinguish between informal and formal settlements (Samper et al., 2020). At settlement levels, the morphological characteristics of organic and inorganic layouts, irregular road networks and buildings, building and population density, lack of open and green space, and land use heterogeneity differentiate formal from informal settlements (Arif et al., 2022; Berhanu et al., 2022; Gizachew et al., 2023; Kuffer, 2017; Lemma et al., 2006; Sliuzas & Kuffer, 2008; Sori, 2012; Tarekegn, 2000; Weldeghebrael, 2022).

There are multiple deprivations and challenges facing informal settlements (Maemeko et al., 2021; Msimang, 2017; Zulch et al., 2023) that seek area-based policy (Gizachew et al., 2023) and sustainable development interventions. Sustainable smart city interventions need to consider the local socio-economic and morphological contexts, as well as the positive attributes of informal settlements' (Alizadeh & Prasad, 2024; Carrilho & Trindade, 2022; Geyer, 2023; Jones, 2017; Ndlangamandla & Combrinck, 2020; Prasad et al., 2023; URBANET, 2024; Zhang et al., 2020). The positive attributes of informal settlements for sustainable development and smart city planning are compact layout, waste recycling and reuse, mixed functions, and affordable housing. Hence, informal settlement merits also include the epicenter of various ethnic groups, local job creation, organized public space, sharing transport resources, and social interaction and cohesion (Carrilho & Trindade, 2022; Charitonidou, 2022; Geyer, 2023). The Ethiopian urban interventions overlooked genuine negotiated planning, the economic resilience of dwellers, and sharing public space for social cohesion (Borri & Asfaw, 2017; Charitonidou, 2022). Informal and formal settlement typologies differ in terms of sustainable urban form (Jabareen, 2006; Yamu et al., 2021), which implies that spatial configuration analysis contributes to detecting some of the positive attributes of settlements.

Researchers distinguish settlement typologies using spatial configuration analysis for planning and resilience interventions (Hidayati et al., 2021; Sandoval et al., 2020). The sustainable urban form differentiates the spatial configuration of settlement typologies by performing research regarding the relationship of space with society (Badhan, 2019; Khoshnaw, 2023; Lyu et al., 2023; Tufek-Memisevic, 2023; Van & Yamu, 2021; VTPI, 2017). Numerous researchers applied space syntax to analyze and interpret settlement forms in relation to sustainability, policy, and planning (Cutini et al., 2020; Hidayati et al., 2021; Khoshnaw, 2023; Mawlan et al., 2011; Sandoval et al., 2020). Spatial configuration influences sustainable urban form by analyzing and interpreting movement patterns, economic activity, land use heterogeneity, land value, density, public spaces, heritage sites, information for upgrading, and accessibility (Badhan, 2019; Hillier et al., 2007; Pappu, 2018; Tufek-Memisevic, 2023; Van & Yamu, 2021). In addition, the residents of informal settlements are also vulnerable to climatic change due to unsustainable urban forms such as substandard housing, poor services, and inadequate infrastructure (Ehebrecht, 2014; Greibe et al., 2020; James, 2023; Jean-Baptiste et al., 2018). Numerous researchers have identified and interpreted deprivation, either through space syntax or the concept of slum ontology. Yet, this research analyzed the morphology and spatial configuration of settlement disparities, combining space syntax and the slum ontology concept. The ontological properties of informal settlements were the conceptual framework for delineating informal and formal settlements for Addis Ababa city jurisdiction. Then, the authors verified the delineated areas by taking 113 GPS-based samples and photographs before producing the final output. The measurement of land use increment and decrement dynamics across informal and formal settlements provided evidence on settlement trends for monitoring SDG 11. The 2010 aerial photograph (20 by 20 cm resolution) was the basis for extracting informal and formal areas for 2010. The real-time Google Earth image, embedded in ARCGIS 10.8, was the backdrop for the delineation of informal and formal areas for 2022. The space syntax software differentiated settlement typologies based on sustainable urban form. The main interpretation components of space syntax were integration, choice, and connectivity (Berhie & Haq, 2017; Charalambous & Mavridou, 2012; Hillier & Hansen, 1984; Hillier et al., 2007; Pafka et al., 2020; Shatu et al., 2019). For space syntax analysis, the study chose five case study areas: three from informal settlements and two from formal settlements. The three case study areas were from informal settlement typologies: inner-city, intermediate, and peri-urban. Hence, two case study areas were selected from the formal settlement parts of the south-western and eastern parts of Addis Ababa. The open street network shape file, dated April 18, 2024, was the data source for spatial syntax analysis. The depth maps and QGIS Desktop 3.36.1 software analyzed road configuration for evaluating sustainable urban morphology. SDG not only monitors informal settlement areas but also requires information pertaining to the population living in informal settlements. Thus, the study used the WorldPop population

forecast per grid cell (100 by 100 m), taking into account built-up, land use/land cover, settled areas, and national census estimates (Loyd et al., 2019). Then, the study computed population density growth and reduction rates for informal and formal settlements. Then, the study computed population density increase and reduction rates for informal and formal settlements. The disproportional land consumption growth in relation to population relates to multipurpose measurements for the SDGs: land use efficiency, proximity of factors of production, rate of resource use, greenhouse gas (GHG) emissions, and reduced travel distance (UN-Habitat, 2015a). There is also empirical evidence on the relationship between high population density, high vulnerability, low income, and high demand for ecosystem services in Addis Ababa (UN-Habitat, 2017).
The research contributes to monitoring SDG 11 by analyzing and interpreting the area and population living in informal settlements in Addis Ababa. The research also shows the relevance of considering the positive attributes of informal settlements and urban form as the basis for smart city, resilient, and sustainable development interventions. The study specified research questions in light of the theoretical, conceptual, and methodological frameworks as follows: 1) "Are the extent and growth trends of the delineated informal and formal settlement areas in Addis Ababa and its sub-cities declining or increasing between 2010 and 2022?; 2) Does the road network configuration analysis and pattern vary with the typology of formal and informal settlements in Addis Ababa?; 3) "What proportions of the population of Addis Ababa were living in informal and formal settlement areas in 2010 and 2020?" The study identified informal (deprived) and formal (less deprived) areas based on the settlement level slum ontology concepts. The study selected five case study areas for analysis of sustainable urban form using space syntax.

2. Review on informal settlements

2.1. Informal settlement morphology configuration, extent and population assessment

Following the various definitions of "informal settlement," the criteria for identification of informal settlement by morphology differ. Most of the definitions focus on one or more factors, such as housing tenure, eviction risks, noncompliance with city building and planning regulations, and a lack of infrastructure and services. Additionally, the notion of informal settlement is linked to a high rate of crime, social marginalization, and proximity to hazardous situations (ECE, 2008; Payne & Majale, 2004; UN-Habitat, 2003; UN-Habitat, 2015b). An "informal settlement is a place where housing is built without the appropriate legal title to ownership (ECE, 2008). According to UN-Habitat and ISDP (2020), "informal settlement" is defined as areas that have sprung up in violation of laws and planning regulations, underscoring legality as the binding criterion. The informal settlement definition also includes land acquired legitimately or illegally, and building permits are partially granted (Arif et al., 2022). The above definition complies with Drakakis-Smith's (1981) claim that a slum is not necessarily illegal. Slums and squatter settlements are two subsets of informal settlements. Slums are the most impoverished and excluded form of informal settlement, characterized by poverty and a substantial agglomeration of dilapidated housing, often located on the most hazardous urban land (UN-Habitat, 2015b). The different countries agreed on the SDG 11.1.1 operational slum definition. Thus, a slum is a household lacking access to improved water, improved sanitation, a sufficient living area, durable housing, and tenure security (UN-Habitat & Global Urban Observatory, 2019). In Ethiopia, informal housing refers to dwellings that do not comply with legally enforced building standards and planning regulations (Mahiteme, 2014). In Ethiopia, de jure tenure rights do not necessarily guarantee whether the building is formal or informal. The old possession right in Ethiopia has legal recognition similar to the lease right as per registration proclamation no. 818/2014, article two (FDRE, 2014), despite most houses being dilapidated and substandard to comply with planning and building standard regulations. The Derg regime confiscated houses in old possession according to promulgation no. 47/1975 and no. 104/76 (Ambaye, 2015; Baker & Claeson, 1990). The mixed urban fabric

consists of regularized informal settlements and formal settlements that are in the process of changing to informal settlement fabrics (Dovey et al., 2020).

The levels of identification of the ontological properties of slums are settlement, environment, and object (Fallatah et al., 2018). Nonetheless, this study focuses on the identification of slum ontological properties at the settlement level using a mixed method of visual interpretation, verification, and observation. A number of authors have identified informal settlements based on settlement-level slum ontological properties (Arif et al., 2022; Kuffer, 2017; Lemma et al., 2006; Sliuzas & Kuffer, 2008; Sori, 2012). Kuffer (2017) characterized slum deprivation areas based on small building sizes, high roof density, a lack of orderly road arrangements, and an organic layout. Sori (2012) and Kuffer (2017) substantiated that in earlier stages of informal settlement evolution, low-density areas were the characteristics of informal settlement. In addition to density, land use homogeneity and heterogeneity differed based on the type and stages of informal settlements. Thus, the older and more densified slum settlements showed land use heterogeneity as opposed to the more homogenous newly developed informal settlements (Arif et al., 2022). Sliuzas & Kuffer (2008) delineated informal settlement areas from satellite imagery and performed correlation analysis with the MDI (Multiple Deprivation Index) of Delhi, India. Researchers extracted deprivation areas, or informal settlements, from the properties of pervious and impervious surfaces. The impervious surfaces are street layouts, small dwelling floor sizes, high building densities, unfenced buildings, and narrow roads. The permeable surface deprivation indicators are lack of green space, open space, vegetation extent, and ecosystem services (Arif et al., 2022; Berhanu et al., 2022; Gizachew et al., 2023; Kuffer, 2017; Lemma et al., 2006; Sliuzas & Kuffer, 2008; Sori, 2012; UN-Habitat, 2017; Weldeghebrael, 2022).

Researchers also identified informal settlements based on Ethiopian contexts. Lemma et al. (2006) used irregular layouts, a lack of green space, and high built-up density to identify inner-city slums in the Addis Ketema sub-city area of Addis Ababa, incorporating visual interpretative elements and focus group discussions. The prominent features of the inner-city slum of Addis Ababa include high building density and small-sized buildings, high population density and concentration, consolidated through "Kitiya" houses or illegal additions to the existing houses (Berhanu et al., 2022; Elias, 2008; Gizachew et al., 2023; Tarekegn, 2000; UN-Habitat, 2017; Weldeghebrael, 2022). In Addis Ababa, the inner-city slum sub-cities scored the lowest in ecosystem service supply, where income is very low, housing is poor, and there is no space for private gardens (UN-Habitat, 2017).

Researchers differentiated and contextualized informal settlements based on criteria, indicators, and interpretation elements. The manual delineation approach from VHR is a more accurate approximation of the ontology of informal settlements at settlement level, though it is labor-intensive (Lilford et al., 2012). Because humans can recognize and interpret subtle variations in form that technology cannot (Samper et al., 2020), the human judgment of an array of criteria better identifies informal settlements. In addition to satellite images, Google Earth historical images are the most viable method for the direct mapping of informal settlements (Samper et al., 2020) and monitoring the temporal expansion of informal settlements.

Researchers applied space syntax to distinguish settlements based on properties of sustainable urban form, investigating aspects of integration, traffic movement patterns, detecting the busiest route, connectivity, as well as planning and policy interventions. The location, size, and street networks are determinants for off-site integration of Erbil's (Iraq's) informal settlement with the mainstream of urban development (Mawlan et al., 2011). The integration analysis in Jakarta, Indonesia, revealed that informal settlement streets have high potential for pedestrians through movement and vehicles (Hidayati et al., 2021). The integration of space syntax and qualitative factors (i.e., morphology and social activity) revealed a low integration value in a new squatter settlement quarter with substandard buildings and a low level of living standard (Cutini et al., 2020). In Latin and Central America, informal settlements with smaller parcels, denser, and more branched street networks perform better in the centrality score (Sandoval et al., 2020). In Sarajevo city, unplanned settlements

in higher-elevation areas exhibited isolation and disintegration, as evidenced by the low integration value of space syntax (Tufek-Memisevic, 2024). In Iraq, Erbil, the gated Italian village with cul-de-sac streets, has the lowest connectivity and integration value in comparison to non-gated neighborhoods (Khoshnaw, 2023).
Moreover, by overlaying informal settlement areas with the spatially distributed population, one can estimate the population living in informal and formal settlement areas. Thus, Worldpop developed population-gridded data in geotiff format, making a population estimate at a 100-m grid cell using a random forest algorithm for 2010 and 2020. The units are the number of people per grid cell (Bondarenko et al., 2020; WorldPop, 2013). WorldPop estimated the population for all land areas on the condition that a small percentage of people were predicted to live in deserts, forests, and unsettled areas (Loyd et al., 2019). However, scholars still argued that the griddled population data is constrained by the uneven population distribution (Thomson et al., 2021).

2.2. Informal settlement problems, challenges and sustainable urban form

The main challenges facing informal settlements were lack of employment and poor remuneration, poverty, flooding, expensive water and electric bills, limited sewerage disposal systems, unfair relocations, poor sanitation, unemployment, and a high crime rate (Maemeko et al., 2021; Zulch et al., 2023). Deprivations or disadvantages associated with informal settlements include inadequate waste management, pollution, overcrowding, and a lack of essential amenities, all of which put public health and the environment in peril (Msimang, 2017). Thus, area-based policies and urban regeneration interventions are rational in Addis Ababa to address the multiple deprivations, social exclusion, and spatial inequality (Gizachew et al., 2023). The globally derived one-size-fits-all model must be resisted for sustainable urbanization to bridge the increasing gap between rich and poor (Jones, 2017). Strategies shall be contextualized, considering the positive attributes of informal settlement areas. Informal settlements reflect the qualities of smart nature: they are compact, use less energy, and practice reuse and recycling (Ndlangamandla & Combrinck, 2020). Informal settlement lacks resources and outward aesthetic appeal relative to formal settlement, despite depicting smart city models and attributes. According to Geyer (2023), informal settlement is organic smart growth characterized by sustainable mixed-uses, ethnic diversity, affordable housing, local job creation, strong social cohesion, and compact building design. Carrilho & Trindade (2022) argued that the peri-urban informal settlement in developing regions is neither necessarily disorganized, chaotic, unpredictable, or impermanent (Carrilho & Trindade, 2022). Research in Algerian mass housing indicated that social interaction increases in the least connected, adjoining spaces to the building, and most closed spaces (Zerouati & Bellal, 2019). The above morphology is similar to the high social interaction areas of the inner-city slum neighborhoods of Addis Ababa (Berhanu et al., 2022; Karadimitriou et al., 2021).
The global south cities are vastly different in their smart city planning efforts from the models and stereotypes of the global north; therefore, there is a need to craft a southern theoretical framework for smart cities (Alizadeh & Prasad, 2024). In Tanzania, for instance, the constraints for the realization of SDG in cities were single-layer-dominated buildings, poor accessibility, and an irregular road network. Thus, the interventions to meet SDG 11 are optimizing building density, land use efficiency, avoiding environmental risks, and implementing vertical growth (Zhang et al., 2020). The level of inclusion and resilience makes a smart city's design of physical and social infrastructure meaningful and sustainable. If they are not inclusive, we witness massive forced evictions (UN, 2017). The new urban agenda of leaving no one behind is realized through ensuring equal rights and opportunities, public participation, accommodating diversity, and integration in the urban space (URBANET, 2024). It is not enough to address inequality by focusing only on those "left behind" at the bottom; it is also pertinent to address the challenges of concentration of wealth, income, and decision-making power at the top (UN, 2018). In the global south, smart cities and urban revitalization interventions are not socially inclusive and do not consider the social and economic resilience of the existing poor communities. For instance, India's smart city implementation violated inclusiveness and resilience by relocating

existing residents to other places and removing the informal economy. The intervention also causes a loss of livelihood and settlement, not allowing effective citizen and informal sector participation (Carrilho & Trindade, 2022; Prasad et al., 2023). In Ethiopia and African countries, urban renewal and redevelopment interventions did not consider social inclusion and urban resilience. In Addis Ababa (Ethiopia), the development renewal and redevelopment interventions did not consider the inner-city slum norms of sharing public space for social interaction among citizens and transport infrastructure. Secondly, the interventions overlooked the dwellers economic resilience and their genuine request for on-site accommodation through negotiated planning (Borri & Asfaw, 2017; Charitonidou, 2022). In Benin, the smart city implementation destroyed 160 houses with a mere 72 hours' notice to transform Cotonou's old slum to the level of Kigali city (URBANET, 2024).

The residents of informal settlements are more vulnerable to the health effects of climate change due to poor housing, pre-existing health issues, and a lack of basic infrastructure, including health care (Greibe et al., 2020). The fragile ecosystem location, coupled with the poor socio-economic and environmental conditions of the informal settlement inhabitants, accentuates climate change-induced hazards (Jean-Baptiste et al., 2018). The high concentration of people, buildings, and infrastructure increases the exposure to floods, earthquakes, infectious diseases, fire, and crime (James, 2023). According to Ehebrecht (2014), there is a risk of flooding, cholera, malaria, respiratory illnesses, and fire hazards due to the dense concentration of informal settlers on steep slopes, at dump stations, and by rivers. The above evidence justifies the pertinence of incorporating climate change into smart city planning for informal settlements.

There is a need to incorporate the smart nature, knowledge, and experience of informal settlers who live in compact morphologies, network with the formal economy, and have small environmental footprints into smart city planning (Dodman, 2017). In light of the climatic change in the global North, European cities redesigned public and private spaces in dense urban areas by creating GHG-emission-free superblocks, rainwater collection basins, and increased permeable, green, and social spaces (Ingaramo & Negrello, 2024). The creation of social spaces through reclaiming urban voids and converting them into green spaces reduces GHG emissions in addition to fostering public participation in informal settlements (Bianconi et al., 2018). Urban areas are growing physically faster than their population, which goes against the principles of sustainability by decreasing the benefits of agglomeration, creating spatial inequality, and negatively affecting land use efficiency and the environment. The ratio of land consumption rate to population growth rate is linked to other SDG indicators, including lower per capita rates of resource usage and GHG emissions, reduced travel distance and cost expended, and proximity to factors of production (UN-Habitat, 2015a). Cities should be redesigned to provide and access green, open, and built space to vulnerable groups to meet SDG 11.7 and reduce climatic change. For instance, older people are more vulnerable to climatic change due to mobility difficulties, vulnerability to extreme heat, and flooding impacts on the spread of disease (Haq, 2021; Gargiulo et al., 2018; UNSD, 2023). Nonetheless, the deprivation study in Addis Ababa indicated that the inner-city slum has a low proportion of green per capita and a high proportion of older and female-headed households, not complying with SDG 11.7 (Gizachew et al., 2023).

2.3. Urban road networks Integration and Connectivity pattern in formal and informal settlement morphologies

The matrix for sustainable urban form includes compactness, sustainable transport, density, mixed land use, diversity, passive solar design, and greening (Jabareen, 2006). The space syntax method analyzes and interprets the spatial properties of sustainable cities (Yamu et al., 2021), despite an array of sustainable urban configuration matrices. The fundamentals of space syntax are based on natural movement theory, which influences economic activity, land use, and building density (Tufek-Memisevic, 2023). Space syntax analysis helps in comprehending the influence of the spatial structure of a street network on mobility, land value, and land use (Pappu, 2018). Space syntax develops insights into the mutually constructive relationship between

society and space, or the social effect of the built environment (Hillier & Hanson, 1984). In space syntax, the two concepts that measure urban morphology relationships are the integration and connectivity of each street or axial line (Badhan, 2019), as well as choice. Thus, the urban morphology or form patterns derived from integration, connectivity, and choice contribute to distinguishing informal from formal settlements. Connectivity is all the direct connections each street has to other streets in its immediate vicinity. A street with many connections to its side street has a high connectivity value, and vice versa for a street with fewer connections (Van Nes & Yamu, 2021). Good street connectivity encompasses many short links and intersections with limited or no cul-de-sacs, creating a more accessible and resilient system (VTPI, 2017). A higher connectivity value indicates a strong association with neighboring space, neighborhood cohesion, and sustainable communities (Khoshnaw, 2023; Lyu et al., 2023; Khoshnaw, 2023). Axial node count is the number of axial lines encountered on the route from a line as an origin to all others (Turner, 2004). Integration is a normalized measure of distance from any space of origin to all others in a system (Hillier & Hansen, 1984). The most preferred routes are those that involve fewer topological turns along the way rather than the shortest routes (Charalambous & Mavridou, 2012; Hillier et al., 2007). Areas with a high level of integration attract a higher flow of movement, pedestrians, mixed land use, and density (Pafka et al., 2020). Higher local integration reduces crime and burglary risk as crime vulnerability is high in cul-de-sac streets and dwellings not directly connected to streets (Lo'pez & Akkelies, 2007). High elevated areas or steep slopes in informal settlements result in isolation and disintegration (Tufek-Memisevic, 2023). Local integration R3 refers to the calculation of the degree of integration of three-step topological relationships or three-directional change. Global integration (Rn) means the calculation of the degree of integration of the global topological relationship (Yamu et al., 2021). Moreover, people who live in proximity to commercial concentrations are likely to walk more and drive less, with a higher integration score. Thus, commercial density and building density displayed a positive correlation with integration and walking (Berhie & Haq, 2017). Choice deals with how many times we need to pass a street if we travel the shortest path from street to street (Xia, 2013). A higher choice value means more movement (busy traffic) would be passing through that segment of the street (Berhie & Haq, 2017). The route choice studies inform policies for built environment interventions to foster walking and lower GHG emissions (Shatu et al., 2019). Node count measures the number of lines or segments encountered on the routes from the selected axial line to all others (Turner, 2004). The increase in node count indicates a richer choice of travel routes and alternatives to access recreation, amenities, and services (Poerbo et al., 2022).

3. Methodology

3.1. Background information for Addis Ababa and its Informal settlement areas

Addis Ababa, founded in 1987 by Emperor Menelik II and Empress Taitu, is the capital and largest city of Ethiopia. It is located between $8^0$55' and 9^0 05' North Latitude and 38^0 40' and $38^0$50' East Longitude. Altitude varies between 2100 and 3000 m (Yeshitela, 2012). It has a subtropical highland climate. Addis Ababa evolved around the imperial palace, the market, and the church (St. George) (Pankhurst, 1961). The Italian occupation of Ethiopia [1935–1941] marked the introduction of western planning practices (Tufa, 2008). Addis Ababa city administration has 10 sub-cities and 99 Weredas, which make up 52.743 hectares of land (Fig. 1). Addis Ababa has a dual identity: the federal capital and an autonomous administration commensurate with the state (UN-Habitat, 2017). The city population in Addis Ababa was 15, 000 in 1889 (UN-Habitat, 2017), 3,292,785 in 2010 (WorldPop, 2013), and 3,406,003 in 2020 (Bondarenko et al., 2020). It is home to 68% of urban jobs. The per capita income was USD 1,359 in 2015 (UN-Habitat, 2017). Addis Ababa is characterized by dwellers with mixed socio-economic backgrounds (Habitat for Humanity Great Britain, 2017). The city of Addis Ababa has an 80% literacy rate, higher than other parts of the country. 72.27% of Addis Ababa residents were without

access to adequate sanitation facilities (UN-Habitat, 2017). The city administration collected 45–50% of the city's solid waste (World Bank Group and Cities Alliance, 2015). 50–55% of the population of Addis Ababa had access to either unsafe water or bought water at a high cost from shops (UN-Habitat, 2017). In 2018, the Addis Ababa Road network was 5,915 kilometers' long (World Highways, 2018). The population density of Addis Ababa was 160 and 190 people per hectare in 2007 and 2016, respectively (AACPPO, 2017). Since 2012, the Addis Ababa city administration has focused on the redevelopment of the inner city for the accumulation of high-end developers (Weldeghebrael, 2022). In Addis Ababa, there are on average 1.2 m2 of green areas per resident, which is 8 times lower than the 9 m2 recommended by the WHO. In Addis Ababa, high-income sub-cities constitute more eco-systems thanks to the presence of garden and street trees (UN Habitat, 2017). In Addis Ababa, formal open space is less than 5%, while in line with the national green infrastructure standard, 30% of the land is for green and shared public uses (Nuriye & Lirebo, 2020).

Informal settlements in Addis Ababa accounted for 44% of the area and 66% of the population (World Bank Group, 2008). Addis Ababa informal settlements consist of inner-city slums, squatter/peri-urban settlements, and regularized informal settlement areas dominated by informal buildings. The inner-city slum consists of old, dilapidated, and a high proportion of rental houses interspersed with their own private tenure and areas subject to redevelopment (Berhanu et al., 2022; Elias, 2008; Hidayati, 2021; Weldeghebrael, 2022). The inner-city consists of 11% of the Addis Ababa area and 40% of the population, situated 4.5 kilometers from the inner-city Central Business District (Elias, 2008; Weldeghebrael, 2022). The inner city consists of the sub-cities of Lideta, Kirkos, Addis Ketema, Arada, and some parts of Kolfekeranyo, Gulele, and Yeka (Elias, 2008). Kebele (i.e., the lowest administrative tier) rental houses constituted 70% of the inner-city slum houses (Elias, 2008). The average monthly rent for Kebele rental houses in the Addis Ketema sub-city case study area was very low and affordable [16.3 Ethiopian birr]. The inner-city dwellers of Addis Ketema sub-city depend on renting beds in the houses and opening small businesses near their dwellings (Berhanu et al., 2022). Studies indicated that 90.3% of the inner-city slums and 76.6% of the peri-urban informal settlements were involved in CBO (community-based organizations) (Berhanu et al., 2022). People who live in unplanned settlements have strong social ties and cohesion. People living in slums have limited access to green space (Karadimitriou et al., 2021). The average house hold size and over crowdedness index in the inner-city slum of Addis Ketema sub-city were '6' and 4.01, respectively (Berhanu et al., 2022). The slum houses in Addis Ababa city are compact, and overcrowded, with 35% of houses only having one room (Habitat for Humanity Great Britain, 2024).

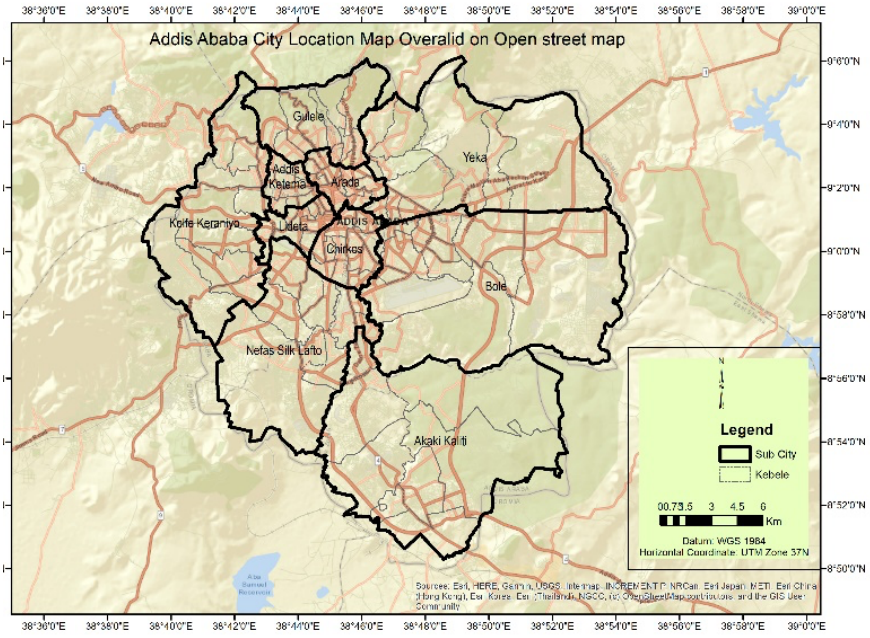

Fig.1 Addis Ababa Location Map

In Addis Ababa, land acquisition through squatting on public land in the outskirts began in the 1980s (Kassahun, 2010) and has increased since 1994 (Minwuyelet, 2005). The squatting and informal subdivision of agricultural land is currently the norm for Addis Ababa's peri-urban informal settlements (Erena et al., 2017; Kassahun, 2010; Minwuyelet, 2005; Tiruneh, 2013;). The peri-urban informal settlements mainly consist of rural-urban migrants (Berhanu et al., 2022; Daniel, 2006; Erena et al., 2017; Minwuyelet, 2005). The squatting or informal subdivision of agricultural land is currently the norm for Addis Ababa's informal fringe settlements (Erena et al., 2017; Kassahun, 2010; Minwuyelet, 2005; Tiruneh, 2013).

The Addis Ababa city government regularized informal settlements in 1996 (1988 E.C.), 2001/02 (1994 E.C.), and 2004/05 (1997 E.C.), based on images and aerial photographs (Hailu, 2016; Erena et al., 2017). The mixed urban fabric consists of regularized informal settlements and formal settlements that are in the process of changing to informal settlement fabrics (Dovey et al., 2020). The regularized informal settlements outside the inner-city slums formed a mix of standard and substandard buildings, marking social gentrification due to the transaction of land right after the regularization of informal settlements. Despite previous time-line-based regularization, squatters and illegal settlements have persisted in the peri-urban area and in some pockets of Addis Ababa's inner-city slum (Berhanu et al., 2022). Hamza (2023) also argued for an increase in suburban informal settlement growth in Ethiopian urban centers despite consistent demolition.

3.2. Methodological approaches and procedures

Overall methodological approaches and procedures

First, the slum ontology concept at settlement levels, enriched with theoretical discourses, empirical findings, and observations, was the basis for developing a criteria table to delineate the settlements. Second, the formal and informal settlements were delineated from 2010 aerial photographs and 2022 Google images. Third, 113 ground verification points verified the delineated formal and informal settlement typologies. Fourth, the completion of the final formal and informal settlement typology delineation. Fifth, the global gridded population estimate, at a 100-meter interval, was downloaded for 2010 (WorldPop, 2013) and 2020 (Bondarenko et al., 2020).

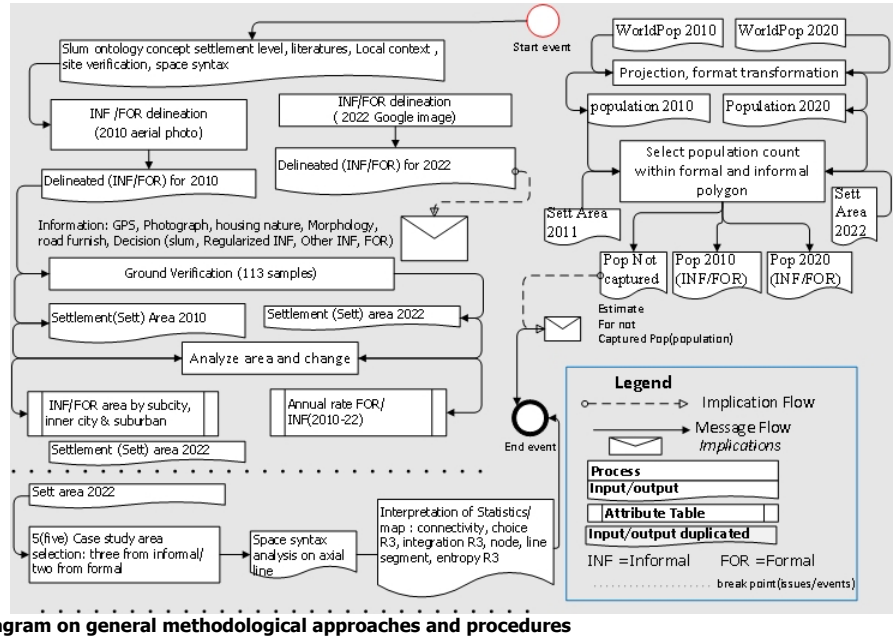

Fig.2 Flow diagram on general methodological approaches and procedures

Sixth, based on formal and informal settlement delineations for 2010 and 2022, the population and density for formal and informal settlements were estimated for 2010 and 2020. Sixth, based on the delineated formal and informal settlement areas, five case study areas were purposefully selected for analyzing urban form based

on road network configuration. Seventh, out of the five case study areas, three were from the three informal settlement typologies—inner, intermediate, and peripheral. Finally, two formal settlement case study areas were selected, one highly consolidated and the other medium-consolidated (see Fig.2).

Informal and formal settlement area delineation at settlement level for Addis Ababa city jurisdiction

The November 2010 aerial photograph of Addis Ababa and the 2022 Google Earth image were the backdrops to delineate informal and formal settlements. Furthermore, the study verified the 113 sampled points on the condition that the settlements existed both in 2010 and 2022 (Tab. 1 and Fig. 3). The ground-verification points were filled in a format, tagged with WGS x and y coordinates, with the relative locations of the points, settlement descriptions, photos, and road furnish materials.

Sub-city	Sample points	Formal	Informal	Sub-city	Sample points	Formal	Informal
Addis ketema	9	2	7	Kolfe Keranyo	10	4	6
Akaki Kaliti	10	3	7	Lideta	11	2	9
Arada	11	0	11	Nifas Silk	11	6	5
Bole	13	5	8	Yeka	13	4	9
Chirkos	15	4	11	Total	113	32	81
Gulele	10	2	8				

Tab.1 Field verification frequency for formal and informal settlements of Addis Ababa by sub-city

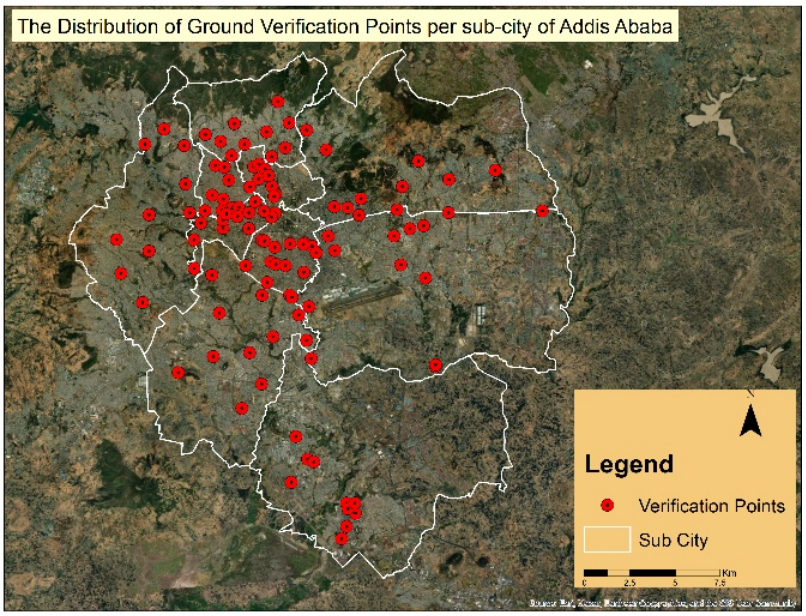

Fig.3 The distribution of Informal and formal settlement ground verification points per sub-cities of Addis Ababa

In Addis Ababa, informal settlements lie in the inner city, intermediate/suburban areas, and peri-urban areas. The analysis of informal settlement definitions and slum ontological concepts is crucial for identifying informal settlement areas based on morphological properties. Thus, in this study, a "settlement area" is a residential or mixed-use residential area with more or less similar morphological characteristics. See Tab. 2 for a review of the level, indicators, interpretation elements, and sources for the interpretation of formal, informal, inner-city slums and regularized informal settlements. The settlement area is either an "informal" or "formal" settlement based on the dominant morphological characteristics. All the interpretation elements of Tab. 2, except the space syntax ones, are used for the manual delineation of informal settlements. The visual

interpretation elements are shape, color, size, orientation, height, texture, width, location, proportion, and heterogeneity.

Here, the authors illustrated the settlement typologies using satellite and aerial photographs (from Fig. 4 to 7). Fig. 4 describes the inner-city slum. The dominant roof color is brown, interspersed with a bluish-white color, high roof density, no setback from property lines, small building size, dead end streets, and absent green or open space (see Fig. 4). Fig. 5 illustrates the pattern of peri-urban informal settlements. The color of the roof ranges from white to bluish-white, reflecting a varied building orientation. The built-up/roof density varies from sporadic based on a 2009 Quick bird satellite image (on the left) to consolidated based on an aerial photograph end of 2010 (on the right). At its inception, a small building was surrounded by an irregular and large fenced plot, surrounded by unpaved and irregular roads. It is lying on previous farmland or at physically hazardous sites—near the sides of hills or river valleys. It is located in a peri-urban area in parts of Addis Ababa and extends to Oromiya National Regional State (see Fig.5). Fig.6 indicates an intermediate informal settlement. The dominant colors are variable. It has a mix of substandard and standard buildings with medium roof density, haphazard vegetation, and open spaces. It has variable building sizes and orientations. The road depicts an irregular pattern despite being paved and furnished. The substandard houses have gradually improved to standard houses through the transactions of land right after regularization and the resultant social gentrification (see Fig.6). Fig.7 describes well-developed formal settlements. It has an inorganic layout consisting of grid-patterned roads and similarly shaped buildings. It consists mostly of buildings with different colors, while some roofs in the neighborhood depict similar colors. It has planned communal green spaces (see Fig.7).

Fig.4 Inner-city slum areas of Addis Ababa based on 2009 quick bird image

Fig.5 Peri-urban informal/squatter settlements of Addis Ababa in Akaki Kaliti using quick bird image of 2009 on the left and aerial photograph of 2011 on the right

Fig.6 Regularized informal settlement areas based on aerial photograph 2011

Fig.7 Formal settlement areas of Addis Ababa based on aerial photograph 2011

Addis Ababa case study areas spatial configuration analysis for informal and formal settlements

The authors screened case study areas for spatial configuration analysis, considering the already demarcated dichotomies of the settlement (i.e., formal or informal) based on slum ontology. Furthermore, the three typologies (inner, intermediate, and periphery) of the informal settlements were the basis for screening three case study areas. From the informal settlements, the three selected case study areas were from the inner-city slum (Addis Ketema and Arada sub-city areas), intermediate (Chirkos sub-city areas), and peri-urban (Kolfe Keranyo subcity on the fringe of the city). From the formal settlements, the first selected case study area was from the consolidated settlement located in the eastern part (located in Bole and Yeka sub-cities). From the formal settlements, the second selected case study was the south-western part of the Nifas silk sub-city area. The size of the open space is relatively ample for the Nifas Silk sub-city formal settlement case study area in comparison to the first selected formal settlement case study area (Fig. 8).

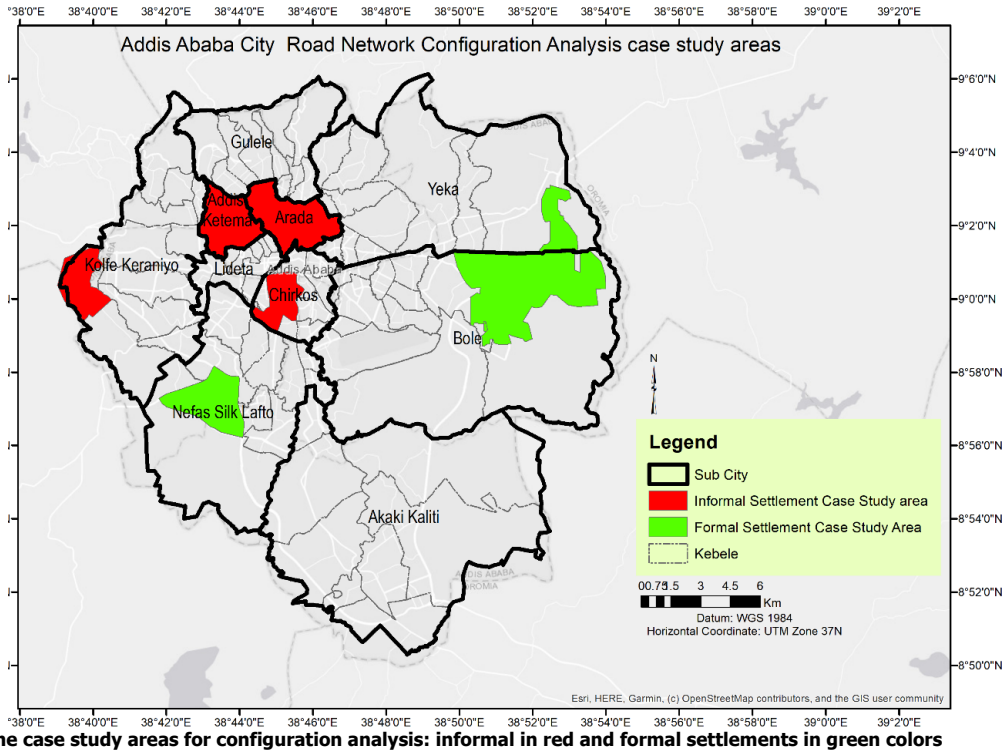

Fig.8 The case study areas for configuration analysis: informal in red and formal settlements in green colors

Sustainable urban form was evaluated by interpreting space syntax analysis results and maps for the five case study areas. The scope is to measure integration and choice at a local scale (R3). The study also measures, for each case study area, all the direct connections each street has to other streets in its immediate vicinity. The other ancillary assessments include node count and line length. The overall methodological approach for informal and formal settlement area identification, mapping, space syntax analysis and estimation of the population living in the informal and formal settlements is illustrated in Fig. 8.

Indicators	Interpretation elements	Settlement characteristics
A) The Concept of slum ontology at settlement levels		
Shape	Irregularity	The informal settlements' have an irregular shape and organic layout, while the overwhelming characteristics are inorganic layouts and standard buildings for formal settlements. The regularized informal settlements have a mix of organic and inorganic settlement layouts, despite the overriding characteristics of organic layouts and substandard buildings. The overall irregular road and buildings formed organic settlement layouts for informal settlements, while regular roads and buildings formed inorganic layouts for formal settlements.
Density	Built-up Density	The inner-city slum is characterized by dense and smaller buildings crammed together in space, with insufficient space or a standard property limit between houses. Smaller built-up proportions out of the parcel area characterized peri-urban informal settlements. For instance, in 2018, according to the Kolfe Keranyo peri-urban informal settlement area survey, the median built-up proportion per plot was 21.4%. The formal settlements have regular space between buildings. The regularized informal settlements have a mix of regular and irregular spaces between the buildings.
0rientation	Pattern	Informal settlements have haphazard building orientations, while formal settlements have more or less similar building orientation patterns.
Size	Area	Small building sizes dominate the inner-city slum and peri-urban informal settlements, while the formal settlements have standard medium- to large building sizes. The regularized informal settlements have a mix of smaller, medium, and large building sizes.
Width	Irregularity	The road width is irregular, mixed with a regular shape, in regularized informal settlements. The road width is mainly irregular local roads and dead-end streets, interspersed with regular collector roads for a portion of the inner-city slum areas. The road width is irregular and dissected by natural drainage channels for peri-urban informal settlements. The road width is regular for formal settlements.
Location	Location	The general agreed-upon areas of informal settlements are the inner city, the peri-urban, and parts of the intermediate. The formal and informal settlements are located side by side in the intermediate areas. The likelihood of informal settlement increases on physically fragile and undeveloped land, such as the sides of river valleys, land slide-prone areas, waste dumps, and hilly areas reserved for afforestation.
Regularization	Organic/inorganic lay-out	The intermediate and suburban informal settlements are partly regularized, but for the inner-city slum, the regularization footprint is restricted to collector roads, furnished with surfaces of block stone, cobblestone, and asphalt. There are no remnants of regularization in peri-urban informal settlements. The regularized informal settlements depict a landmark of social gentrification and high- to low-income mixed social groups as the result of the transfer of property and land rights from poor to affluent groups.
Green space	Pattern/ Size/ shape	Formal settlements have planned common areas—greenery and open spaces. High-income formal areas have more ecosystems. There is a critical lack of planned green spaces and high demand for eco-system services in the dense inner-city slum areas, except for a few sporadic trees in the midst of settlements. The peri-urban informal settlements have sporadic and irregularly laid natural green space.
B) Urban form based on space syntax analysis		
Connectivity	statistics	Formal settlements have good street connectivity with limited or no cul-de-sacs. The informal settlements have less connectivity, with a reasonable proportion of dead-end streets, especially prominent in informal settlements less exposed to regularization.
Integration	statistics	Formal settlements have a high level of integration [based on space syntax analysis], characterized by a higher flow of pedestrian and vehicle movement, mixed land use, and density. However, informal settlements have a low level of integration, which in turn leads to a high level of segregation of land use and less flow of movement. The peri-urban informal settlements on higher slopes and valley sides have low integration value.
Choice	Statistics	In general trends, streets near commercial, cultural centres, furnished roads, and formal settlements are the busiest ones for pedestrian movement. The peri-urban informal settlement streets are not busy due to the fact that the settlement lies on a higher slope, on an unpaved and irregular road, and there are virtually no drainage facilities.

Author-based assumption sources: Sliuzas & Kuffer, 2008; Kohli et al, 2012; Wurm et al., 2019; VTPI, 2017; UN-Habitat, 2017; Berhie & Haq, 2017; Shatu et al., 2019; Kuffer et al., 2020; Arif et al., 2022; Pafka et al., 2020; Tufek-Memisevic, 2023.

Analysis based assumption sources: own visual image interpretation of Addis Ababa, observation, ground verification, and the 2018 survey on informal settlements of Addis Ketema and Peri-urban Kolfe Keranyo (Berhanu et al., 2022).

Tab.2 Settlement identification assumptions for Addis Ababa city based on the concept of slum ontology at settlement level and space syntax

4. Results

4.1. Informal and formal area location and characteristics: based on the slum ontology concept at settlement level

Characterizing deprived and less deprived areas relies on the ontological framework: the intrinsic spatial characteristics and their interaction. The prior observation and ground verification validated the morphological characteristics and indicators of informal settlements. The ontological properties of irregular road networks, tiny building sizes, and haphazard building orientations are the predominant characteristics of deprived residential areas (informal settlements). The typologies of informal settlements are slums, regularized informal settlements, and peri-urban informal settlements. The main rationale for informal settlement typology is due to settlement evolution, tenure, planning interventions, morphological characteristics, location, and land use heterogeneity. The inner-city slum depicted aged buildings, dilapidated and dense houses, a lack of open or green space, and exposure to urban revitalization interventions. Hence, the inner-city slum features include small buildings crammed together in space, as well as a lack of local roads and right-of-way access for most residents interspersed with planned collector and arterial roads. A portion of the inner-city slum population also lives along a polluted river filled with excreta and waste, which emits an offensive odor.

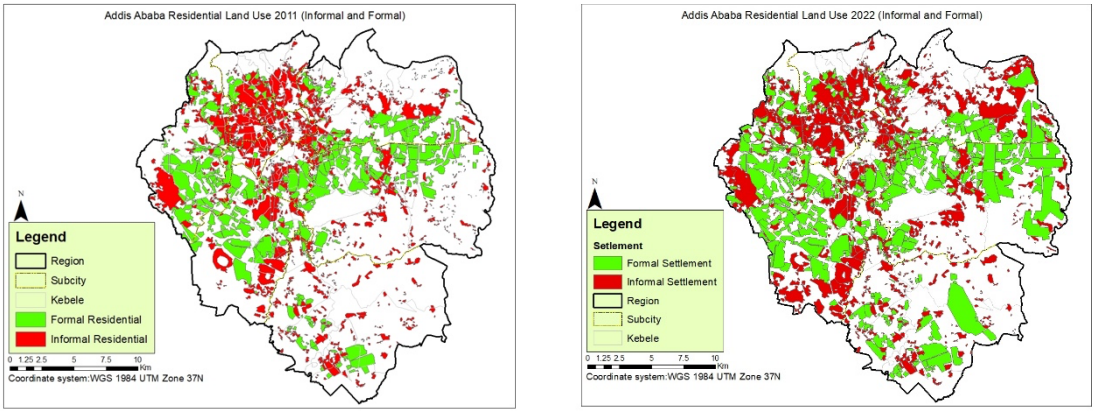

Fig.9 formal and informal settlement areas for 2010 aerial photograph(left) and 2022 google image (right)

Inner-city slum houses are either residential or mixed residential-use activities, while their function is overwhelmingly residential for peri-urban informal settlements. The informal settlement is a continuous process, as illegal additions ("kitiya") to the existing buildings are the most common practice in the inner-city slum areas. The earlier peri-urban informal settlements were consolidated with a new building at this stage, comparing images from earlier and later stages. Regularized informal settlements have a mix of regular and dominant irregular roads interspersed with a mix of standard and substandard buildings, displaying the landmarks of social gentrification. The peri-urban informal settlement has shown a pattern of spontaneously mushroomed buildings, irregular building and road layouts, the absence of drainage, and unplanned open and green space. The peri-urban informal settlement has shown a pattern of a small building with a relatively large undeveloped plot, while a parcel encompasses housing with different forms of tenure rights (kebele and permit rights) in the inner-city slum areas. Formal settlements have regular shapes and orientations of buildings and roads, as well as planned common areas—greenery and open spaces (Fig. 9).

4.2. Informal and formal area characteristics based on space syntax

Based on the displayed maps in Figg.s 10, 11, and 12, the connectivity values of the space syntax have three classes: 0-2, 2-3, and > 3. The inner-city slum showed clusters of well-connected and accessible roads crossing the market area around the north and south-central parts. Yet, the larger portion of the inner-city slum case

study area has irregular roads and cul-de-sac streets (Figure 10 on the left). The Kolfe Keranyo peri-urban area indicated reasonable proportions of isolated and segregated areas due to higher slopes (Fig.10 on the right). The map illustrated that the intermediate informal settlement has higher connectivity for roads crossing the settlement to the major roads of the city, while the residential neighborhood has cul-de-sac streets with lower connectivity values (Fig.11 left).

	Formal Settlements		**Informal Settlements**		
	Sub-cities for case study		Sub-cities for case study		
	(Yeka & Bole)	Nifas Silk	Addis Ketema & Arada (Inner-city)	Kolfe Keranyo (Peri-urban)	Chirkos & Nifassilk (Intermediate)
Connectivity	3.34	3.27	2.74	2.63	2.76
Choice R3	22.74	22.15	14.3	12.64	14.65
Integration HH R3	1.43	1.41	1.17	1.14	1.20
Line Length	39.89	39.70	22.15	25.40	27.1
Node Count R3	18.62	18.11	12.84	11.7	13.05

Tab.3 Formal and Informal Settlements of Addis Ababa space syntax result based on axial line

The well-connected, accessible, and resilient system-based streets dominated the major portions of the formal settlement case study areas: Bole & Yeka and Nifassilk sub-cities (Fig. 11 right and Fig. 12). Yet, Yeka and Bole formal settlements (Fig. 12) have overwhelmingly red-colored streets, which illustrates the dominance of high connectivity values (>3) relative to Nifas Silk sub-city formal settlements (Fig. 11 on the right) and other case study areas.

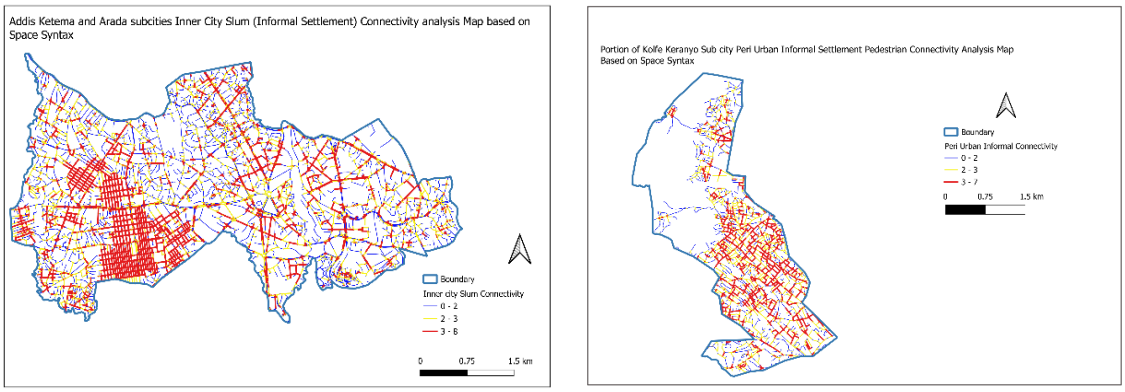

Fig.10 Connectivity for Addis Ketema and Arada sub-cities Inner-city slum case study area (left) and Kolfe Keranyo sub-city Peri-urban Informal Settlement case study area (right)

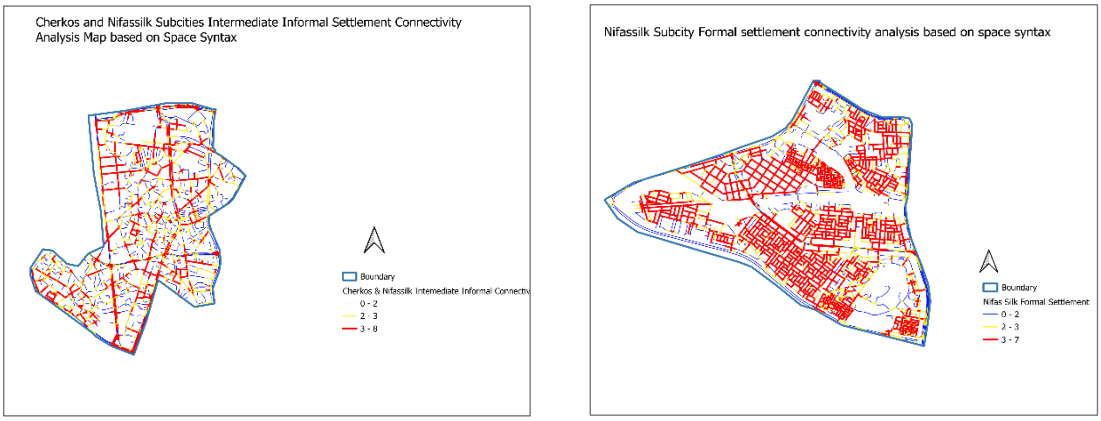

Fig.11 Connectivity for Cherkos and Nifassilk sub-cities Intermediate Informal settlement case study area (left) and Nifas silk sub-city Formal settlement case study area (right)

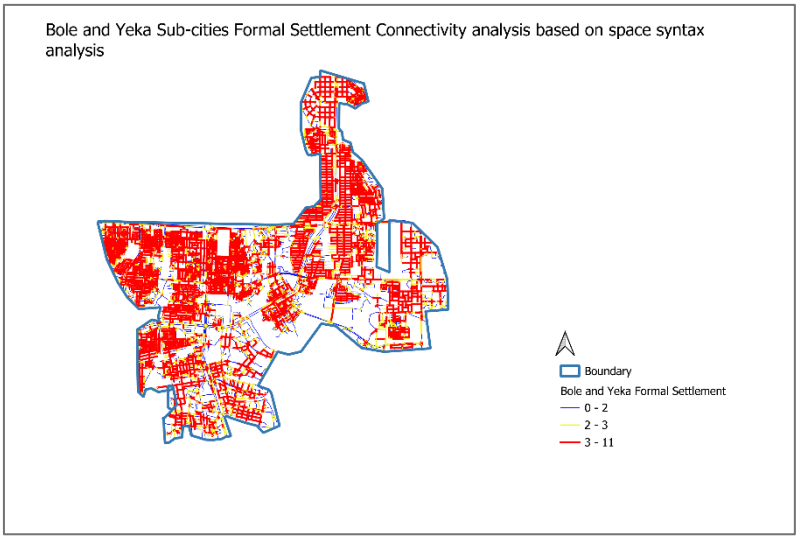

Fig. 12 Connectivity for Bole and Yeka sub-cities Formal settlement case study area

The formal settlement areas of Bole and Yeka sub-cities had the highest value in terms of overall space syntax score, followed by the formal settlement area of Nifassilk sub-city. The overall score of space syntax for the two formal settlement case study areas is higher than the three typologies of informal settlement case study areas (Tab. 3). For instance, the Bole and Yeka sub-cities formal settlement case study area has scored the highest in terms of connectivity (3.34), integration HH R3 (1.43), choice R3 (22.74), line length (39.89), and node count R3 (18.62). On the contrary, Kolfe Keranyo peri-urban has scored the lowest in the overall space syntax result (see Tab. 3). In sum, the space syntax score for formal settlements is higher than that for informal settlements. In informal settlements, the space syntax results are lower as one goes from the intermediate regularized informal settlements via inner-city slums to the peri-urban informal settlements. The space syntax result for peri-urban informal settlement explains that the area is isolated, segregated, inaccessible, non-resilient, and less feasible for pedestrian movement. Thus, the Tab. 3 result depicts the sustainability of urban form for formal settlements with characteristics of accessibility, resilience, pedestrian friendliness, social interaction, mixed uses, and proximity to amenities and public spaces. The regularized informal settlements override inner-city slums and peri-urban informal settlements in terms of accessibility, neighborhood cohesion, mixed use, proximity to amenities and services, traffic movement facilities and attractions, and route business.

4.3. Informal /formal settlement area change analysis for 2010 and 2022

The concept of slum ontology, augmented with ground verification, was the basis for the delineation of formal and informal settlements in Addis Ababa. Informal settlement areas constituted 49.6% and 45.6% of residential land use in 2010 and 2022, respectively. The above result implies that informal settlements showed a 4% decline in the intervening periods. The annual growth rates of Addis Ababa's informal and formal settlements between 2010 and 2022 were 2.68% and 4.56 percent, respectively. On the contrary, informal settlement areas in the four slum-dominated central sub-cities decreased by -0.106% per year between 2010 and 2022, owing to the effect of urban renewal on the area. Nonetheless, for the four inner-city slum-dominated sub-cities, the formal settlement area has shown a sluggish increment of 0.793% per year in the intervening period (Tab. 4).

Yet, the informal settlement annual growth rate for 2022 is declining compared to the 2010 informal areas in the sub-cities of Addis Ketema, Arada, and Chirkos. For outside inner-city slum sub-cities, the informal and formal settlement areas have increased annually by 3.51% and 4.87%, respectively, from 2010 and 2022. From 2010 to 2022, the informal settlement area has shown a drastic annual growth increment, surpassing

formal settlement growth trends, for the sub-cities of Nifas Silk, Kolfe Keranyo, and Yeka. At sub-city levels, between 2010 and 2022, formal settlement has shown remarkable annual growth trends (17.35%) for Akaki Kaliti, followed by Arada (6.88%) and Bole (6.49%). (See Tab. 4 for detailed deprived and less deprived area and growth rate).

	2010 (Aerial photograph)				**2022 (Google image)**				**2022-10 change (Gross ha)**		**The annual rate of change**	
Subcity	FR (ha)	IN (ha)	RE (ha)	IN (%)	FR (ha)	IN (ha)	RE (ha)	IN (%)	FR (ha)	IN (ha)	FR (%)	IN (%)
Addis Ketema*	41	509	550	93	41	504	545	92	0	-5	0	-0.082
Lideta*	151	385	536	72	165	474	639	74	14	89	0.773	1.926
Arada*	23	533	556	96	42	483	525	92	19	-50	6.884	-0.782
Chirkos*	384	376	760	49	408	319	727	44	24	-57	0.521	-1.263
Akaki Kaliti	649	979	1,628	60	2,000	1,108	3,108	36	1,351	129	17.347	1.098
Bole	2,121	807	2,928	28	3,773	1,152	4,925	23	1,652	345	6.491	3.563
Gulele	217	856	1,073	80	229	864	1,093	79	12	8	0.461	0.078
Kolfe Keraniyo	1,593	1,079	2,672	40	1,984	1,488	3,472	43	391	409	2.045	3.159
Nefas Silk Lafto	1,658	1,130	2,788	41	2,119	1,919	4,038	48	461	789	2.317	5.819
Yeka	1,149	1,190	2,339	51	1,599	2,055	3,654	56	450	865	3.264	6.057
Total	7,986	7,844	15,830	61	12,360	10,366	22,726	59	4,374	2,522	4.564	2.679
Central subcitie*	599	1,803	2,402	77	656	1,780	2,436	76	57	-23	0.793	-0.106
Other Sub cities	7,387	6041	13,428	50	11,704	8,586	20,290	47	4,317	2,545	4.870	3.511

Source: based on own delineation of formal and informal settlements of Addis Ababa

Tab. 4 Informal (IN) and formal (FN)areas areal extent and change for Addis Ababa sub-cities for 2011(aerial photograph) and 2022(google image)

Nonetheless, the formal settlement area for the four slum-dominated sub-cities has shown a sluggish increment of 0.793% in the intervening period, adding 57 hectares between 2010 and 2022. For sub-cities located outside the inner city, the informal and formal settlement areas have increased by 3.51% and 4.87%, respectively. Formal settlement has shown remarkable annual growth trends for Akaki Kaliti sub-city (17.35%), followed by Arada sub-city (6.88%) and Bole sub-city (6.49%), which is due to a mix of condominium housing and real estate development, as well as private cooperative residential housing. Addis Ketema sub-city has shown only a 4-hectare decrement in informal settlement areas due to commercial building development since formal settlement areas have not shown change in the intervening periods (see figures 28 and 29 for formal and informal residential area maps for 2010 and 2022).

4.4. Formal and Informal settlement population estimate based on settlement area

The informal and formal settlement areas had an equivalent share in 2010—nearly 50 percent for both. In contrast, formal and informal settlement areas were 54 and 46 percent, respectively, in 2022. Selecting the 2010 gridded population data at a 100-meter interval, located in informal and formal settlement areas, 68% and 32% of people lived in formal and informal settlements, respectively. This result indicates that even if the area of formal and informal settlements were equivalent in 2010, more people lived in informal settlements in an overcrowded manner. Similarly, in 2020, the population living in informal settlements was 54%, greater

than the formal settlement population (46%). The above result indicated that even if the formal settlement area were larger, the proportion of the population living in smaller areas in informal settlements would still be higher (Tab.5 and Fig.13).

Informal and Formal Population estimate for 2020					
Informal Population	Formal Population	Not estimated	Population	Informal Population (adjusted	Formal Population (adjusted)
1258348	1,082,163	1,065,492	3,406,003	1,831,197	1,574,806
Informal and Formal Population estimate for 2010					
Informal Population	Formal Population	Not estimated	Population	Informal Population (adjusted	Formal Population (adjusted)
1303605	617,587	1,371,593	3,292,785	2,234,285	1,058,500

Tab.5 Formal and Informal population estimate based on griddled data for 2011 and 2020

Population density is computed for 2010 and 2020 based on gridded population points at 100-meter grid intervals located in formal and informal settlement polygons. In other words, the density and population estimate skip the gridded population points in non-residential-dominated areas, which are not delineated as formal and informal settlements. Thus, in 2010, Addis Ababa's jurisdiction had a population of 1,303,605 lying completely within an informal residential area polygon (7844 hectares) delineated in 2010. Thus, in 2010, the population density for informal settlements was 166 people per hectare.

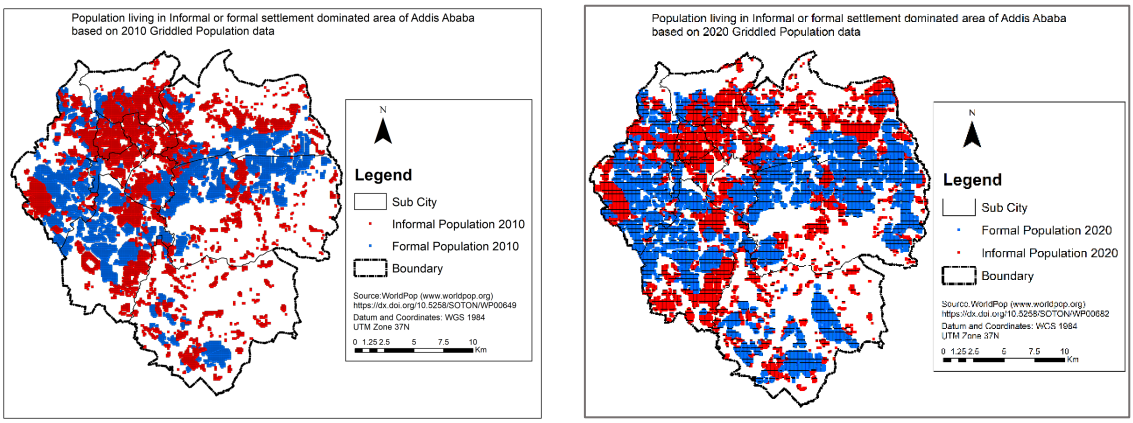

Fig.13 Population living in informal or formal settlement-dominated areas of Addis Ababa based on 2010 population-griddled data (on the left) and based on 2020 population-griddled data (on the right)

Considering the 2010 population in the delineated formal area (617,587 people) and the formal area (6041 hectares) for 2010, the population density for the formal settlement area was 102 people per hectare. Similarly, for 2020 gridded population points at a 100-meter grid interval, Addis Ababa's jurisdiction had a population of 1,258,348, lying completely within an informal residential area polygon (10,366 hectares) for 2022. Accordingly, the population density for informal settlements in 2020 will be 121 people per hectare. Finally, for 2020, Addis Ababa's jurisdiction had 1,082,163 inhabitants lying completely within a formal residential polygon for 2022 (12,360 hectares). Thus, for formal settlement, the population density for 2020 will be 88 people per hectare (Figure 9).

5. Discussion

The concept of settlement-level slum ontologies, supported by literature reviews and local context verifications, is a useful framework for delineating informal and formal settlement areas. At the settlement level, the core criterion for delineating informal from formal settlement areas was the shape of the settlement, buildings, roads, green and open spaces, and density of built-up. The morphologies of informal settlements are disaggregated into three categories, such as slums, regularized informal settlements, and peri-urban informal

settlements. Regardless of typologies, informal settlements generally depict the ontological properties of irregular road networks and organic layouts, small building sizes, and haphazard building orientation (Berhanu et al., 2022; Kuffer, 2017; Lemma et al., 2006; Sliuzas & Kuffer, 2008;). A slum's typical features include old, dilapidated dwellings; high building and population density; an irregular local road; high demand for ecosystem services; low income; and a lack of open space (Gizachew et al., 2023; Lemma et al., 2006; Tarekegn, 2000; UN-Habitat, 2015b; UN-Habitat, 2017). In addition, the slum's morphological properties include a lack of access to the right of way for some local residents, as well as the intermingling of irregular local roads with renovated arterial and collector roads. In Addis Ababa, informal and squatter settlements proliferate in areas not used for residential purposes, such as along the banks of the river, in agriculture, on steep slopes, around religious institutions, and in forests (African Development Bank Group & Municipal Development Fund, 2021; Azagew & Werku 2020; Bikis & Pandey 2022). The peri-urban informal settlement started in the late 1970s or early 1980s (Daniel, 2006; Erena et al., 2017), and it has increased since 1994 after regularization (Berhanu et al., 2022; Erena et al., 2017; Kassahun, 2010; Minwuyelet, 2005; Zewdie et al., 2021). Thus, farmers' informal transactions of agricultural land are a defining characteristic of peri-urban informal settlements (Berhanu et al., 2022; Erena et al., 2017; Kassahun, 2010). In the peri-urban informal settlements, the early genesis of the haphazardly located buildings is currently consolidated, conforming to informal settlement evolution theoretical frameworks (Sori, 2012). Regularized informal settlements in the intermediate areas have mixed characteristics, with organic layout dominance marking social gentrification. The morphological properties of formal settlements are inorganic settlement layout, a regular road layout, and similar space between buildings (Kuffer, 2017; Lemma et al., 2006; Sliuzas & Kuffer, 2008), as well as planned communal green and open spaces.

The movement theoretical framework enables us to identify and analyze sustainable urban form using space syntax (Jabareen, 2006; Tufek-Memisevic, 2023; Yamu et al., 2021) and test some indicators of slum ontology. The space syntax statistics and mapping of connectivity, integration, choice, line length, and node count can distinguish formal from informal settlements, as well as differentiate informal settlement typologies. The space syntax result revealed that the formal settlements performed higher in connectivity, integration, choice, node count, and axial line length. The spatial configuration result, coupled with other empirical findings, shows that formal settlements are more accessible to amenities, services, alternative routes, and public spaces than informal settlements. Hence, formal settlements scored higher in mixed uses, neighborhood cohesion, resilient systems, and sustainable communities (Khoshnaw, 2023, Lyu et al., 2023; Poerbo et al., 2022; Van Nes & Yamu, 2021; VTPI, 2017;). Hence, higher local integration for formal settlements implicates pedestrian-friendly movement, lower GHG emissions, adequate public space, lower crime risk, and building density (Lo'pez & Akkelies, 2007; Pafka et al., 2020; Shatu et al., 2019; UN-Habitat, 2017). Based on mapping of the road configurations, the inner-city slum showed well-connected, integrated, and accessible roads in and around the major market areas of Ethiopia in Addis Ketema sub-city, with reasonable proportions of cul-de-sac roads in residential neighborhoods. The above result conforms to the claim that people who live in proximity to commercial concentrations are likely to walk more and drive less (Berhie & Haq, 2017). The peri-urban informal settlements located on steep slopes are the most inaccessible and integrated settlements, characterized by less busy streets, pedestrian-unfriendly roads, isolated spaces, and segregated neighborhoods (Tufek-Memisevic, 2023). The older slum settlement depicted more land use heterogeneity than the more recent peri-urban informal settlement (Arif et al., 2022). Moreover, there is a relationship between low integration value, substandard building, and a low level of living standard (Cutini et al., 2020), as the inner-city slum and peri-urban squatter settlement case study areas depict low integration R3 value. The intermediate informal settlement performed better relative to other informal settlement typologies in connectivity, integration R3, choice R3, node count, and line length. The above result indicates regularization contributes to building accessible, planned, integrated, traffic-accommodating, and resilient systems in informal settlements.

Smart city interventions and strategies require the incorporation of local contexts and particularities rather than globally derived one-size-fits-all approaches (Jones, 2017; Ndlangamandla & Combrinck, 2020; Carrilho & Trindade, 2022). Addis Ababa informal settlements have positive attributes such as affordable housing, mixed socio-economic groups, strong social bondages, neighborhood cohesiveness, mixed land use (except the peri-urban), employment opportunities (near or inside the house in the inner-city), and integrated roads with the mainstream of urban development (Berhanu et al., 2022; Elias, 2008; Habitat for Humanity Great Britain, 2017; Hidayati, 2021; Karadimitriou et al., 2021; UN Habitat, 2017; Weldeghebrael, 2022). Thus, smart city implementations shall not dismantle the long-standing social bondage, neighborhood cohesion, and job opportunities of the existing dwellers and focus on the integration of settlement through optimum density rather than complete urban renewal. Hence, the smart city shall provide affordable housing for mixed income groups through on-site accommodation (social housing, land sharing, earmarking auctioned for subsidizing poor housing, and land reservation for the poor), bargain and negotiate with residents regarding livelihood capitals, and create open and green space and resilient infrastructure for smart city planning and implementation. Ethiopia shall envisage robust and legally binding planning implementation frameworks to address the new urban agenda of leaving no one behind, not only from equal rights, opportunities, and participation perspectives but also addressing the concentration of wealth and decision-making power at the top (UN, 2018; URBANET, 2024). Smart city interventions in Addis Ababa informal settlements, if implemented considering the synergy of global framework and local context, will contribute to reducing climatic change (Dodman, 2017; Ehebrecht, 2014; Greibe et al., 2020; James, 2023; Jean-Baptiste et al., 2018). The proportion of formal open and green space is very low in Addis Ababa (Nuriye & Lirebo, 2020; UN_habitat, 2017); thus, the reclaiming of urban voids and converting them to green and formal public spaces play a crucial role in complying with global standards, fostering a sense of community, and reducing GHG emissions (Bianconi et al., 2018).

Informal settlements have dropped slightly, by 4%, between 2010 and 2022. Though sluggish, the preceding declining trends corresponded with global trends of informal settlement decline (UN-Habitat & Global Urban Observatory, 2019). The urban renewal interventions (Weldeghebrael, 2022; Zewdie et al., 2021) are the reason for a minor drop in the informal settlements' growth rate in the pure inner-city slum and a slight increase for formal settlements. Yet, outside the inner-city slum, the formal and informal settlements have shown reasonable growth. The justifications for the formal settlement increase in suburban areas are the construction of large-scale condominium houses, real estate housing, and the relocation of dwellers from the city center (Weldeghebrael, 2022; Zewdie et al., 2021). The trend in Addis Ababa indicates that formal settlement growth corresponds with urbanization growth (World Bank Group & Cities Alliance, 2015), and in general, the average annual growth rate for formal settlement is higher than the informal settlement annual growth rate. In sum, formal settlement growth is the current dominant urbanization trend in Addis Ababa. Nonetheless, the informal settlement annual growth rate has surpassed formal settlement growth trends for 2010–22 for the suburban sub-cities, such as Nifas Silk, Kolfe Keranyo, and Yeka. The increasing informal settlement growth in the above-mentioned sub-cities conforms to Hamza's (2023) argument regarding suburban informal settlement growth in Ethiopian urban centers despite consistent demolition. In 2010, even though the area per hectare is almost similar for formal and informal settlements, the population living in informal settlements was 68 percent, and the informal settlement population density was 166 people per hectare. In comparison to the 44% informal settlement area assessed by the World Bank Group (2008), Addis Ababa's area for informal settlement in 2010 (50%) has exhibited a 6% increase. According to the World Bank Group (2008), 66% of people reside in informal settlements. However, the estimate of the population in this study based on the informal area was 68% in 2010, which implied a 2% logical increase in informal settlements in 2010 as compared with the World Bank Group (2008). The population density result (166 people per hectare) for 2010 is slightly higher than the average population density (160 people per hectare) estimates

for 2007 in Addis Ababa (AACPPO, 2017). The above-triangulated result revealed the overcrowded nature of informal settlements, especially inner-city slums, in the past decades (Elias, 2008; UN-Habitat, 2017; Habitat for Humanity Great Britain, 2017). Yet, in 2020, the proportion of the population living in informal settlements declined to 54 percent. Hence, in 2020, the population density declined to 121 people per hectare, respectively, which is lower than the average Addis Ababa city density estimate (190 people per hectare) for 2016 by AACPPO (2017). The above result further indicates that the once-important role of high population density as a driving force of informal settlement (deprived areas) in the past decade is declining in recent trends with the suburbanization of formal settlement growth. On the other hand, the population size has increased in formal settlements by 14% between 2010 and 2020, despite a declining population density figure. The result indicated how large-scale condominium housing development, other low-cost housing, and real estate development are driving the formal settlement growth in Addis Ababa (Weldeghebrael, 2022; Zewdie et al., 2021). The general picture showed that the growth rate of the population living in formal settlements has increased relative to deprived areas in recent years. The overall population density decline indicates a lower rate of land consumption per population, which implies inefficiency in GHG emission reduction, inefficient land use, inefficiency in reducing friction of distance, higher infrastructure costs, and higher inequality (UN-Habitat, 2015a).

6. Conclusion

The study has performed demarcation, interpretation, and analysis of deprived and less deprived areas from satellite and Google images, considering the conceptual framework of slum ontology and prior survey experience of informal settlement areas. The observations and ground verification further refined and corrected the delineated settlement areas. The study also developed a framework of indicators and interpretation elements for identifying the typologies of settlements, considering literature, observation, and visual interpretations. The mapping of deprivation areas revealed the enduring physical expression of inequality and marginalized places in terms of housing, infrastructure, and services. The spatial configuration analysis not only differentiated the formal and informal settlement dichotomies but also distinguished the typologies of informal settlements based on sustainable urban forms. The spatial configuration analysis of road networks, triangulated with theoretical discourses and empirical findings, allows for prioritizing urban forms of settlements based on smart city parameters. The parameters for differentiating settlements based on sustainable urban form include integration, infrastructure inequality, accessibility to services and amenities, resilient and redundant infrastructure, mixed land use and efficiency, traffic mobility patterns, neighborhood cohesion, the GHG emission effect, and sustainable communities. Thus, planners and policymakers need to tailor sustainable urban forms, optimum density, or smart cities contextualized to the typologies, particularities, and positive attributes of informal settlements rather than one-size-fits-all approaches for smart city implementation. The informal settlement area proportion and annual area growth trends have shown declining trends in the twelve-year period (2010–2022). From 2010 to 2022, formal settlements have shown increasing trends with the construction of grand condominium housing projects, real estate development, and the relocation of inner-city slum dwellers due to urban renewal. A decade ago, high population density was a particular feature of inner-city slum settlements, which relates to poverty, vulnerability, and a high demand for eco-system services. Nonetheless, currently, grand condominium housing projects and other formal housing modalities are becoming population concentration areas. Manual settlement delineation, relative to automatic detection, requires a lot more time, even though it gives the opportunity to detect small deviations in recognizing informal settlement areas. Deprivations and spatial configuration vary in formal and informal settlement areas; however, there are also significant differences in accordance with the typologies of informal settlements. Thus, further research is crucial to distinguish deprived areas, sustainable urban form, and spatial inequalities using a combination of manual, artificial intelligence, space syntax, and deep learning algorithms.

The current study reveals that small and medium-sized cities in the vicinity of Addis Ababa have demonstrated higher annual urbanization rates, which requires monitoring deprivations and spatial inequality trends in line with SDG 11. Moreover, further research is necessary on the driving forces behind the city's change in urban form and morphology, density, land value, centrality, mobility, and diversity of land uses. The analysis and interpretation of deprived areas and populations contributes to achieving SDG 11 and refines strategic upgrading areas for planning interventions. The lower land consumption rate, indicated by lower population density, implies that the adoption of sustainable urban forms is crucial to solving the multifaceted challenges of meeting SDGs, such as reducing GHG emissions, reducing friction of distance and infrastructure costs, and bridging spatial inequality gaps. Future in-depth research is also pertinent regarding the relationship between informal settlements and climate change, as well as the relationship between settlement typologies, sustainable communities, and social interaction. The city government shall reclaim urban voids to formal green and open space, with an emphasis on informal settlements, to reduce the climate change impact and create sustainable communities. In the global south, smart city planning and implementation strategies need to integrate the smart city nature of informal settlements with the global north's experiences of redesigning urban settlement structures in light of climate change. Further studies shall also be conducted on the relationship between vulnerable groups and climate change, comparing the typologies of settlements.

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Image Sources

Fig. 1: World Street map from the Environmental System Research Institute (ESRI), Garmin, and USGS overlaid on the Addis Ababa city administrative tier layers obtained from the Central Statistics Agency (CSA) of Ethiopia;

Fig.2: Authors' conceptualization;

Fig. 3: Authors' Garmin GPS coordinates taken for verification of formal and informal settlement areas overlaid on Google Earth images obtained from ESRI;

Figs. 4 and 5: Addis Ababa City Administration;

Figs. 6 and 7: Addis Ababa City Administration;

Fig. 8: Central Statistics Agency of Ethiopia.

Fig. 9: Addis Ababa City Administration and 2022 Google Earth images obtained from ESRI.

Figs. 10, 11, and 12: Authors' elaboration on the base of Open Street Map;

Figure 13: Authors' elaboration on the base of Bondarenko et al. (2010) database and WorldPop (2013) database.

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