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Decoding the Sprawl Paradigm: How New Building Typologies Shape Energy Consumption and Environmental Degradation in Erbil, Iraq

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ABSTRACT



The city of Erbil, Iraq, has expanded physically far faster than its population since 2003. This sprawl has accompanied an abrupt shift from traditional horizontal typologies — courtyard houses (mal-i hewshidar) and low-rise villas -toward high-rise apartments. A Geographic Information System (GIS) analysis of multi-temporal Land-Use/Land-Cover classifications (2004, 2014, 2024) quantifies the magnitude and rate of urban expansion through Shannon's entropy: the urban footprint grew from 31.2 km² (23.4%) in 2004 to 88.7 km² (67.3%) in 2024, a 184.6% increase, while landscape entropy declined from 0.855 to 0.766. A household-level Partial Least Squares Structural Equation Modeling (PLS-SEM) analysis of apartment residents formerly living in horizontal dwellings tests a five-construct model: Urban Sprawl Intensity (USI), High-Rise Adoption (HRA), Lifestyle Shift (LS), Energy Consumption (EC), and Environmental Degradation Awareness (EDA). Grounded in social-practice theory, the model indicates that perceived sprawl is strongly associated with high-rise adoption, which predicts lifestyle change, the strongest predictor of household energy use, while higher energy use is associated with greater environmental-degradation awareness. Framed within urban economics, the findings link macro-scale spatial growth to the household energy burden and the broader economic cost of sprawl, informing planning that reconciles metropolitan expansion with the realities of vertical living.

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Highlights:

- Erbil's urban footprint grew 184.6% during 2004–2024.
- Sprawl intensity predicts high-rise adoption ($\beta = 0.707$).
- Lifestyle shift best predicts energy use ($\beta = 0.384$).
- Serial USI → HRA → LS → EC mediation holds ($\beta = 0.183$).
- Energy use predicts environmental awareness ($\beta = 0.207$).

Contribution to the field statement:

This study couples two decades of Landsat-based sprawl measurement with a five-construct PLS-SEM household model, delivering one of the first quantitative sprawl-to-energy pathways for a MENA city and showing that social-practice theory is operationalisable in variance-based SEM.

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1. Introduction

1.1 Background and Problem Statement

Erbil, also known as Hawler, is one of the oldest cities that still exist today; in fact, the citadel of Erbil has been home to people for at least seven thousand years according to the UNESCO World Heritage Centre (2014). Erbil city, as well as the old part of the city, has changed almost beyond recognition since 2003, when regime change in Iraq occurred and Erbil expanded from an administrative centre to a large metropolitan area in which urban sprawl became the dominant growth pattern (Jawhar & Atakara, 2026). Erbil's city guidelines for development have changed dramatically since the inception of the master plan a few generations ago – even recently. As development continues, further modifications and extensions to those guidelines will follow. The city's growth is continuing to evolve, along with the addition of leapfrog (development from the city core to outer areas) and radial developments on the outskirts of the city (Abbas, 2019). The courtyard house (*mal-i hewshidar*), which has dominated in recent decades, has been supplanted at the building scale by two newer types – detached peripheral villas and, more recently, high-rise apartment buildings (Abbas, 2018, 2019; Jawhar, 2018). The creation of new districts in Erbil such as Empire World, Royal City, and English Village has brought a new design and lifestyle to a community whose previous domestic lifestyle was centred around the inward facing passively cooled home and now has also seen more changes in the heating and cooling process than before as well as greater changes in the environment from the small housing units to the larger districts. The present study quantifies both ends of this transformation, the macro-scale geospatial sprawl through Geographic Information System (GIS) analysis of multi-temporal Landsat imagery, and the micro-scale behavioural consequences through Partial Least Squares Structural Equation Modeling (PLS-SEM) analysis of household survey data, within a unified mixed-methods framework. Framed within urban economics, this transformation matters because it converts spatial growth into a recurring household energy burden and reshapes land and housing markets, raising the infrastructure and service costs of metropolitan expansion.

This double dislocation-macro-scale sprawl coupled with micro-scale typological inversion-is the empirical object of this study. Hot-arid and semi-arid cities across the Middle East and North Africa region are experiencing analogous transitions that now dominate the regional urbanisation literature. Tehran's four-stage demographic sequence from urbanisation through re-urbanisation (Talkhabi et al., 2022) illustrates how post-war rapid expansion couples with peripheral fragmentation; Dubai's aggressive built-up expansion against negligible green-area growth (Abulibdeh, 2021) shows how Gulf oil-economy urbanisation produces extreme typological concentration without attendant sustainability outcomes; and Dhaka's partial verification of the carbon benefits of transit-oriented development (TOD) for commuting trips (Ashik et al., 2022) illustrates the conditional nature of transit-oriented interventions in Global South megacities. Erbil's specificity lies elsewhere: it has undergone the sprawl-typology inversion without any functional mass-transit infrastructure, no urban rail, no bus rapid transit (BRT), only nascent fixed-route bus service. This infrastructural void means TOD discussion for Erbil is strictly forward-looking, and it shapes both the empirical scope of this study and the character of its policy recommendations, discussed in the upcoming Section 6. Three interlocking problems drive the research question. First, macro-scale sprawl has elongated commuting distances, entrenched car dependency, and consumed peri-urban agriculture, a process this study quantifies through GIS-based Land-Use/Land-Cover (LULC) analysis. Second, the shift to vertical living has imposed energy-intensive cooling regimes on a population whose practices were calibrated to horizontal typologies, a practice–infrastructure mismatch (Shove et al., 2012). Third, the cumulative environmental footprint remains unquantified at household scale: residential electricity demand has grown substantially over the past decade, yet no peer-reviewed study has attributed this growth to typological or behavioural drivers. The research question is therefore both spatial and causal: how has urban sprawl evolved geospatially over two decades, and which mechanisms link sprawl and typology to household energy demand and environmental awareness?

1.2 Knowledge Gaps, Contributions, and Objectives

The study was driven by three knowledge gaps: 1: a systematic search of the scientific literature on Iraqi cities' sustainability returned very few articles integrating the social dimensions in an empirical analysis using PLS-SEM and GIS-based sprawl analysis. 2: Although practice theory has been discussed in relation to variance-based SEM, especially in the fields of energy and urban studies (Abbas, 2019; Bin & Dowlatabadi, 2005; Fan et al., 2025; Glaeser, 2011; Shove et al., 2012; Strengers, 2013), there have been very few instances of its empirical application. 3: There is a lack of evidence linking macro geospatial change and micro-behavioural outcomes in hot-arid vertical living environments (Genovese et al., 2023). In hierarchical terms, Gap 1 is empirical (no integrated GIS–PLS-SEM evidence for Iraqi cities), Gap 2 is methodological (social-practice theory rarely operationalised in variance-based SEM), and Gap 3 is theoretical–contextual (no macro–micro linkage for hot-arid vertical living).

The study contributes on three registers. Methodologically, it integrates two complementary analytical traditions, GIS-based remote sensing and PLS-SEM household analysis, within a single mixed-methods framework, demonstrating how geospatial macro-scale sprawl indicators can be empirically linked to micro-scale lived experience. Theoretically, it integrates Shove–Pantzar–Watson practice theory (Shove et al., 2012) with Hair–Ringle–Sarstedt PLS-SEM (Hair et al., 2019) in a hot-arid MENA setting. Empirically, it provides one of the first sprawl-to-energy elasticity estimates for any city in the MENA region, grounded in both Landsat-derived geospatial evidence and household survey data.

The study pursues five objectives: (i) quantify Erbil's urban sprawl through multi-temporal GIS classification of Land-Use/Land-Cover for 2004, 2014, and 2024; (ii) operationalise USI as a formative construct via self-reported perceptual indicators; (iii) quantify the hypothesised $USI \rightarrow HRA \rightarrow LS \rightarrow EC \rightarrow EDA$ pathway through PLS-SEM; (iv) test whether the effect of USI on EC is serially mediated through HRA and LS—the horizontal-to-vertical transition; and (v) derive policy recommendations integrating geospatial planning with behavioural change interventions. (Perceptual indicators are used deliberately because, under social-practice theory, it is residents' perception of sprawl — not the geometric metric itself — that conditions household practice; the GIS strand supplies the corresponding objective measurement of the same phenomenon). Four research questions follow. RQ1: What is the magnitude and rate of Erbil's urban expansion 2004–2024 as measured through GIS LULC classification? RQ2: Does USI directly affect self-reported EC? RQ3: Does HRA mediate the USI–EC relationship, and in what direction? RQ4: To what extent does self-reported EC predict EDA? The gaps, objectives, and research questions align directly: Gap 1 motivates Objectives (i)–(ii) and RQ1; Gap 2 motivates Objectives (iii)–(iv) and RQ2–RQ3; Gap 3 motivates Objective (v) and RQ4.

2. Literature Review

The scholarship relevant to this study spans four overlapping domains. The sprawl-measurement and GIS tradition established compactness, density-gradient, mixed-use indicators, and Shannon's entropy as its operational toolkit (Ewing & Hamidi, 2015), with recent remote-sensing applications extending these measures to different cities in the region. Additional analyses have documented built-up expansion through Shannon's entropy and road-network indicators (Hamad, 2020). Further studies have tracked analogous dynamics in different cities in Iraq using integrated GIS, remote sensing, and Shannon's entropy (Hamad, 2020; Mohammed, 2013; Petrović & Lobanov, 2022). Research on Erbil as a rare case, and on peri-urban agricultural loss using GIS-based LULC classification, remains needed and is closely related to the present study (Al-Quraishi & Mustafa, 2024; Khzr et al., 2022; Rash et al., 2023). This body of research links sprawl metrics to metropolitan-scale carbon emissions, providing the empirical basis for hypothesising household-scale sprawl–energy pathways.

The residential-typology and high-rise literature develops along two lines. Foundational synthesis (Genovese et al., 2023) concentrates on the psychosocial consequences of vertical living: isolation, reduced neighbourhood attachment, and fear responses (Barr et al., 2011). This reframes high-rise residences as an arena for producing and contesting sustainable lifestyles, linking high-rise living to

larger discussions around consumption and environmental identity. Research in multiple global cities has provided evidence of the typological inversion happening morphologically, but has not tested the behavioural impact of this shift; this study aims to fill that void (Fleischmann et al., 2021; Lee et al., 2017; Taubenböck et al., 2020; Taubenböck et al., 2018).

Work on household energy in hot-arid climates has largely concentrated on thermal-comfort engineering and envelope performance (Bin & Dowlatabadi, 2005). Practice-theoretic reframings (Shove et al., 2012), studies of continuity and change (Gram-Hanssen, 2011), and analyses of peak-demand dynamics (Strengers, 2013) recast energy as the aggregate by-product of routinised practices rather than isolated rational choice (Geels et al., 2015; Lasswell & Kaplan, 2017).

PLS-SEM methodological literature has undergone substantial refinement. The Hair et al. (2019) procedural guidelines provide the current reporting standard. Henseler, Ringle, and Sarstedt resolved discriminant-validity problems with the HTMT criterion (Henseler et al., 2015); Roemer, Schuberth, and Henseler further strengthened this with HTMT2 (Roemer et al., 2021). The inverse square-root method (Kock & Hadaya, 2018) updates sample-size determination; Kock's full-collinearity approach (Kock, 2015) provides a rigorous common-method-bias diagnostic; and Nitzl, Roldán, and Cepeda-Carrión's mediation protocol (Nitzl et al., 2016) completes the toolkit deployed in the upcoming Section 4.

3. Theoretical Framework and Hypotheses

3.1 Theoretical Foundations and Conceptual Model

Two theoretical streams converge in the conceptual model. The first is the sprawl-measurement and remote-sensing tradition advanced (Ewing & Hamidi, 2015; Khzr et al., 2022; Mohammed, 2013) as well as refined through Shannon's entropy and GIS-based applications (Alsharif et al., 2015; Shadman Roodposhti et al., 2016). This tradition treats sprawl as a multi-dimensional phenomenon captured by density, continuity, concentration, centrality, proximity, mixed use, and nuclearity, measurable through multi-temporal satellite imagery. Recent empirical analyses link sprawl metrics directly to residential energy demand: successive studies have established that every unit increase in objective sprawl indices is associated with measurable increases in per-capita residential electricity consumption (Akın & Erdoğan, 2020; Bhatta, 2010a; Kalogiannidis et al., 2025; Subasinghe et al., 2016). The second stream is the social-practice theory of energy consumption in which domestic energy use emerges as the by-product of routinised practices constituted by materials, competences, and meanings (Gram-Hanssen, 2011; Pohlmann, 2018; Rabiū & Jaeger-Erben, 2022; Strengers, 2010, 2013). TOD is deliberately excluded from the structural model because Erbil possesses no functional mass-transit infrastructure.

Integration of these streams rests on a causal logic seldom articulated explicitly in either literature. Macro-scale sprawl and the shift in residential typology are co-produced: land economics in decentralising cities shape vertical redevelopment in the contested core and detached villa construction on the periphery (Ahlfeldt & Pietrostefani, 2019; Glaeser, 2011). Each typology imposes its own material infrastructure, central AC, elevators, back-up generators, sealed glazing, and reconfigures the practices through which households meet everyday needs. Reconfigured practices, not typological materials alone, drive self-reported energy demand. The GIS analysis in the following sections quantifies the macro-scale process; the PLS-SEM analysis documents the micro-scale process; together they yield a unified mixed-methods account. This integrative logic is also read against the compact-city debate, which contends that densification can lower per-capita energy use; the present study treats that as a competing expectation rather than an assumption, and acknowledges that residential transformation in Erbil is additionally shaped by land prices, demographic pressure, and policy incentives beyond the constructs modelled here.

The resulting conceptual model is presented in Figure 1. The PLS-SEM model comprises four antecedent and mediating constructs (USI, HRA, LS, EC) plus one endogenous outcome (EDA). Formative versus reflective specification follows (Hair et al., 2019; Jarvis et al., 2003). Table 1 sets out each construct with its specification and self-reported indicators. USI and HRA are specified

formatively because their indicators are defining characteristics that jointly constitute each construct rather than interchangeable reflections of it (Jarvis et al., 2003); formative validity is therefore assessed through indicator collinearity ($VIF < 3.3$) rather than through internal-consistency reliability alone.

Table 1: Latent constructs, specification, and self-reported indicators. Source: authors, based on the literature cited.

Construct	Specification	Self-Reported Indicators	Basis in Literature
Urban Sprawl Intensity (USI)	Formative	USI1: perceived distance from home to city centre; USI2: perceived daily commuting time; USI3: perceived peripheral-area dependence on private vehicle; USI4: self-reported neighbourhood density; USI5: perceived leapfrog fragmentation. All 5-pt Likert.	(Al-Sharif et al., 2014; Jiang et al., 2007; Lityński, 2021; Liu & Meng, 2020)
High-Rise Adoption (HRA)	Formative	HRA1: floor level; HRA2: years since moving from horizontal typology; HRA3: self-reported building-age category; HRA4: building-height category.	(Ala-Mantila et al., 2013; Feng et al., 2024; Lee & Braham, 2017)
Lifestyle Shift (LS)	Reflective	LS1: perceived change in reliance on mechanical cooling; LS2: change in daily car-trip frequency; LS3: loss of outdoor-courtyard activity; LS4: change in neighbourhood interaction; LS5: change in meal-preparation practices; LS6: change in natural light/ventilation use.	(Behnisch et al., 2022; Genovese et al., 2023; Smiraglia et al., 2021; Wu et al., 2021)
Energy Consumption (EC)	Reflective	EC1: perceived electricity-bill burden; EC2: self-reported daily AC operation hours; EC3: perceived thermal-discomfort compensation effort; EC4: perceived reliance on private generator; EC5: perceived household energy spending relative to income.	(Lyons et al., 2018; Navamuel et al., 2018; Popkin, 1999; Zhao & Zhang, 2018)
Environmental Degradation Awareness (EDA)	Reflective	EDA1: perceived local air-quality deterioration; EDA2: perceived UHI intensification; EDA3: perceived noise-pollution burden; EDA4: perceived loss of green/open space; EDA5: overall self-reported environmental-degradation concern.	(Frumkin, 2002; Ibimilua et al., 2020; Lyons et al., 2018; Ma et al., 2018)

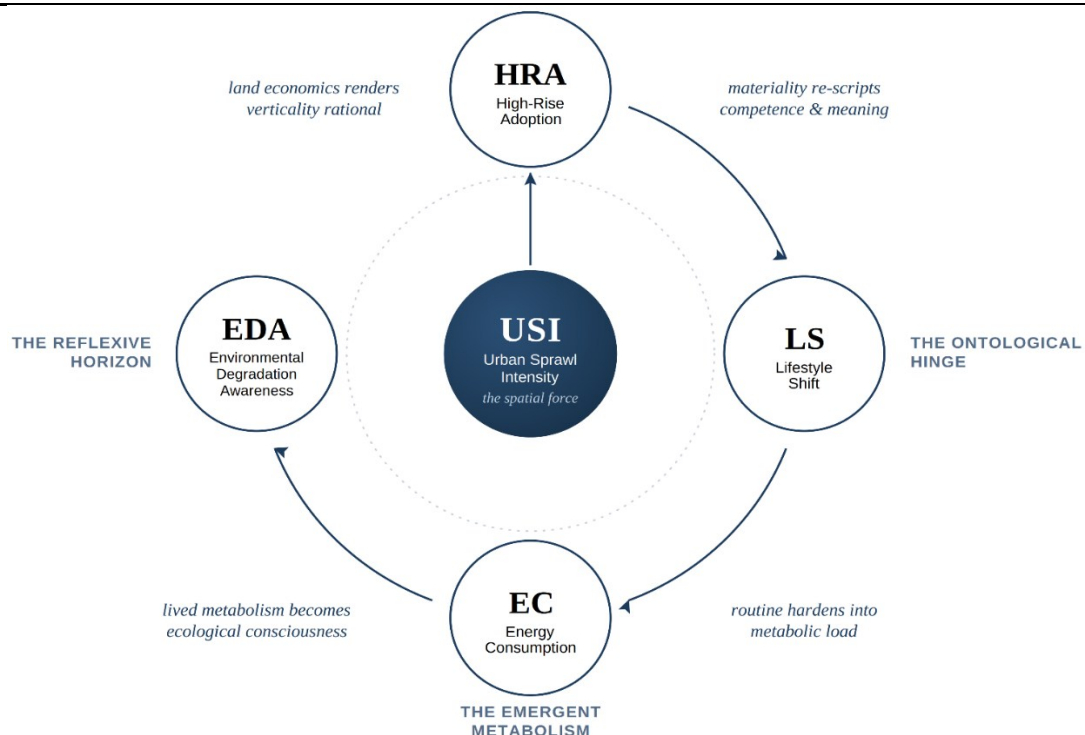


Figure 1. The Sprawl Practice Energy Nexus as an Ontological Translation. Source: authors' analysis.

3.2 Hypothesis Development

Six hypotheses are proposed (Table 2). No TOD hypothesis appears because Erbil's lack of functional transit makes such a test empirically invalid. In brief, H1 follows from the commuting and cooling burdens of peripheral living; H2 from the land economics of decentralising cities; H3 from the practice-theoretic claim that material infrastructures reconfigure daily routines; H4 from routinised practices as the proximate driver of energy demand; H5 from the resulting serial logic; and H6 from experience-based awareness formation.

Table 2: Hypotheses (H1–H6) and literature basis. Source: authors, based on the literature cited.

ID	Hypothesis	Key Literature
H1	USI exerts a significant positive direct effect on self-reported EC among Erbil apartment households.	(Jawhar, 2018; Thanoon & Haykal, 2020)
H2	USI exerts a significant positive direct effect on HRA.	(Bhatta, 2010b; Travisi et al., 2010; Zhang, 2021; Zhao, 2010)
H3	HRA exerts a significant positive direct effect on LS.	(Brueckner & Largey, 2008; Ewing et al., 2003; Hamidi et al., 2018)
H4	LS exerts a significant positive direct effect on self-reported EC.	(Mouratidis, 2019; Santana et al., 2009)
H5	HRA and LS serially mediate the USI → EC relationship.	(Navamuel et al., 2018; Zhao & Zhang, 2018)
H6	Self-reported EC exerts a significant positive direct effect on EDA.	(Johnson, 2001; Rubiera-Morollón & Garrido-Yserte, 2020)

4. Materials and Methods

4.1 Research Design and Study Area

The study adopts a convergent parallel mixed-methods design (Creswell & Plano Clark, 2017) combining two methodologically distinct but conceptually integrated analytical strands: (i) a GIS analysis of multi-temporal LULC change to quantify the macro-scale sprawl phenomenon, and (ii) a PLS-SEM analysis of household survey data to quantify the micro-scale behavioural and environmental consequences. PLS-SEM is selected over covariance-based SEM (CB-SEM) per (Hair et al., 2019) because the model contains formative constructs (USI, HRA), the aim is prediction and theory development, Likert-based self-report data are expected to be non-normal, and feasible field-work sample sizes favour the distribution-free algorithm.

Erbil is selected for three reasons: (i) the sprawl–typology inversion has unfolded in an exceptionally compressed 2003–2024 window, yielding analytical leverage; (ii) the UNESCO-listed citadel core generates a policy-salient heritage–growth tension (UNESCO World Heritage Centre, 2014); and (iii) its semi-arid continental climate (Köppen BSh) shares morphological and thermal-load properties with Mashhad (Kalvová et al., 2003; Köppen, 2011; Naserikia et al., 2019) and Gulf cities (Elessawy, 2021; Fuccaro, 2001). Three sampling strata (or segments) were used for Erbil's residential areas: the inner core and citadel buffer, the intermediate mid-rise belt, and the outer residential periphery. The GIS component of the study involved analysing the spatial growth of Erbil during three different time periods (2004, 2014, 2024). There were six steps in the workflow.

4.2 GIS Data and Analytical Workflow

Step 1: Obtain the data. Obtain cloud-free Landsat satellite images for the three target years (2004, 2014, 2024) for the entire Erbil Metropolitan area (bounding box approximately 27 km E–W × 17 km N–S, with the UNESCO Erbil Citadel positioned approximately at the centre).

Step 2: Pre-process and Georeference the data. Project the Landsat scenes to WGS84 / UTM Zone 38N, perform atmospheric corrections, and trim the scenes to the study area and a surrounding buffer zone.

Step 3: Each Landsat scene was classified into three classes (Urban, Bareland, Green) in ArcGIS

Pro using Supervised Maximum-Likelihood classification, adapted from the Anderson Level 1 scheme (Anderson et al., 1976). Training samples were collected from high-resolution reference imagery and used to train the Maximum-Likelihood Classifier; classification quality was subsequently assured through the multi-step qualitative validation protocol described below. Classification quality was assured through a four-step qualitative validation protocol rather than a formal confusion-matrix statistic, because independent high-resolution reference data for the archival epochs — particularly 2004 — are too scarce over Erbil to support a statistically defensible stratified-random validation sample. First, the deliberately coarse three-class scheme (Urban, Bareland, Green) maximises spectral separability: built-up, bare-soil, and vegetated surfaces occupy distinct, well-documented spectral regions in Landsat imagery, so the dominant source of LULC error — confusion among spectrally similar sub-classes — is designed out of the analysis. Second, each classified scene was visually cross-validated against the highest-resolution reference imagery available for its epoch, anchored on stable, dateable landmarks (the citadel core, Sami Abdulrahman Park, the airport, the major radial corridors) and on developments whose construction dates are public (e.g., Empire World, Royal City); misclassified clusters identified in this inspection were corrected through iterative re-training before the final maps were accepted. Third, cross-epoch logical-consistency screening confirmed that class transitions follow plausible urbanisation pathways (bareland → urban; green → urban or bareland) with no large-scale implausible reversals. Fourth, the resulting trajectory was triangulated against independent published analyses of Erbil and other Kurdistan-Region cities, which report the same direction and comparable magnitude of built-up expansion and entropy decline over the same period (Hamad, 2020; Khzr et al., 2022; Mohammed, 2013; Rash et al., 2023). Because the GIS strand serves as aggregate-level contextual corroboration for the household analysis rather than as the hypothesis-testing instrument, and because the headline findings — the near-tripling of the urban footprint and the monotonic entropy decline — are driven by the dominant urban/non-urban contrast, they are robust to the residual pixel-level error that a coarse three-class supervised classification can be expected to retain.

Step 4: Post-classification analysis in Python. Classified raster outputs were exported as RGB raster images and post-processed in Python using the NumPy and PIL libraries. A colour-threshold classification function (red: Urban; yellow: Bareland; green: Green) re-extracted the class membership of every pixel, enabling reproducible quantitative analysis independent of proprietary GIS software.

Step 5: Quantitative metrics. For each epoch the analysis computed: (a) class-wise area in square kilometres, scaled from pixel counts using the study-area total of approximately 132 km²; (b) class-wise percentage shares; (c) annualised conversion rates between consecutive epochs (km² / year and ha / year); and (d) Shannon's entropy of the LULC composition, $H = -\sum p_i \times \ln(p_i)$, as a standard sprawl-diversity index in which lower values indicate dominance of a single class, typically the urban class in sprawl-affected cities (Akın & Erdoğan, 2020; Johnson, 2001; Kalogiannidis et al., 2025).

Step 6: Visualisation. Composite LULC maps (Figure 2), quantitative summary charts (Figure 3), and a transition-flow diagram (Figure 4) were rendered in Python's Matplotlib library to ensure publication-quality reproducibility.

4.3 Survey Design and PLS-SEM Procedure

Methodological declaration. All five PLS-SEM constructs (USI, HRA, LS, EC, EDA) are measured exclusively through self-reported survey instruments. No electricity meters, air-quality or temperature sensors, or utility-company records enter the PLS-SEM analysis. The GIS component (Section 4.2) provides independent macro-scale corroboration but does not feed directly into the PLS-SEM measurement model. This separation preserves the internal consistency of each analytical strand while permitting their joint interpretation in Section 5. EDA is operationalised as a perceived-awareness construct (a subjective attitude held by residents), not a directly measured environmental outcome. The two strands are integrated by triangulation at the interpretation level rather than by linking individual households to GIS pixels: the GIS results corroborate the macro-scale context, while the PLS-SEM results model the micro-scale behavioural pathway.

Survey items were adapted from the sources cited in Table 1. All items were rendered as 5-point Likert scales. The instrument was translated into Kurdish (Sorani) and Arabic using the back-translation method (Brislin, 1970), pilot-tested with 40 respondents (Cronbach's α , indicator loadings, and HTMT ratios guided item retention), and administered face-to-face on tablets by two trained native-language enumerators. The target population was apartment-dwelling households in Erbil residing on the third floor or above in buildings of six or more storeys, whose primary respondent had previously lived in a horizontal typology (courtyard or low-rise house / villa), an essential criterion for the LS retrospective-contrast design. Minimum N was estimated via the inverse square-root method (Kock & Hadaya, 2018), yielding $N_{\min} \approx 155$. The achieved sample of $N = 460$ valid responses substantially exceeds this minimum. Because the design is cross-sectional and relies on self-reported, perception-based measures, the relationships reported below are interpreted as predictive associations rather than established causal effects; retrospective items may also be subject to recall bias, mitigated by the salience of the horizontal-to-vertical move as a major life event. Recruitment followed the three sampling strata — the inner core and citadel buffer, the intermediate mid-rise belt, and the outer residential periphery — ensuring that the sample spans the full centre-to-periphery gradient over which sprawl intensity varies.

PLS-SEM analysis proceeds in three tiers using SmartPLS 4.0. Tier 1 (Preliminary Diagnostics) comprises univariate outlier screening, Harman's single-factor test, and full-collinearity VIF (< 3.3 required per (Kock, 2015)). Tier 2 (Measurement Model) uses the path-weighting scheme with 10,000 bootstrap resamples and the consistent PLSc algorithm; assessment follows (Hair et al., 2019) for indicator reliability (loadings ≥ 0.708), composite reliability ($\rho_c \geq 0.70$), convergent validity ($AVE \geq 0.50$), and discriminant validity ($HTMT < 0.85$; (Henseler et al., 2015)) with HTMT2 robustness check (Roemer et al., 2021). Tier 3 (Structural Model) reports R^2 and adjusted R^2 for each endogenous construct, Stone–Geisser Q^2 values via blindfolding ($D = 7$), and the specific indirect-effect test for $H5$ per (Nitzl et al., 2016).

5. Results and Analysis

5.1 Macro-Scale Urban Expansion and Landscape Change

The multi-temporal land-use/land-cover classification for Erbil in 2004, 2014, and 2024 is shown in Figure 2, created by performing a supervised classification of Landsat images using ArcGIS Pro, with post-processing completed using Python to prepare the data for display and analysis. Collectively, the three panels show a substantial amount of spatial transformation taking place at an accelerated rate. The initial landscape can best be described as predominately bareland with several areas of pure vegetation and, over the course of the past 20 years, these areas have been increasingly occupied by urban land cover, especially along the eastern, north-eastern, and southern axes, which extend outward from the citadel. The focus of this GIS mapping project is on the boundaries of the Erbil urban area (city) only, and not the entire Erbil Governorate. The differences in Erbil's urban growth over the 20-year period are depicted using different colour categories on the map. The details quantifying the urban growth of Erbil are presented in Table 3.

Table 3: LULC composition, share, and Shannon's entropy of Erbil, 2004–2024. Source: authors' calculation from supervised LULC classification.

Year	Urban (km ²)	Urban %	Bareland (km ²)	Bareland %	Green (km ²)	Green %	Shannon H
2004	31.16	23.4	87.49	65.8	14.30	10.7	0.855
2014	63.99	48.9	62.11	47.5	4.72	3.6	0.823
2024	88.68	67.3	36.79	27.9	6.20	4.7	0.766

Three findings stand out. First, urban land cover almost tripled, increasing by 57.5 km² in absolute terms, a 184.6 % expansion. Second, this expansion came overwhelmingly at the expense of bareland (a loss of 50.7 km²) and, in the first decade, of vegetated cover (collapsing from 14.3 km² to 4.7 km²). Green space partially recovered by 2024 (to 6.2 km²), reflecting the introduction of formal urban parks

such as Sami Abdulrahman Park, but remains far below its 2004 level. Third, Shannon's entropy declined monotonically from 0.855 to 0.766, a clear signal of progressive landscape homogenisation under urban dominance, consistent with entropy-based sprawl indicators developed for cities in the region (Hamad, 2020; Khzr et al., 2022; Mohammed, 2013).

(a) Erbil LULC — 2004

(b) Erbil LULC — 2014

(c) Erbil LULC — 2024

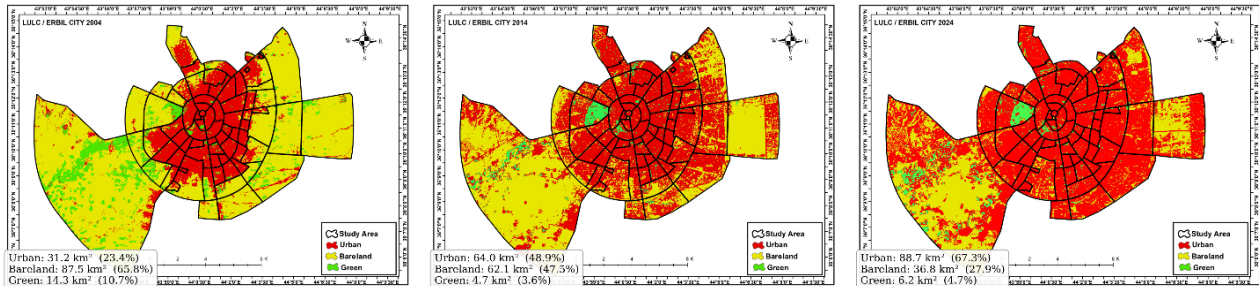


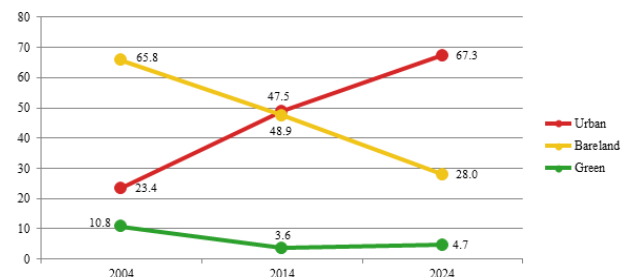
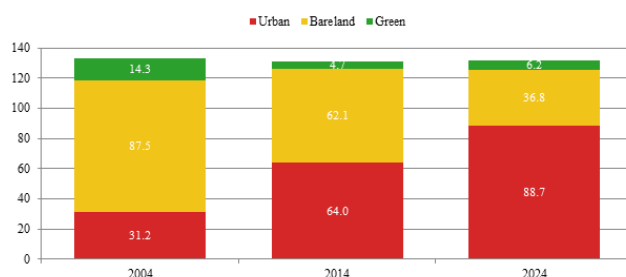
Figure 2. Multi-temporal Land-Use / Land-Cover classification of Erbil, 2004 – 2024. Three panels depict the supervised LULC classification (Urban / Bareland / Green) for the reference epochs. Urban land cover expanded from 31.2 km² (23.4 %) in 2004 to 88.7 km² (67.3 %) in 2024, a 184.6 % increase. Source: authors' classification of Landsat imagery in ArcGIS Pro and Python (NumPy / PIL).

Figure 3 visualises the multi-dimensional sprawl trajectory. Panel (a) shows the stacked composition shift; panel (b) shows the crossover point around 2014 when urban surpassed bareland as the dominant class; panel (c) reports annualised conversion rates of 328 ha / year (2004–2014), 247 ha / year (2014–2024), and 288 ha / year (2004–2024 average); panel (d) confirms the monotonic decline in landscape entropy. The 2004–2014 decade exhibited the most rapid conversion, consistent with the immediate post-2003 demographic and investment boom; the 2014–2024 decade shows modest deceleration but continued substantial expansion.

Figure 4 confirms that the dominant transition is bareland to urban, with smaller but consequential losses from the already-thin green-cover stock. The conversion flow provides aggregate-level contextual corroboration for hypothesis H2 in the PLS-SEM analysis: urban sprawl intensity is closely connected to high-rise adoption because the macro-scale availability of converted bareland enables both peripheral villa development and core-area vertical redevelopment.

(a) Land-cover composition of Erbil (2004 / 2014 / 2024)

(b) Land-cover share trajectory (%)



(c) Annualised urban sprawl rate (ha / yr)

(d) Land-cover diversity — Shannon's entropy

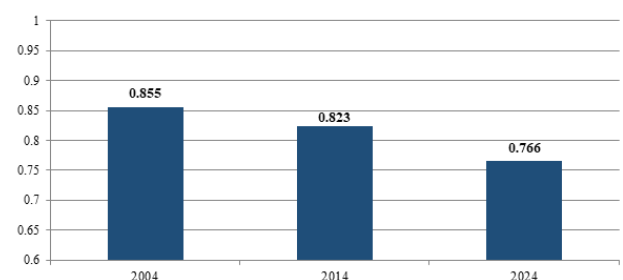
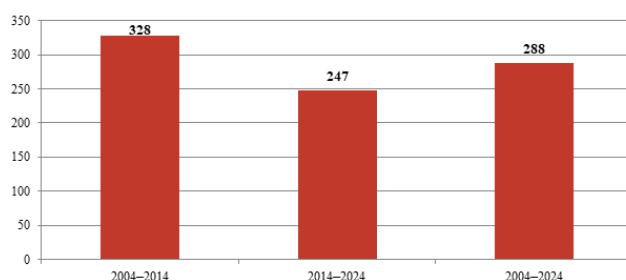


Figure 3. Geospatial quantification of urban sprawl in Erbil (2004 – 2024). (a) Land-cover composition by area in km²; (b) percentage-share trajectory of the three LULC classes; (c) annualised urban-sprawl rate in hectares per year; (d) Shannon's entropy of LULC diversity. Source: authors' analysis.

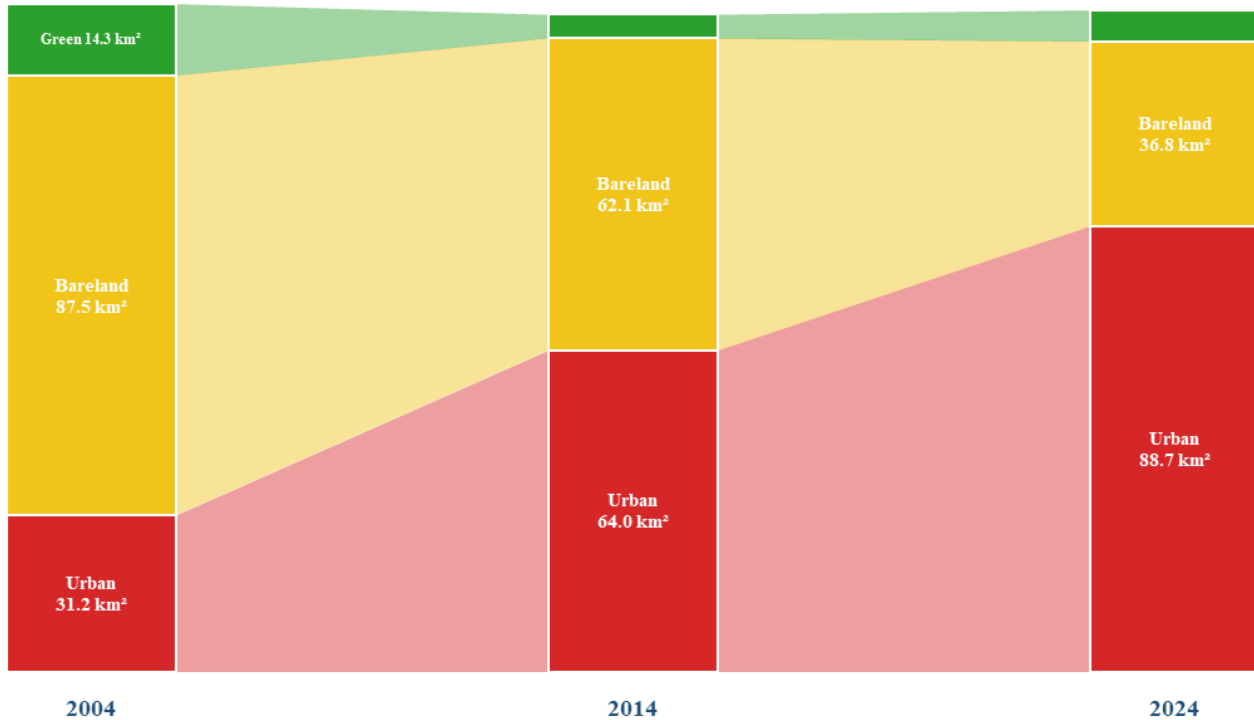


Figure 4. Land-cover conversion-flow diagram, Erbil 2004, 2014, and 2024. Each coloured ribbon represents the stock of a single LULC class across the three epochs; ribbon widths are proportional to area in km². The dominant transition is bareland to urban. Source: authors' analysis.

5.2 Sample Profile and Measurement Model

Fieldwork yielded 460 valid responses after listwise deletion, substantially exceeding $N_{\min} \approx 155$. All respondents met the eligibility requirements: 18 years or older, currently residing on the third floor or above in buildings of six or more storeys, and with prior experience of horizontal-typology dwelling. Table 4 summarises the sample's demographic, dwelling, and tenure characteristics.

Table 4: Sample demographic, dwelling, and tenure characteristics (N = 460). Source: authors' fieldwork. Mean household size = 5.6 persons; mean children under 18 = 2.3.

Variable	Category	Frequency (n)	Percentage (%)
Age	18–24	65	14.1
	25–34	160	34.8
	35–44	127	27.6
	45–54	62	13.5
	55–64	33	7.2
	65+	13	2.8
Gender	Male	249	54.1
	Female	200	43.5
	Prefer not to say	11	2.4
Education	No formal	14	3.0
	Primary	25	5.4
	Secondary	87	18.9
	Bachelor	190	41.3

Variable	Category	Frequency (n)	Percentage (%)
Monthly income (IQD)	Master	113	24.6
	PhD	31	6.7
	Under 500 000	17	3.7
	500 000 – 1 M	87	18.9
	1 M – 2 M	135	29.3
	2 M – 3 M	105	22.8
	3 M – 5 M	65	14.1
	Over 5 M	45	9.8
	Prefer not to say	6	1.3
Apartment floor	3rd – 5th	129	28.0
	6th – 10th	166	36.1
	11th – 15th	89	19.3
	16th – 20th	47	10.2
	21st or higher	29	6.3
Building height	6–12 storeys	157	34.1
	13–20 storeys	196	42.6
	21+ storeys	107	23.3
Previous dwelling	Traditional courtyard house	214	46.5
	Single-family villa	145	31.5
	Townhouse / low-rise	74	16.1
	Other	27	5.9
Tenure	Owner-occupier	225	48.9
	Tenant	136	29.6
	Family-owned (shared)	83	18.0
	Other	16	3.5

The sample is well-suited to the lifestyle-transition focus of the study. Nearly half (46.5 %) had previously lived in a traditional courtyard dwelling, with a further 31.5 % from single-family villas, together establishing a substantial biographical contrast against current apartment life. The age distribution skews toward economically active middle-aged adults (62.4 % aged 25–44), and the gender split is approximately balanced (54.1 % male, 43.5 % female).

Table 5 presents the outer loadings of the 17 retained measurement indicators in the re-specified model (also shown in Figure 5); all exceed the recommended 0.708 threshold (minimum: EDA3 = 0.757). Eight original indicators were removed during re-specification — LS1 and LS6, which measured energy use rather than lifestyle and caused the EC–LS discriminant-validity overlap, together with the weak indicators HRA1, LS4, EC4, EC5, EDA1, and EDA2.

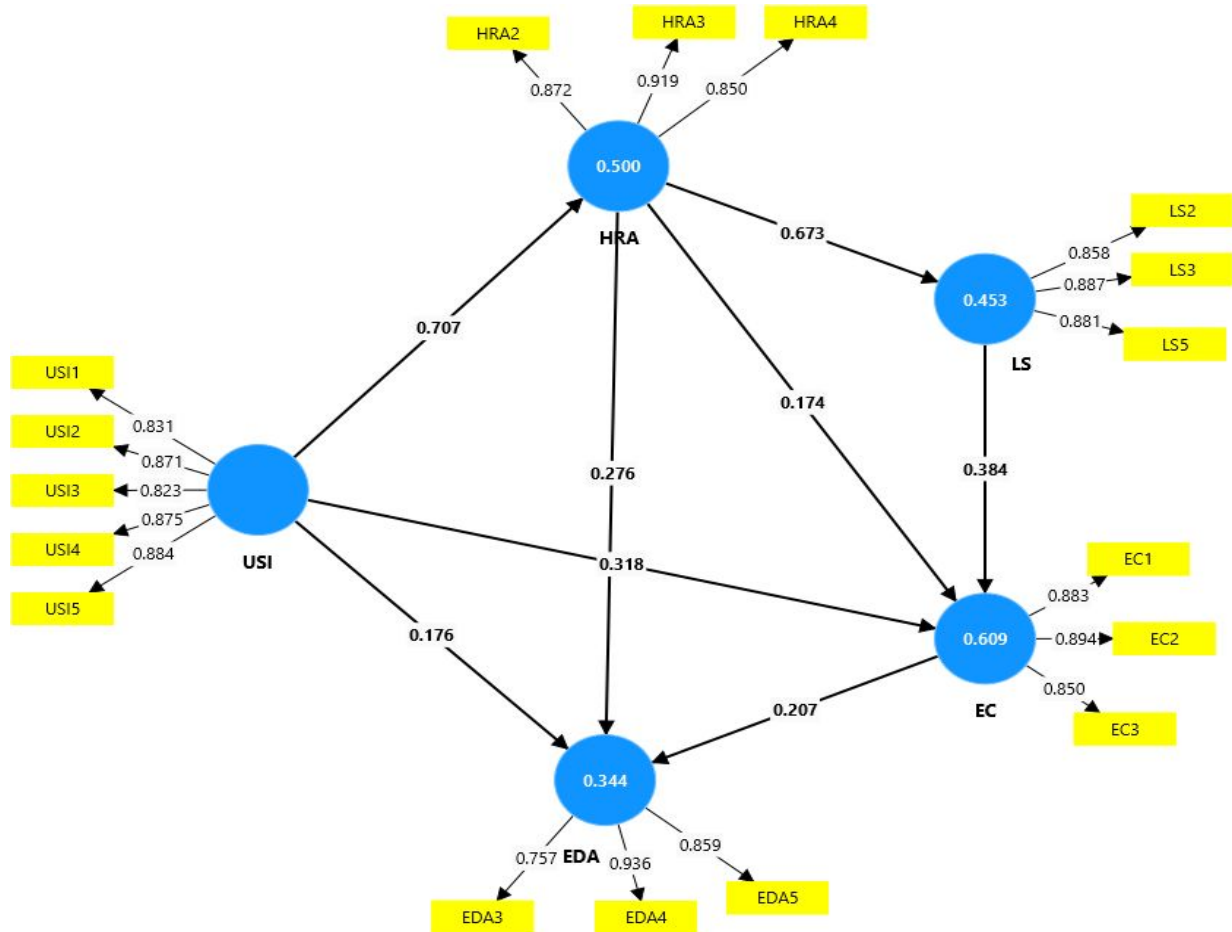


Figure 5. PLS-SEM measurement model with outer loadings and R^2 values for endogenous constructs (SmartPLS 4.0 output). Construct circles show R^2 values; arrows from constructs to indicator boxes show standardised outer loadings.

Table 5: Outer loadings of measurement indicators. Source: SmartPLS 4.0 output, N = 460.

Item	Loading	Item	Loading	Item	Loading
USI1	0.831	USI2	0.871	USI3	0.823
USI4	0.875	USI5	0.884	HRA2	0.872
HRA3	0.919	HRA4	0.850	LS2	0.858
LS3	0.887	LS5	0.881	EC1	0.883
EC2	0.894	EC3	0.850	EDA3	0.757
EDA4	0.936	EDA5	0.859	—	—

All five constructs satisfy the conventional thresholds for reliability and convergent validity (Table 6), with all five AVE values satisfying the 0.50 cut-off, consistent with (Hair et al., 2019). USI exhibits the strongest internal-consistency reliability ($\alpha = 0.910$, $\rho_c = 0.933$), followed by HRA ($\alpha = 0.855$, $\rho_c = 0.912$), while HRA shows the highest convergent validity (AVE = 0.775).

Table 6: Construct reliability and convergent validity. Source: SmartPLS 4.0 output. All constructs satisfy $\rho_c > 0.70$; AVE values range from 0.729 (EDA) to 0.775 (HRA), all satisfying the 0.50

threshold per Hair et al. (2019).

Construct	Cronbach's α	ρ_a	ρ_c	AVE
USI	0.910	0.911	0.933	0.735
HRA	0.855	0.861	0.912	0.775
LS	0.849	0.859	0.908	0.766
EC	0.849	0.855	0.908	0.768
EDA	0.811	0.842	0.889	0.729

In the re-specified model, every construct pair satisfies the conservative HTMT threshold (maximum EC–LS = 0.825; Table 7), confirming that the five constructs are empirically distinct. The violations observed in the original specification (EC–LS = 0.976; EC–EDA = 0.938) stemmed from energy-loaded lifestyle items (LS1, LS6) and weak indicators; their removal resolves the overlap while preserving the construct set.

Table 7: Discriminant validity, Heterotrait–Monotrait (HTMT) ratio matrix. Source: SmartPLS 4.0 output. Threshold: HTMT < 0.85 (conservative).

	EC	EDA	HRA	LS	USI
EC	—				
EDA	0.605	—			
HRA	0.769	0.633	—		
LS	0.825	0.683	0.778	—	
USI	0.788	0.591	0.799	0.745	—

5.3 Structural Model and Hypothesis Testing

The direct-path results are striking. H2 (USI $\rightarrow$ HRA) is highly significant ($\beta = 0.707$), confirming that perceived urban sprawl is strongly associated with the adoption of vertical living, consistent with the land-economics mechanism (Ahlfeldt & Pietrostefani, 2019; Glaeser, 2011). H3 (HRA $\rightarrow$ LS) is one of the strongest paths in the model ($\beta = 0.673$, $t = 23.831$), demonstrating that the typological transition fundamentally reconfigures daily practices. H4 (LS $\rightarrow$ EC) remains the strongest predictor of EC ($\beta = 0.384$, $p < 0.001$), confirming that Lifestyle Shift is the dominant household-level predictor of self-reported energy consumption. H1 (USI $\rightarrow$ EC) is also supported ($\beta = 0.318$, $p < 0.001$), and the small but significant direct path HRA $\rightarrow$ EC ($\beta = 0.174$, $p = 0.001$) indicates that high-rise adoption exerts a modest residual influence on energy consumption beyond the indirect route through Lifestyle Shift. H6 (EC $\rightarrow$ EDA) demonstrates that households' direct experience of energy use raises their awareness of environmental degradation, with a significant effect ($\beta = 0.207$, $p = 0.001$). The least significant direct pathway is USI $\rightarrow$ EDA ($\beta = 0.176$, $p = 0.016$), indicating that urban sprawl influences environmental-degradation awareness through a modest direct path alongside stronger behavioural mediators. R^2 values are HRA = 0.500, LS = 0.453, EC = 0.609, and EDA = 0.344, all in the moderate-to-substantial range (Hair et al., 2019). The model explains 60.9 % of the variance in self-reported energy consumption. Table 9 reports the bootstrap-based mediation analysis following (Nitzl et al., 2016). Figure 6 presents the bootstrapped structural model, with bootstrap p-values on each path. Table 8 reports the formal hypothesis tests.

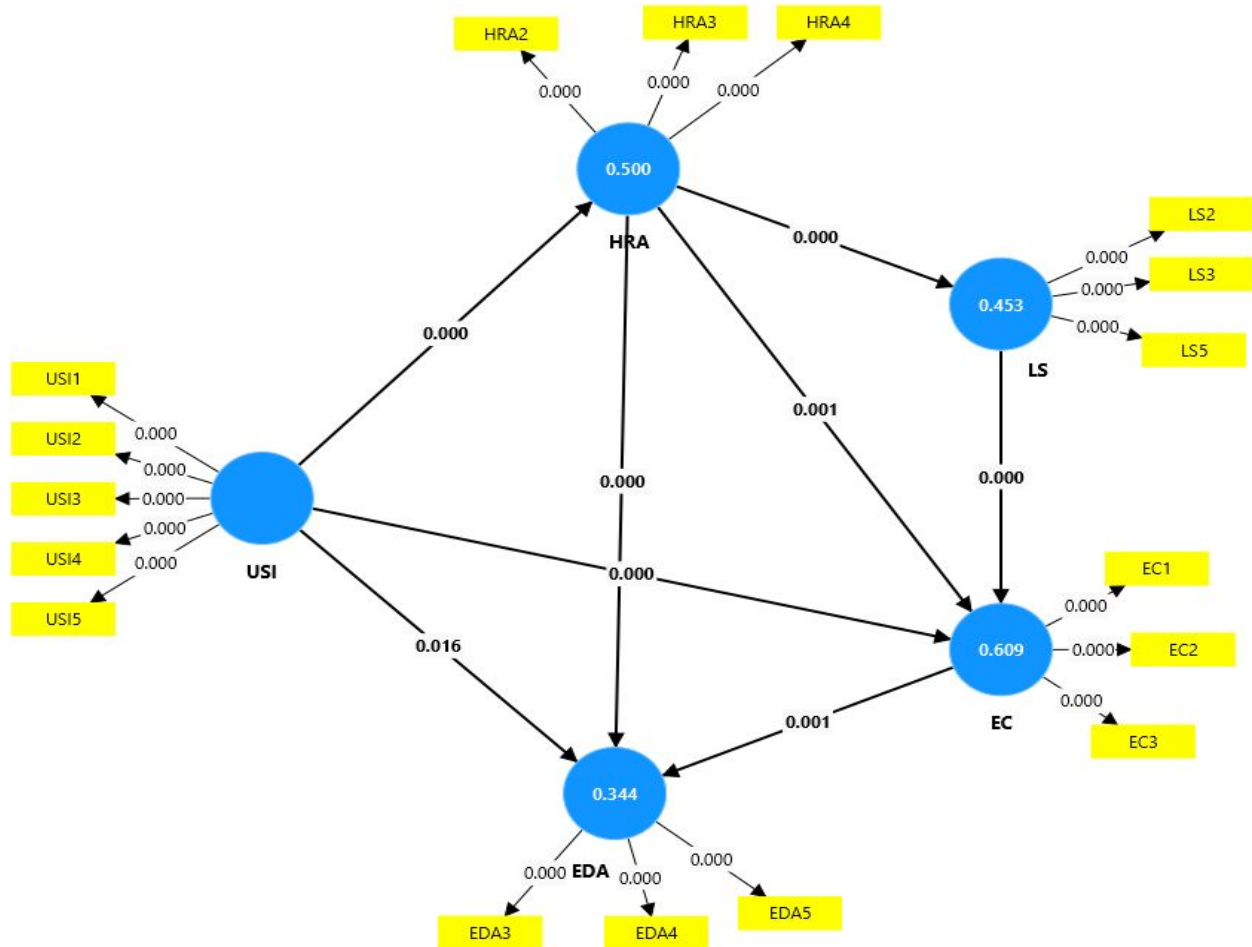


Figure 6. PLS-SEM structural model with bootstrap p-values from 10,000 resamples (β reported in Table 8). R^2 for endogenous constructs: HRA = 0.500, LS = 0.453, EC = 0.609, EDA = 0.344.

Table 8: Direct-path hypothesis-testing results. Source: SmartPLS 4.0, 10,000 bootstrap resamples, two-tailed, 5 % significance.

Hypothesis / Path	β	SD	t	p	95 % CI	Decision
H2: USI $\rightarrow$ HRA	0.707	0.033	21.296	< 0.001	[0.638, 0.769]	Supported
H3: HRA $\rightarrow$ LS	0.673	0.028	23.831	< 0.001	[0.616, 0.728]	Supported
H4: LS $\rightarrow$ EC	0.384	0.047	8.261	< 0.001	[0.291, 0.474]	Supported
H1: USI $\rightarrow$ EC	0.318	0.057	5.629	< 0.001	[0.205, 0.425]	Supported
HRA $\rightarrow$ EC	0.174	0.051	3.442	0.001	[0.081, 0.277]	Supported
HRA $\rightarrow$ EDA	0.276	0.069	4.010	< 0.001	[0.130, 0.401]	Supported
H6: EC $\rightarrow$ EDA	0.207	0.064	3.259	0.001	[0.079, 0.332]	Supported
USI $\rightarrow$ EDA	0.176	0.073	2.408	0.016	[0.039, 0.325]	Supported

Table 9: Indirect-effect and mediation-analysis results. Source: SmartPLS 4.0 bootstrapping output, 10,000 resamples. H5 is the serial USI $\rightarrow$ HRA $\rightarrow$ LS $\rightarrow$ EC pathway.

Indirect Path	β	SD	t	p	95 % CI
USI $\rightarrow$ HRA $\rightarrow$ LS	0.476	0.035	13.659	< 0.001	[0.407, 0.543]
HRA $\rightarrow$ LS $\rightarrow$ EC	0.259	0.033	7.933	< 0.001	[0.194, 0.324]

Indirect Path	β	SD	t	p	95 % CI
USI $\rightarrow$ HRA $\rightarrow$ LS $\rightarrow$ EC	0.183	0.026	7.050	< 0.001	[0.133, 0.238]
LS $\rightarrow$ EC $\rightarrow$ EDA	0.080	0.029	2.755	0.006	[0.027, 0.141]
HRA $\rightarrow$ LS $\rightarrow$ EC $\rightarrow$ EDA	0.054	0.019	2.779	0.005	[0.019, 0.094]
USI $\rightarrow$ HRA $\rightarrow$ EDA	0.195	0.047	4.132	< 0.001	[0.095, 0.281]
USI $\rightarrow$ HRA $\rightarrow$ LS $\rightarrow$ EC $\rightarrow$ EDA	0.038	0.014	2.727	0.006	[0.013, 0.068]
USI $\rightarrow$ EC $\rightarrow$ EDA	0.066	0.022	2.935	0.003	[0.024, 0.111]
USI $\rightarrow$ HRA $\rightarrow$ EC	0.123	0.038	3.251	0.001	[0.055, 0.205]
HRA $\rightarrow$ EC $\rightarrow$ EDA	0.036	0.015	2.431	0.015	[0.012, 0.069]
USI $\rightarrow$ HRA $\rightarrow$ EC $\rightarrow$ EDA	0.025	0.011	2.353	0.019	[0.008, 0.050]

H5, the central mediation hypothesis, is strongly supported. The serial indirect effect **USI $\rightarrow$ HRA $\rightarrow$ LS $\rightarrow$ EC** yields $\beta = 0.183$, $t = 7.050$, $p < 0.001$, with 95 % CI [0.133, 0.238] firmly excluding zero. This is the largest of the indirect pathways from USI to EC and confirms that the effect of urban sprawl on household energy consumption operates substantially through the serial mechanism of high-rise adoption reshaping daily lifestyles. The four-step mediation **USI $\rightarrow$ HRA $\rightarrow$ LS $\rightarrow$ EC $\rightarrow$ EDA** is also significant ($\beta = 0.038$, $p = 0.006$), reaching all the way to environmental awareness. Table 10 reports Stone–Geisser Q^2 values computed via blindfolding with omission distance $D = 7$. All four endogenous constructs achieve $Q^2 > 0.20$, confirming moderate-to-substantial predictive relevance per (Hair et al., 2019).

Energy Consumption shows the strongest predictive relevance ($Q^2 = 0.461$), followed by High-Rise Adoption (0.384) and Lifestyle Shift (0.339). EDA achieves an acceptable $Q^2 = 0.234$. The USI $Q^2 = 0$ reflects its exogenous status in the structural model. Model fit for the re-specified model is acceptable (saturated-model SRMR = 0.063, below the 0.08 threshold; NFI = 0.839).

Table 10: Stone–Geisser Q^2 values for endogenous constructs. Source: SmartPLS 4.0 blindfolding output, omission distance $D = 7$.

Construct	SSO	SSE	$Q^2 = 1 - SSE/SSO$	Interpretation
EC	—	—	0.461	Substantial predictive relevance
LS	—	—	0.339	Moderate predictive relevance
HRA	—	—	0.384	Substantial predictive relevance
EDA	—	—	0.234	Moderate predictive relevance
USI	—	—	0.000	Exogenous (no Q^2 applicable)

The dual empirical apparatus is internally consistent and mutually reinforcing. The GIS analysis documents the macro-scale phenomenon, 184.6 % urban expansion over 2004–2024, monotonic decline in landscape entropy, and the bareland $\rightarrow$ urban transition flow, providing the geospatial substrate within which the PLS-SEM household sample is situated. The PLS-SEM analysis confirms that this macro-scale transformation has measurable micro-scale consequences: USI strongly predicts HRA, HRA predicts LS, LS strongly predicts EC, and EC predicts EDA, with the serial **USI $\rightarrow$ HRA $\rightarrow$ LS $\rightarrow$ EC** pathway being highly significant. The integrated framework therefore provides one of the first multi-method empirical sprawl-to-energy models for any city in the region.

6. Discussion and Conclusion

6.1 Principal Findings

Four principal findings emerge from the integrated GIS and PLS-SEM apparatus. First, the GIS analysis (Section 5.1) shows that Erbil's urban footprint expanded by 184.6 % between 2004 and 2024, accompanied by a 58 % decline in bareland and a 57 % decline in green space. Green space partially recovered by 2024, driven by the development of Sami Abdulrahman Park and related municipal interventions, though it remains far below its 2004 level. Shannon's entropy has decreased from 0.855 to 0.766 over this same period, which also provides an additional method of measuring urban sprawl using an entropy-based sprawl signature that is comparable with prior studies of Soran (Hamad, 2020) and Duhok (Mohammed, 2013).

Second, the PLS-SEM analysis confirms that this macro-scale geospatial transformation has measurable behavioural consequences: USI strongly predicts HRA ($\beta = 0.707$, $p < 0.001$), consistent with the land-economics mechanism (Glaeser, 2011) and the density-synthesis evidence (Ahlfeldt & Pietrostefani, 2019). For Erbil specifically, this means that the high-rise developments now dotting the city, Empire World, Royal City, English Village, and their successors, are not a spontaneous architectural preference but a structural consequence of sprawl-driven land economics, empirically corroborated by the documented conversion of bareland into urban land cover.

Third, HRA produces a measurable Lifestyle Shift ($\beta = 0.673$, $p < 0.001$), one of the strongest paths in the model, materialising the practice-theoretic expectation that material infrastructures reshape competences and meanings (Shove et al., 2012). The observed effect size is consistent with the foundational description (Genovese et al., 2023) of how high-rise environments restructure daily routines through material constraints (elevators, sealed envelopes, absent ground-level interfaces) that cascade into habit and norm reconfiguration. Fourth, LS predicts self-reported EC ($\beta = 0.384$, $p < 0.001$) and substantially mediates the HRA $\rightarrow$ EC relationship, providing the first PLS-SEM-based empirical confirmation of practice-theoretic mediation in a hot-arid MENA setting. The serial mediation USI $\rightarrow$ HRA $\rightarrow$ LS $\rightarrow$ EC ($\beta = 0.183$) is the most analytically consequential finding of the study and the one with the sharpest policy implications. EC subsequently predicts Environmental Degradation Awareness ($\beta = 0.207$), suggesting that households' direct experience of high bills and thermal discomfort correlates with heightened perception of broader environmental problems, a result consistent with the perception-behaviour literature (Ewing & Hamidi, 2015; Genovese et al., 2023; Subasinghe et al., 2016) and indicative of a latent constituency for demand-side environmental policy among Erbil's apartment-dwelling population (Abbas, 2018; UNESCO World Heritage Centre, 2014). We note that household-level factors such as income, education, household size, dwelling age, and tenure are plausible alternative explanations for the energy and awareness outcomes; controlling for these in a respondent-level dataset is recommended, and the directional reading here is therefore offered as a predictive rather than a definitive causal account.

Erbil presently lacks any functional TOD infrastructure: no urban rail, no BRT, only nascent fixed-route buses, making TOD methodologically inadmissible as an empirical PLS-SEM construct. It is nonetheless retained here as a *theoretical policy benchmark* against which Erbil's business-as-usual (BAU) trajectory can be evaluated.

International evidence for TOD's potential is well established. Ashik et al. (2022) found significant transport-CO₂ reductions for work and school trips in Dhaka's TOD neighbourhoods. Fan et al. (2025) identify 2,000–2,500 persons/km² density and 0.8–0.9 land-use-mix entropy as carbon-neutrality accelerators across 340 Chinese cities. Ibraeva et al. (2020) conclude that TOD's energy and emission benefits are conditional on integrated land-use-transit planning. Erbil's BAU trajectory replicates the Tehran signature documented by (Bokaie et al., 2016; Talkhabi et al., 2022), demographic inflation outpaced by physical expansion, with attendant urban-heat-island intensification. The sprawl $\rightarrow$ HRA $\rightarrow$ LS $\rightarrow$ EC chain demonstrated in Section 5 suggests that without TOD principles introduced *before* motorisation calcifies, aggregate residential energy will continue rising with sprawl intensity, regardless of building-envelope improvements.

6.2 Comparative Context and Contributions

Placing the Erbil findings in comparative context clarifies both their specificity and their transferability. Tehran offers the closest demographic and climatic analogue. The four-stage demographic analysis of the Tehran Metropolitan Region (Talkhabi et al., 2022) documents exactly the urban-growth-sprawl decoupling Erbil now exhibits, and the LST–LULC analysis (Bokaie et al., 2016) demonstrates that such decoupling produces measurable urban-heat-island consequences. The Erbil case extends this evidence base by modelling, via PLS-SEM, the behavioural-mediating pathway that Tehran studies have hypothesised but not empirically tested.

Dhaka, analysed by Ashik et al. (2022), provides the most rigorous empirical baseline for benchmarking Erbil's hypothetical future TOD performance. Its finding that TOD reduces transport-CO₂ for work and school trips but not for non-work trips transfers directly to Erbil, where commuting is expected to dominate aggregate vehicle-kilometres. The implication is that TOD's carbon benefits in Erbil, were the infrastructure introduced, would likely be front-loaded on commuting reduction rather than spread evenly across the trip portfolio, reinforcing the case for corridor-specific rather than network-wide implementation.

Gulf cities — particularly as analysed by Abulibdeh in Qatar and across eight arid and semi-arid GCC cities (Abulibdeh, 2021; Patel et al., 2024) — establish the upper bound of typological and thermal stress that Erbil could approach under unchecked BAU continuation.

The rapid pace of built-up growth in Dubai compared to the almost nonexistent growth of green areas is the model that Erbil now appears to be following as it develops outwards. The results from studying Erbil thus place it importantly in between: the behavioural patterns are like those of Tehran; the potential for future transit-oriented development would be like what has occurred in Dhaka; and thermal-stress risks are already similar to those in the Gulf. These comparative attributes yield policy implications specific to each location rather than generic ones.

This research has three main contributions, each of which extends beyond its empirical Erbil claim. The first (methodological) contribution is the successful operational integration of macro-scale GIS-based sprawl measurement with micro-scale PLS-SEM-based behavioural analysis within one convergent parallel mixed-methods research design (Creswell & Plano Clark, 2017). It generates two complementary data streams in which both bodies of evidence support and contextualise one another without the methodological problems of forcing them together into a single aggregate model; the second indicates that practice theory is (theoretically) quantitatively operable, not just evoked in variance-based SEM when the practice-shift construct is defined as a retrospectively explicit contrast — as evident in Table 9, where the statistically significant indirect effect through LS (H5) provides direct support for the assertion (Shove et al., 2012) that materials, competences, and meanings are the mechanism by which built-infrastructure change converts into energy-behaviour change. The previous literature provides this evidence as a theoretical assertion but rarely has it been quantitatively verified.

The third (empirical) contribution is that the study is among the first to present a sprawl-to-energy elasticity estimate, using both Landsat-derived geospatial data and survey data from households. The size of the measured effects allows empirical rather than anecdotal comparison with Tehran (Talkhabi et al., 2022), Gulf cities (Abulibdeh, 2021; Patel et al., 2024), and Dhaka (Ashik et al., 2022), and provides a reproducible benchmark for successor studies in Sulaymaniyah, Duhok, and comparable MENA settings.

6.3 Policy Recommendations, Limitations, and Conclusions

Five propositions follow from the findings, adapted to Erbil's current infrastructural realities:

- (1) Prepare for TOD in the next master-plan cycle. The 5Ds, density, diversity, design, destination accessibility, distance to transit, should become binding design criteria for the three radial corridors (120 m Street, Kirkuk Road, Dohuk Road) before motorisation calcifies retrofit costs.
- (2) Institute a Residential Typology Impact Assessment. High-rise proposals above ten storeys should submit a standardised lifestyle-and-energy forecast calibrated against this study's H1–H6 coefficients, with mandatory consideration of the documented USI → HRA → LS → EC

pathway.

- (3) Codify the Citadel buffer zone. Strict height and use-mix codes aligned with the UNESCO revitalisation agreement (Abbas, 2018, 2019) will pre-empt the fate of other MENA heritage cores.
- (4) Mandate residential energy disclosure. U-values, AC-load projections, and post-occupancy lifestyle profiles at point of sale or lease will create demand-side pressure for efficient stock, addressing the LS → EC pathway directly.
- (5) Build longitudinal data infrastructure combining GIS and survey data. The KRG Ministry of Municipalities should support successor studies that triangulate the Landsat-derived LULC time series with meter-level energy data and household behavioural surveys.

There are six limitations that should be acknowledged. First, because the PLS-SEM was designed as a cross-sectional analysis, strict counterfactual inferences cannot be made with these data; directional claims are limited by theoretical ordering; however, the longitudinal GIS analyses at the macro-scale partially compensate by establishing temporal precedence at the macro scale. Second, all PLS-SEM constructs rely on self-reporting; meter-level validation will be the focus of future research. Third, the original specification exhibited an EC–LS HTMT of 0.976; the re-specified model resolves this (EC–LS = 0.825), though future replications should continue to monitor the conceptual proximity of lifestyle and energy measures. Fourth, as discussed above, the effects of TOD are not available for testing through empirical means (Ashik et al., 2022; Fan et al., 2025). Fifth, findings are specific to Erbil's semi-arid climate and KRG governance context; cross-MENA generalisability requires replication. Sixth, the LULC classification is validated qualitatively — through visual cross-checks against epoch-matched reference imagery, logical-consistency screening of class transitions, and triangulation with independent published studies — rather than through a formal confusion-matrix statistic, because reference data sufficient for a stratified-random accuracy sample are unavailable for the archival epochs; the coarse three-class scheme and the corroborative (rather than inferential) role of the GIS strand bound the impact of residual classification error, and successor studies with contemporary ground-truthing are planned.

Four extensions are prioritised: (i) triangulation of self-reported EC with meter-level or utility-company data; (ii) multi-group SEM comparing apartment, villa, and courtyard residents to formalise typology differences, integrating their GIS-mapped neighbourhoods; (iii) a longitudinal panel tracking households across future TOD pilot interventions, combining annual GIS LULC updates with repeated household surveys; and (iv) extension to Sulaymaniyah, Duhok, and comparable MENA cities, replicating the integrated GIS and PLS-SEM methodology.

Erbil's post-2003 transformation is neither inevitable nor irreversible. The evidence assembled, 184.6 % expansion of urban land cover documented through multi-temporal GIS classification, and a fully specified PLS-SEM behavioural pathway from urban sprawl through high-rise adoption and lifestyle reconfiguration to household energy consumption and environmental awareness, indicates that the city's trajectory is shaped at three scales: macro-scale master-plan choices visible in the Landsat record, meso-scale typology approvals expressed in the new high-rise stock, and micro-scale household practices captured in the survey instrument. The PLS-SEM results reveal these three scales to be closely linked. A sustainable Erbil requires coherent action at all three scales. The citadel at the city's heart, now under renewed UNESCO protection, stands as a structural reminder that the city's future, like its history, is being authored today by choices still reversible. Theoretically, the study shows that the practice–infrastructure mismatch — vertical material infrastructures meeting practices calibrated to horizontal living — is the mechanism that converts macro-scale sprawl into micro-scale energy demand, extending social-practice theory into a quantitative, variance-based setting and linking it to the urban economics of residential transformation.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

Data Availability Statement

Data are available upon request.

Institutional Review Board Statement

This study involved an anonymous, voluntary household survey of adult respondents, conducted in accordance with the ethical principles of the Declaration of Helsinki. Informed consent was obtained from all participants before participation, no personally identifying information was collected, and respondents were free to withdraw at any time without penalty. Formal ethical review and approval were not required for this non-interventional perception survey in accordance with the applicable institutional and national regulations.

CRedit Author Statement

Shad Sherzad Jawhar: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. Sarko Hassan Sleman: Investigation, Resources, Data curation, Writing – review & editing. Cemil Atakara: Supervision, Validation, Project administration, Writing – review & editing. All authors have reviewed and approved the final version of the manuscript.

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