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Assessing New Urbanism–Transit-Oriented Development Principles in Al Malqa District, Riyadh: Adaptations for Sustainable Development Under Saudi Vision 2030

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Abstract

This study develops and applies an adapted New Urbanism–Transit-Oriented Development (NU–TOD) framework to evaluate spatial, functional, and climatic performance in Al Malqa District, Riyadh. Integrating NU–TOD principles with hot-arid microclimate research, Saudi sociocultural norms, and Vision 2030 governance, the study employs a convergent mixed-methods design that combines Geographic Information Systems (GIS)-based land-use and network analyses, shading and microclimate indicators, and policy review. Results show that Al Malqa benefits from strong civic anchors and proximity to a Line 1 metro station but exhibits limited walkability, low station-area densities, constrained mixed-use intensity, and insufficient shading, which together reduce effective walking catchments and transit viability. A phased intervention strategy is proposed: short-term shading and feeder-mobility improvements; medium-term TOD zoning, parking reform, and public-realm upgrades; and long-term mixed-use redevelopment and district-scale green infrastructure. A reproducible Multi-criteria Decision Analysis (MCDA) feasibility assessment (impact, regulatory ease, cost, timeline) prioritises shaded pedestrian corridors and feeder mobility as the most implementable early actions. The study contributes a replicable evaluation model for hot-arid cities and offers actionable guidance for Vision 2030, aligned with suburban intensification in Riyadh.

Keywords: urban morphology; station-area accessibility; thermal comfort; microclimate indicators; mixed-use intensity; pedestrian connectivity; arid-climate urbanism; governance capacity; feasibility assessment

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1. Introduction

Urban form and mobility patterns fundamentally shape how cities function, influencing social interaction, environmental performance, and economic vitality. Since the late twentieth century, New Urbanism (NU) has emerged as a leading planning paradigm that critiques low-density, car-dependent suburbanisation and advocates for compact, mixed-use, walkable neighbourhoods supported by civic anchors and human-scaled public realms [1–4]. Foundational NU texts, including the Charter of the New Urbanism [3], Suburban Nation [2], and Katz's architectural synthesis [4], codify principles such as permeability, block structure, land-use mix, housing diversity, and the integration of civic institutions. These principles have been widely applied in Western contexts, where empirical studies demonstrate associations between NU-aligned form and improved walkability, public health, and local economic performance [5–9].

Complementing NU, Transit-Oriented Development (TOD) provides a land-use and governance framework that links density, diversity, and design (the "3Ds") to transit accessibility and modal shift [10,11]. TOD scholarship emphasises zoning reform, parking management, first/last-mile connectivity, and coordinated public investment as essential mechanisms for converting transit infrastructure into compact, mixed-use, high-activity districts [6,12–16]. Together, NU and TOD offer a coherent theoretical basis for evaluating neighbourhood form and identifying interventions that support walkability, transit viability, and sustainable urban development.

NU's normative goals-walkability, mixed use, social diversity, and civic life translate into operational constructs that can be measured and compared across contexts. These include block length and intersection density (permeability), active frontage ratios, land-use mix indices, housing tenure and typology diversity, and distribution of civic anchors such as mosques, schools, and parks [1,3,7,17–20]. These critiques underscore the need for transparent, measurable indicators that capture both physical form and social outcomes. Despite their global influence, NU and TOD frameworks were largely developed in temperate Western contexts, raising questions about their applicability in hot-arid climates and culturally conservative societies. Riyadh exemplifies these challenges. Extreme summer temperatures exceeding 40–43 °C, high solar radiation, and low humidity significantly reduce comfortable walking distances unless shading, vegetation, and microclimate interventions are provided [21,22]. Regional studies show that thermal-comfort variables are as important as distance in determining walkability [22–27].

Cultural norms also shape public-realm design. Privacy expectations, gendered patterns of public space use, mosque-centred social life, and family-oriented leisure require adaptations to conventional NU typologies [17,28–30]. Traditional Arabian forms offer climate-responsive precedents, but contemporary suburban development prioritises low-density villas and car access [29,31,32]. These climatic and cultural modifiers necessitate context-specific adaptation of NU/TOD benchmarks rather than direct transfer.

Riyadh is undergoing rapid transformation under Saudi Vision 2030, which positions livability, sustainability, and economic diversification as national priorities [22,23,33]. Major municipal programmes, including the Riyadh Metro, Green Riyadh, and new urban design and streetscape manuals, signal a shift toward more walkable, transit-enabled, and climate-responsive urbanism [24–27]. However, suburban expansion and automobile dependence persist [31,34–37]. Seasonal cultural events such as Riyadh Season generate concentrated pedestrian activity and highlight the latent demand for high-quality public space [22,30].

These dynamics create a policy window for testing how NU/TOD principles can be adapted to Riyadh's climatic, cultural, and governance realities. Yet empirical evaluations of NU/TOD in Saudi Arabia remain limited, and few studies provide transparent, reproducible indicator frameworks that integrate microclimate, cultural norms, and governance capacity.

Despite the extensive global literature on NU and TOD, there is no established, operationalised framework for evaluating NU principles in hot-arid, culturally specific contexts such as Riyadh. Existing studies either focus on macro-scale urban expansion [31,34,36,37], micro-cale walkability modelling [26], or policy-level analyses of Vision 2030 [23,33,38], but none provide a criterion-by-criterion district-scale assessment that integrates:

1. NU/TOD design principles.
2. Thermal-comfort and microclimate indicators.
3. Cultural and social-use patterns.
4. Governance and implementation feasibility.

This gap limits the ability of municipal actors and developers to prioritise interventions that are both climatically effective and culturally appropriate.

This study develops and applies an adapted New Urbanism–Transit-Oriented Development (NU–TOD) evaluation framework to Al Malqa, a suburban district in Northern Riyadh characterised by a Line 1 metro station, substantial civic infrastructure, and immediate adjacency to the Riyadh Boulevard Zone. The research is motivated by a core problem: while New Urbanism offers a coherent set of principles for walkable, mixed-use, socially cohesive neighbourhoods, its direct application in Saudi residential districts is constrained by climatic, cultural, and governance realities. As Riyadh advances its sustainable development agenda under Vision 2030, there is a growing need to adapt NU principles, originally developed in temperate Western contexts, to the spatial practices, microclimatic conditions, and institutional structures of Saudi cities.

The study therefore seeks to operationalise NU principles into measurable, context-sensitive indicators adapted for hot-arid climates and Saudi sociocultural norms; evaluate Al Malqa across nine NU-derived criteria using Geographic Information Systems (GIS)-based spatial metrics and municipal datasets; and propose a sequenced, feasibility-based intervention package aligned with Vision 2030 and Riyadh's governance and market conditions.

The paper makes three contributions. Methodologically, it offers a transparent, multi-sourced indicator framework with explicit scoring and harmonisation rules that reduce subjectivity in NU assessments and support reproducibility [1,39,40]. Empirically, it delivers a detailed district-scale diagnosis of a Riyadh neighbourhood that is civic-rich but density-poor and climate-challenged yet transit-enabled, filling a gap in Gulf city NU/TOD evidence [4,5,41]. Practically, it provides a phased intervention roadmap, with short-, medium-, and long-term measures ranging from shaded corridors to TOD zoning and inclusionary housing, grounded in feasibility analysis and local governance realities to aid municipal decision-making and Vision 2030 implementation [12,42–45].

2. Local Context: Saudi Urbanisation and Riyadh

2.1. Policy Environment and Vision 2030

Saudi Arabia's Vision 2030 positions urban transformation as a central pillar of national development, emphasising livability, sustainability, economic diversification, and improved quality of life [22,23,33]. Within this framework, Riyadh is undergoing a major strategic repositioning, supported by large-scale public investments and regulatory reforms. The Royal Commission for Riyadh City (RCRC) has translated national priorities into metropolitan initiatives such as the Riyadh Metro, the Green Riyadh Programme, and updated urban design and streetscape manuals intended to guide station-area development and public-realm improvements [24,25,27]. These initiatives reflect a shift from traditional expansion-driven planning toward sustainable, transit-enabled, and climate-responsive urbanism [9,23]. Their effectiveness, however, depends on zoning reform, implementation capacity, and cross-agency coordination, which remain uneven across the metropolitan governance landscape [37,42,46].

2.2. Climatic Constraints and Implications for Design

Riyadh's hot-arid climate imposes severe constraints on walkability and outdoor activity. Summer temperatures frequently exceed 40–43 °C, with high solar radiation and low humidity, producing extreme thermal stress for pedestrians [47–49]. Empirical studies across the Gulf and wider MENA region demonstrate that thermal-comfort variables, shade continuity, street orientation, vegetation, evaporative cooling, and surface albedo are as important as horizontal distance in determining walkability [43,50–53].

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Recent research in Riyadh and other Saudi cities highlights the need for microclimate-responsive design, including:

- Continuous shading (≥60% on primary pedestrian routes) [47,51,52].
- Covered arcades and colonnades [49,50].
- High-albedo materials and heat-mitigating surfaces [51].
- Xeric vegetation and water-efficient greening [39,40,53,54].
- Shade-oriented routing and dynamic pathfinding [52].

These conditions require recalibrating NU/TOD benchmarks, particularly walking-catchment assumptions, to reflect thermal comfort rather than distance alone [26]. As a result, microclimate indicators must be integrated into any operational evaluation of NU principles in the city.

2.3. Cultural Norms and Spatial Practices

Urban form and public-realm use in Riyadh are strongly conditioned by social norms around privacy, gendered movement patterns, mosque-centred communal life, and family-oriented leisure. Traditional Arabian morphologies, courtyard houses, shaded souqs, narrow alleys and covered walkways, historically reconciled climatic and social requirements by providing semi-private outdoor spaces and thermally moderated circulation routes that supported everyday social interaction while protecting privacy and gendered norms. These precedents illustrate how spatial configuration can simultaneously address comfort, privacy, and social expectations [17,34,35].

Contemporary suburban development in Riyadh, however, has tended toward detached villas, gated compounds and automobile-oriented layouts, producing large plots, low plot ratios and limited opportunities for incidental social encounters. These patterns limit mixed-use street life and reduce the effectiveness of station-area intensification unless design and policy interventions explicitly reconcile market preferences with cultural norms [2,37,55]. In districts such as Al Malqa, the predominance of private green space over distributed public greenery further limits street-level amenity and thermal comfort. Culturally sensitive public-realm interventions, mosque-anchored nodes, shaded family parks, gender-appropriate programming, and semi-private thresholds are therefore essential for adapting NU principles to local spatial practices [4,17,25,26,34].

2.4. Urban Structure, Mobility, and Recent Infrastructure Investments

Riyadh's urban expansion since the 1970s has been characterised by low-to-moderate densities, hierarchical arterial networks, and high dependence on private vehicles [25,31,34,36]. The city's spatial structure has produced fragmented land-use patterns and limited walkability, with most daily activities requiring car travel.

The Riyadh Metro, a six-line, citywide rapid transit system, represents a transformative investment intended to shift mobility patterns and support TOD [12,26]. However, international evidence shows that transit infrastructure alone is insufficient; supportive zoning, parking reform, and first/last-mile connectivity are required to generate compact, mixed-use station areas [10–12,15].

In Riyadh, the metro's potential is amplified where municipal design guidance and public-realm investment (e.g., Green Riyadh) are coordinated with zoning changes and incentives for higher-density, mixed-use development [24,27,37]. These synergies are particularly relevant for districts like Al Malqa, where transit access and emerging commercial corridors create favourable conditions for TOD.

2.5. Land Market Dynamics and Housing Patterns

Land markets in Northern Riyadh, including Al Malqa, have historically favoured low-rise villa development on large plots, resulting in low plot ratios and housing products primarily targeted at middle- and upper-income households. These entrenched patterns limit the feasibility of mid-rise, mixed-use typologies near transit without proactive public intervention [37,41,56]. Principal market and supply-side constraints observed in Al Malqa are: fragmented parcelisation and limited opportunities for land assembly; elevated land values along commercial corridors; developer preference for lower-risk villa typologies; and weak financial or regulatory incentives for the delivery of mixed-use or affordable housing [28,31,55]. Although vacant and under-utilised parcels adjacent to the Line 1 metro station present strategic infill opportunities, realising TOD-oriented redevelopment will require coordinated measures, regulatory reform, density bonuses, inclusionary housing instruments, and structured public–private partnerships, to overcome parcel fragmentation and market risk [12,20,43].

2.6. Governance, Institutional Capacity, and Implementation Challenges

Delivering NU-aligned TOD in Riyadh depends on effective coordination across national agencies, the RCRC, municipal departments and private developers. Key governance challenges include fragmented institutional responsibilities, legacy zoning regimes that privilege low-density residential forms, limited mechanisms to enforce design codes or mixed-use requirements, and the absence of dedicated district-level governance structures to coordinate transit, public-realm and land-use decisions [12,20,28,37,43,45,47,52,57]. International TOD experience highlights the importance of sustained governance continuity, zoning reform, parking management and targeted public-realm investment for successful station-area transformation [7,22,23]; in Riyadh, these instruments must be adapted to local political–economy conditions and operationalised through coordinated district mechanisms (for example, TOD task forces or special planning zones) to be effective. Collectively, the market and governance conditions described here motivate the context-specific conceptual framework presented in Section 3, which integrates NU theory, TOD mechanisms, arid-climate considerations and Saudi governance realities. Detailed spatial definitions of the Al Malqa study area, sub-zone geometry, metro catchments, and data provenance are provided in Section 4.1 (Case Study: Al Malaqa District).

3. Theoretical Framework

3.1. New Urbanism: Foundations, Evaluation, and Critiques

New Urbanism (NU) emerged in the late twentieth century as a response to the social, environmental, and spatial consequences of post-war suburbanisation. Foundational works such as the Charter of the New Urbanism [3], Duany, Plater-Zyberk and Speck's Suburban Nation [2,58], and Katz's architectural synthesis [4] articulate a coherent set of principles centred on walkability, mixed land uses, human-scaled streets, housing diversity, and the integration of civic anchors. These ideas build on earlier urbanist traditions, including Jacobs' advocacy for street-level vitality [8] and Gehl's human-centred public-realm theory [9], which emphasise fine-grained urban form and active ground-floor environments as foundations of vibrant neighbourhoods. Over time, NU has evolved from a normative movement into a more empirically grounded planning paradigm, with operational constructs such as block permeability, land-use mix, proximity to daily needs, and the distribution of civic institutions forming the basis for measurable evaluation frameworks [19,20].

Despite its influence, NU has been subject to sustained critique. Talen argues that NU's social goals, particularly diversity and inclusion, are often under-realised without explicit policy instruments such as inclusionary zoning or tenure diversification [1]. Day highlights the challenges of designing for diversity in culturally heterogeneous contexts [46], while Trudeau questions whether NU can be considered sustainable development without stronger socio-economic safeguards [55]. Ellis synthesises critiques around market capture, gentrification, and the risk that form-based interventions alone may not deliver equitable outcomes [41]. These debates underscore the need for transparent, reproducible frameworks that integrate social and governance dimensions alongside physical form, especially when NU is transferred to non-Western contexts. In Saudi Arabia, early work by Saleh [28] and Naim [29] demonstrates that NU-aligned neighbourhood transformations require adaptation to local social norms and environmental conditions, highlighting the importance of contextualisation.

3.2. Transit-Oriented Development and Sustainable Mobility

Transit-Oriented Development (TOD) complements NU by providing a land-use and governance framework that links density, diversity, and design, the "3Ds", to transit accessibility and modal shift. Seminal studies by Cervero and Kockelman [10] and Ewing and Cervero [11] demonstrate that compact, mixed-use, transit-accessible environments are associated with reduced automobile dependence and increased transit ridership. TOD scholarship emphasises enabling mechanisms such as zoning reform, parking management, first/last-mile connectivity, and coordinated public investment [12,13,15,16]. Comparative work on European and North American regions shows that integrated land-use and transport planning, combined with parking and pricing policies, can significantly shift travel behaviour [13]. More recent TOD evaluation methods, including index-based and corridor-scale approaches, provide structured tools for assessing station areas and prioritising interventions [15,16,44].

In the Gulf context, TOD is increasingly framed as a lever for sustainable urban renewal. Mazzetto et al. show how TOD principles can guide redevelopment around Riyadh's metro stations but emphasise that transit infrastructure alone is insufficient without regulatory reform, governance coordination, and public-realm investment [12]. Jarrar and Al-Homoud similarly demonstrate that walkability and transit accessibility in Riyadh depend heavily on microclimate design and pedestrian-friendly streets [26]. These findings reinforce the view that TOD mechanisms must be embedded within broader institutional and design frameworks to deliver durable, neighbourhood-scale change.

3.3. Walkability, Urban Form, and Measurement Frameworks

A substantial body of research has focused on operationalising walkability and urban form as measurable indicators. Frank et al. developed a widely used walkability index that combines land-use mix, residential density, and street connectivity [19], while Ewing et al. identified urban design qualities, imageability, enclosure, human scale, transparency, and complexity that correlate with pedestrian activity and can be systematically assessed [20]. Studies by Leslie et al. and others further highlight the importance of residents' perceptions of walkability attributes, suggesting that objective metrics should be complemented by experiential dimensions [39]. This literature converges on several methodological principles: the use of network-based accessibility rather than simple Euclidean buffers, harmonised density measures, and mixed-methods designs that combine GIS analysis with qualitative or perceptual data.

In parallel, multi-criteria decision analysis (MCDA) has gained prominence as a means of structuring complex urban evaluations and prioritising interventions. Reviews by Bousquet et al. and Mecca show how MCDA frameworks are increasingly used to assess urban sustainability, green infrastructure, and planning alternatives [45,59]. Applications in Saudi and regional contexts demonstrate the potential of combining GIS with MCDA to evaluate road networks, green space provision, and urban development scenarios [57,60].

These approaches provide methodological guidance for indicator selection, weighting, and scoring, elements that are directly relevant to constructing a transparent, reproducible evaluation framework for NU/TOD in Riyadh.

3.4. Hot-Arid and Culturally Specific Urbanism

In hot-arid climates, walkability is fundamentally shaped by thermal comfort. Empirical studies across the Gulf and wider MENA region show that shade continuity, street orientation, vegetation, evaporative cooling, and surface albedo significantly influence outdoor thermal comfort and pedestrian behaviour [47,61]. Wen et al. demonstrate the importance of shade-oriented routing in arid cities [52], while Binabid and colleagues highlight the cooling effects of greenery in Saudi residential zones [43,62]. Research on outdoor thermal comfort in Riyadh, Jeddah, Dhahran, and other regional cities confirms that microclimate interventions, such as shading devices, tree canopies, and reflective or high-albedo materials, can substantially improve pedestrian conditions [40,43,61,63]. These findings challenge the universality of conventional NU/TOD benchmarks, such as 800-metre walking catchments, by showing that climatic conditions can reduce effective walking distances unless microclimate design is embedded in the public realm.

Cultural norms further shape the design and use of public space in Saudi Arabia. Privacy expectations, gendered patterns of public-space use, mosque-centred social life, and family-oriented leisure influence both the acceptability and functionality of public-realm typologies [17,28]. Traditional Arabian urban forms, courtyards, shaded souqs, covered walkways, and mosque forecourts, offer climate-responsive precedents that reconcile social and environmental needs [17,28,53]. However, contemporary suburban development in Riyadh has often prioritised detached villas, gated communities, and automobile access, producing spatial patterns that limit incidental social interaction and constrain the kinds of mixed-use street life promoted by NU [31,34,36]. This tension between traditional spatial practices, modern suburban forms, and imported planning models underscores the need for context-specific adaptation of NU/TOD principles.

3.5. Comparative Western Case Studies and Transferability

Comparative Western cases provide mechanism-level evidence for how NU and TOD principles operate in practice and therefore offer valuable insights for contextual adaptation. Seaside, Florida, is frequently cited as an early exemplar of NU, demonstrating how compact grids, mixed-use town centres, and design covenants can generate walkable, human-scaled environments with a strong sense of place [64,65]. The Portland Pearl District illustrates how rail-adjacent regeneration, supported by upzoning, public–private partnerships, and targeted public-realm investment, can catalyse mixed-use intensification and transit ridership [7]. The Rosslyn–Ballston corridor in Arlington, Virginia, provides a corridor-scale example of TOD implementation, showing how coordinated zoning reform, parking management, and phased densification can concentrate employment and housing around high-capacity transit [13]. Although these cases differ in scale and governance context, they reveal a consistent set of transferable mechanisms, zoning and regulatory change, public-realm investment, parking reform, and governance continuity, that underpin successful NU/TOD outcomes. At the same time, their climatic, cultural, and institutional conditions differ markedly from those of Riyadh, underscoring the need for adaptation rather than replication. These cases, therefore, serve as mechanism guides that inform benchmark selection and intervention design in this study, rather than prescriptive templates.

3.6. Conceptual Synthesis and the Adapted NU-TOD Framework

The strands of literature reviewed above converge on several key insights that inform the conceptual framework of this study. NU and TOD provide complementary lenses for understanding and shaping neighbourhood form: NU offers a fine-grained design grammar centred on walkability, mixed use, and civic structure, while TOD supplies the land-use, mobility, and governance mechanisms needed to support transit-oriented, compact development [2,4,12]. Walkability and urban form research underscore the importance of transparent, reproducible indicators and mixed-methods approaches that capture both spatial structure and experiential qualities [19,20,45,57,59,60]. Hot-arid and the culturally specific urbanism literature demonstrates that climatic and cultural modifiers, thermal comfort, shading, greenery, privacy norms, and mosque-centred social life fundamentally reshape the interpretation and application of NU/TOD principles in Riyadh. Finally, studies of Riyadh's urban transformation and governance highlight both the constraints of existing suburban patterns and the policy window created by Vision 2030, major infrastructure investments, and emerging sustainability agendas [23,25,33,35].

Synthesising these insights, the study develops an adapted NU–TOD framework tailored to Riyadh's climatic, cultural, and institutional context. The framework identifies a set of criteria that collectively capture neighbourhood structure, land-use mix, accessibility, housing diversity, transit integration, civic anchors, urban design quality, and green infrastructure, while explicitly incorporating microclimate performance and governance feasibility. Each criterion is linked to measurable indicators and benchmark ranges derived from the literature and is embedded within a scoring logic informed by MCDA approaches. This conceptual synthesis provides the theoretical and methodological foundation for the district-scale evaluation of Al Malqa presented in the subsequent methodology and results sections.

4. Materials and Methods

This study adopts a convergent mixed-methods design integrating quantitative spatial analysis, qualitative policy review, and multi-criteria evaluation to operationalise the adapted NU–TOD framework developed in Section 3. Mixed-methods approaches are widely recommended in urban form and walkability research because they allow spatial metrics to be interpreted within governance, cultural and climatic contexts [19,20,59]. This is particularly relevant in Riyadh, where climatic modifiers, cultural norms and institutional arrangements significantly shape the feasibility and performance of NU/TOD principles [34,35,44,46,48,50].

The methodological structure follows established practice in TOD evaluation [12,15,16], walkability measurement [19,20], and MCDA-based urban assessment [45,59,60]. It comprises: (1) definition of the study area and spatial frame; (2) construction of indicators and benchmarks; (3) harmonised measurement rules; (4) scoring and aggregation; (5) feasibility assessment; and (6) data provenance and validation.

All spatial datasets, processing steps and parameter files are documented in Appendices A.1–A.4, and benchmark sources are cited where they inform thresholds and calibration choices [2–4,12,15,16,22–25,31–33,59,60,66,67]. Spatial analysis and mapping were conducted using ArcGIS Pro 3.2 and QGIS 3.34. Network-based accessibility calculations were performed using Python 3.10 routing scripts, and microclimate indicators were processed using GIS-based spatial overlays and AutoCAD 2024 tools for diagram refinement. All datasets were harmonised and georeferenced using municipal GIS base layers.

4.1. Case Study: Al Malaqa District

4.1.1. Conceptual Framework for Evaluating Al Malaqa District

The conceptual framework diagram illustrated in Table 1 visually synthesises the literature into a structured evaluation model. It links four theoretical inputs, New Urbanism principles, TOD mechanisms, arid-climate urbanism, and Saudi governance and cultural context to the nine adapted evaluation criteria, the indicator system, the scoring logic, and the feasibility assessment.

Table 1. NU-TOD evaluation framework Al—Malaqa fact sheet (Source: Elaborated by authors).

	Al-Malaqa Evaluation Framework
THEORITICAL INPUTS	1 New Urbanism (NU) Principles
	Walkability, mixed use, block permeability, human-scaled streets, housing diversity, civic anchors [1,4,19,20].
	2 Transit-Oriented Development (TOD) Mechanisms
	Density, diversity, design (3Ds); zoning reform; parking management; first/last-mile connectivity; governance coordination.
	3 Hot-Arid Climate and Microclimate Urbanism
	Shade continuity, street orientation, vegetation, evaporative cooling, surface albedo, thermal-comfort thresholds.
	4 Saudi/Gulf Cultural and Governance Context
	Privacy norms, mosque-centred social life, gendered public-space use; Vision 2030; RCRC regulatory environment; suburban land-market patterns [17,21,23–25,28,29,32,35–38,42,46,56,68].
SYNTHESIS LAYER: ADAPTATION LOGIC	A Climatic Adaptation
	Recalibration of walkability benchmarks for thermal comfort. Integration of shading, greenery, and microclimate indicators.
	B Cultural Adaptation
	Incorporation of mosque forecourts, privacy-sensitive public-realm typologies, and gender-appropriate spatial programming.
	C Governance Adaptation
	Alignment with Vision 2030, RCRC design manuals, zoning practices, and implementation capacity.
	D Mechanism Transferability
	Western NU/TOD mechanisms (zoning reform, public-realm investment, parking management, PPPs) adapted to Riyadh's climatic, cultural, and institutional context [7,44,48,52,55,60].
NINE ADAPTED EVALUATION CRITERIA	1 Neighbourhood Structure (NU). 2 Mixed-Use Intensity and Land-Use Mix (NU/TOD). 3 Daily Needs Accessibility (NU). 4 Housing Diversity and Affordability (NU). 5 Transit Integration and Station-Area Organisation (TOD). 6 Transit-Supportive Density (TOD). 7 Civic and Institutional Anchors (NU/Saudi context). 8 Urban Design Quality and Public Realm (NU + microclimate). 9 Green Infrastructure and Microclimate Performance (arid-urbanism). Each criterion is linked to: • Indicators (quantitative + qualitative). • Benchmark ranges (Western evidence + Riyadh adaptation). • Data sources (GIS, municipal data sets, market data). • Scoring logic (3-tier alignment).

Table 1. *Cont.*

	Al-Malaqa Evaluation Framework
SCORING	Indicator scoring (1–3 scale) • Criterion aggregation. • Domain grouping (Form, Access, Social/Economic, Climate, Governance). • Composite performance profile for Al Malqa.
⇩	
FEASIBILITY [MCDA]	• Impact (40%). • Regulatory ease (30%). • Cost (20%). • Timeline (10%). [45,59,60]
⇩	
OUTPUTS	• District-scale performance assessment (Section 5). • Prioritised intervention package (Section 6). • Policy and design recommendations aligned with Vision 2030 (Section 7).

The framework synthesises four theoretical inputs, New Urbanism principles, Transit-Oriented Development mechanisms, hot-arid climate and microclimate research, and Saudi/Gulf cultural and governance context, into nine adapted evaluation criteria. These criteria are operationalised through measurable indicators, benchmark ranges, and a three-tier scoring logic, supported by a feasibility assessment based on multi-criteria decision analysis. The framework integrates Western mechanism-level evidence [7,23–25,29,35–38,47,48,52,55,56,63,64], with Riyadh-specific climatic, cultural, and institutional modifiers [23–25,29,35–38,55,56], enabling a context-sensitive evaluation of Al Malqa District, Figure 1, Table 1.

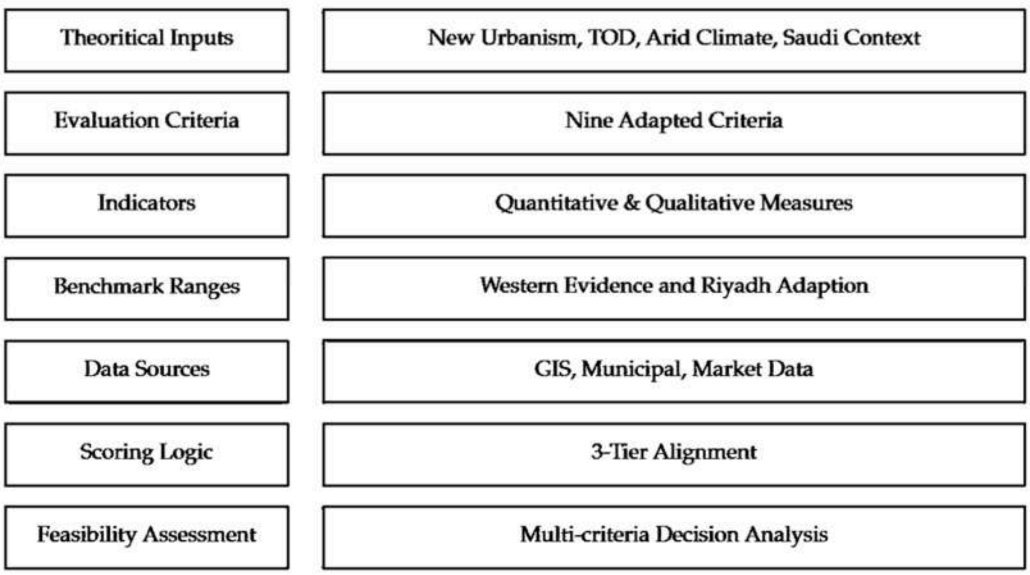

Figure 1. Evaluation framework. Source: Authors, based on [23–25,29,35–38,47,55,56].

4.1.2. Overview and Purpose

Al Malqa is a 21.85 km^2 residential district in Northern Riyadh (Figure 2) that developed during the city's early-2000s expansion, shaped by rapid population growth and rising demand for high-quality suburban living [25,34,35]. The district accommodates 87,931 residents, predominantly middle- to upper-income Saudi families and expatriates, and is characterised by villas, mid-rise apartments and gated compounds, patterns consistent with Riyadh's suburban development trajectory [35,37,50].

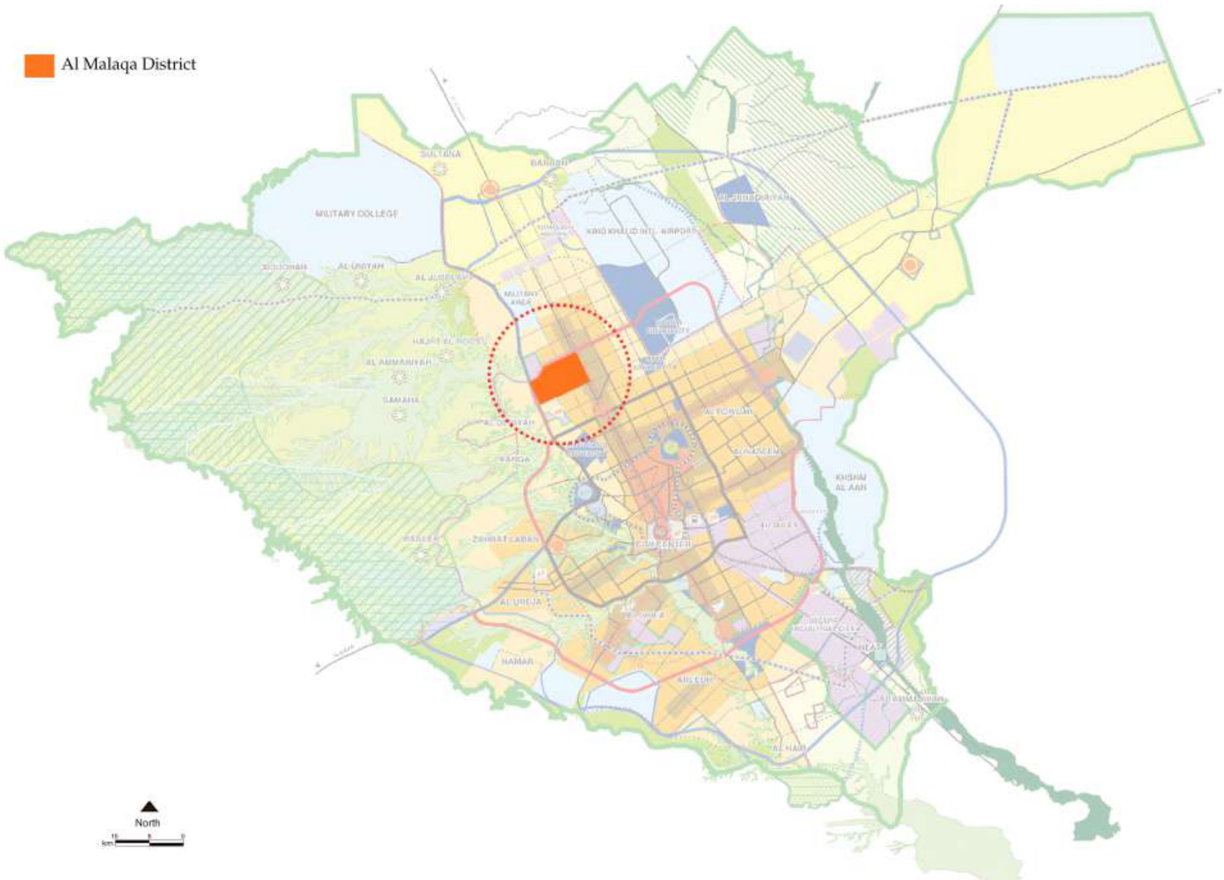

Figure 2. Location of Al Malqa District within the Riyadh metropolitan structure, showing major arterial roads and the surrounding districts. Source: Authors using municipal GIS base layers. Source: Authors, based on [24,42], [GIS surveys].

The district is bounded by major mobility corridors: King Fahd Road (east), King Khalid Road (west), King Salman Road (north), and Imam Saud bin Faisal Road (south), with Anas Ibn Malik Road serving as its primary internal spine. This structure supports efficient vehicular circulation but reinforces car dependence, reflecting broader suburbanisation patterns observed across Riyadh, Figure 3 [37,50,52].

A Line 1 metro station is located along the district's eastern edge, and the southern boundary interfaces directly with the Riyadh Boulevard Zone, creating a unique combination of constraints and opportunities: low walkability and limited mixed-use intensity on one hand, and strong civic anchors, transit access and emerging commercial corridors on the other [36,55,69].

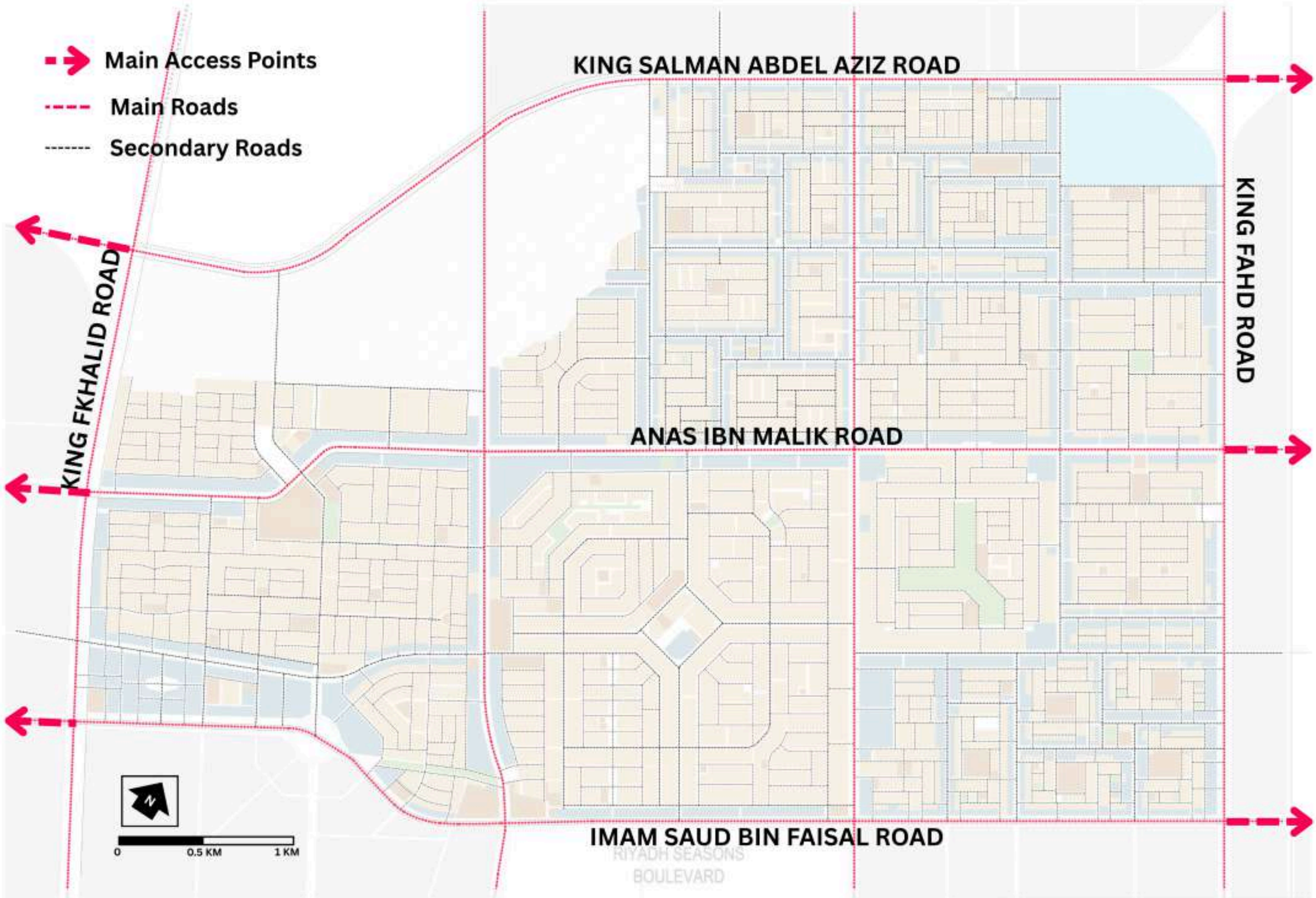

Figure 3. Al Malaqa District main network. Source: Authors, based on [24], [GIS surveys].

4.1.3. District Metrics

District-level spatial and demographic data were extracted from municipal GIS layers and validated against satellite imagery and field verification. Population estimates were triangulated using World Population Review [70], Business Atlas [69] and municipal datasets. Table 2 summarises the headline metrics used as denominators in subsequent indicators. All spatial datasets, provenance details, and pre-processing steps are provided in Appendix A.1.

Table 2. Al-Malaqa fact sheet. Source: Authors, based on [30,67], [GIS surveys].

S/N	Item	Count/Area
1	Total District Area	21.85 km^2
2	Population	87,931 Residents
3	No of Parcels	14,588
4	Density	4025 Persons per km^2 (Medium Density)
5	No of Mosques	68
6	Educational Parcels	24
7	No of Streets within the District	868

4.1.4. Sub-Zone Land-Use Composition

The district's spatial extent, land-use composition, and street network were delineated using municipal GIS layers and validated against satellite imagery and field verification. Population estimates were triangulated using World Population Review [70], Business Atlas [69], and municipal datasets. This case study approach aligns with Riyadh-specific urban scholarship that emphasises district-scale analysis as a critical lens for understanding the city's evolving form under Vision 2030 [21,23,25,38].

To illustrate the current Al Malaqa mixed-use platform, Table 3 lists key malls, hotels, and commercial spaces within the district, showcasing its blend of residential and commercial elements that support daily needs and economic activity.

Table 3. Key developments within Al Malaqa. Source: Author, based on [30,67], [GIS surveys].

Category	Name	Description	Location/Proximity
Malls	Sahara Plaza	Retail, dining, entertainment	Central Al Malaqa
	Riyadh Park Mall	Major regional mall with cinema	Near the northern boundary
Hotels	Al Malqa Elite Hotel	3-star hotel with amenities	Within Al Malaqa
	Al Yamama Palace—Al Malqa Branch	Hotel with retail access	Al Malaqa
	Al Majidiya Project 127	Fitness, parking, near Riyadh Park	Al Malaqa District
Commercial Spaces	Commercial Almalqa and Office Centre	Offices and commercial services	Central Al Malaqa
	Souqs and Local Markets	Daily shopping and local goods	Scattered throughout Al Malaqa

4.1.5. Spatial Frame and Sub-Zoning

For reproducibility, the analysis distinguishes between the analytical envelope used for mapping and figure production (6.2 km $\times$ 4.0 km; 24.8 km^2) and the measured municipal area used for all density and percent-area indicators (21.85 km^2). The difference between these two representations reflects the district's irregular western boundary and the tapered geometry of the north-west sector; reconciliation procedures and cross-section calculations are documented in Appendix A.3.

To support comparative diagnostics, the district is partitioned into six sub-zones, NW, NC, NE, SW, SC and SE as illustrated in Figure 4, derived directly from CAD/GIS parcel geometry. All sub-zone denominators therefore use actual measured polygon areas, ensuring consistency across land-use, accessibility and density indicators.

Transit access is anchored by two Line 1 metro nodes located at the SE corner of the NE block and the NE corner of the SE block. A Euclidean 1 km radius is retained for policy comparability, while network-based 400 m and 800 m service areas are used for accessibility and walkability indicators. Network impedance incorporates shading penalties to reflect hot-arid comfort constraints, following recent thermal-comfort research in arid cities [24,25,31–33].

Two special polygons influence baseline treatment. The north-west undeveloped tract (3,000,000 m^2) lies entirely outside the station catchments and is therefore excluded from baseline station-area denominators; it is incorporated only in dedicated infill scenarios (Appendix A.4). Conversely, the Boulevard interface along the southern boundary functions as the district's primary mixed-use corridor and is used in Boulevard-catchment indicators and feasibility scoring.

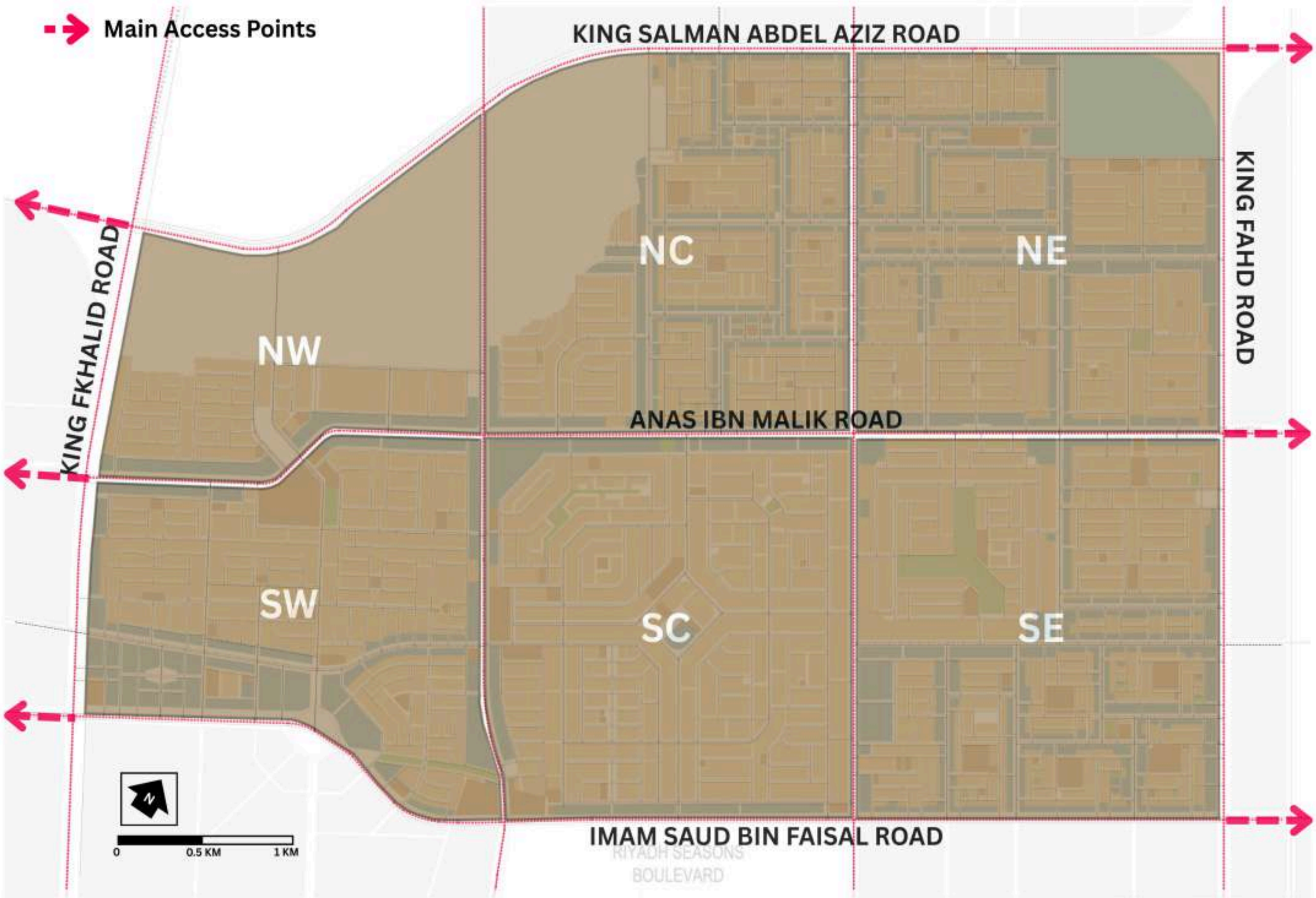

Figure 4. Al Malaqa District sub-zones. Source: Authors, based on [24], [GIS surveys].

4.1.6. Sub-Zone Summary Metrics

The spatial analysis of Al Malqa was further disaggregated into six sub-zones to capture variations in land-use composition, development intensity, and proximity to key mobility anchors. Each sub-zone was evaluated using CAD-derived area calculations and harmonized land-use categories, allowing direct comparison of residential, community/service, open-space, mixed-use, and undeveloped shares. TOD and Boulevard catchment overlaps were computed to identify which sub-zones fall within effective walking radii and to quantify the proportion of land uses accessible from transit and major activity nodes. Table 4 summarize these metrics and provide a structured basis for interpreting spatial heterogeneity across the district.

Table 4. Sub-Zone Land-Use Composition and Catchment Overlap Metrics.

Sub-Zone	Area (m^2)	Residential (m^2/%)	Community/Service (m^2/%)	Open Space (m^2/%)	Mall/Mixed Use (m^2/%)	Undeveloped (m^2/%)	TOD Catchment (m^2/%)	Boulevard Catchment (m^2/%)
NE	4,126,326	2,970,954.72 72.0%	247,579.56 72.0%	247,579.56 6.0%	405,000.00 9.8%	206,316.30 5.0%	785,195.00 19.0%	—
NC	4,045,224	2,346,229.92 58.0%	161,808.96 4.0%	202,261.20 5.0%	323,617.92 8.0%	1,011,851.22 25.0%	—	—
NW	2,712,582.26	542,516.45 20.0%	114,550.72 4.2%	122,066.20 4.5%	135,629.11 5.0%	1,883,689.00 69.4%	—	—
SE	4,141,377	2,981,791.44 72.0%	248,482.62 6.0%	248,482.62 6.0%	405,000.00 9.8%	207,068.85 5.0%	785,195.00 19.0%	525,345.00 12.7%

Table 4. *Cont.*

Sub-Zone	Area (m^2)	Residential (m^2/%)	Community/ Service (m^2/%)	Open Space (m^2/%)	Mall/Mixed Use (m^2/%)	Undeveloped (m^2/%)	TOD Catchment (m^2/%)	Boulevard Catchment (m^2/%)
SC	4,096,612	2,949,560.64 72.0%	163,864.48 4.0%	204,830.60 5.0%	614,491.80 15.0%	—	—	1,780,405.00 43.5%
SW	3,466,783	2,253,408.95 65.0%	277,342.64 8.0%	173,339.15 5.0%	416,013.96 12.0%	105,263.00 3.0%	—	576,842.00 16.7%

Notes: Percentages computed as $100 \cdot \frac{A_k}{A_{\text{subzone}}}$. Blank catchment cells indicate no CAD overlap. Minor residual areas were treated as ROW/other; add an explicit ROW classification if required. Full catchment-by-land-use tables, processing logs and CAD filenames are provided in Appendices A.1–A.4.

4.1.7. Interpretation

Al Malqa is predominantly residential with concentrated mall/mixed-use pockets and a southern Boulevard interface. Station-area coverage is spatially limited in several blocks (NE/SE ≈ 19% catchment overlap), while SC shows substantial Boulevard adjacency (≈43.5%). NW is largely undeveloped and distant from metro nodes and is therefore treated as a long-term infill reserve in feasibility scenarios. These spatial patterns determine which sub-zones are prioritised in station-area indicators and in the MCDA prioritisation; they also inform the selection and weighting of climate-sensitive measures (e.g., shading continuity) in the scoring framework [22–25,31–33,59,60,66].

4.2. Indicator Construction and Benchmark Derivation

The nine evaluation criteria identified in Section 3.6 were operationalised into a structured set of measurable indicators derived from New Urbanism theory [1–4], TOD practice and station-area evaluation methods [10,12–16,66], Western mechanism-level evidence on density, block structure and transit performance [7,44,52], and arid-climate and cultural adaptations documented in Gulf scholarship [24–27,31–35,55,66]. This approach ensures that each criterion is grounded in both international best practice and Riyadh-specific climatic, cultural and institutional realities.

The indicator system is organised around the nine adapted NU–TOD criteria: (1) density, (2) land-use mix, (3) access and connectivity, (4) urban form, (5) public-realm quality, (6) climate and microclimate performance, (7) housing diversity, (8) social and civic anchors, and (9) transit integration. Each criterion is represented by 1–4 indicators selected for empirical relevance, data availability and policy applicability. Indicators are computed at both the district-scale and the station-area scale (400 m and 800 m network-based catchments and adjusted 300 m comfort balancing), enabling a multi-scalar assessment of NU–TOD performance. The full indicator catalogue, definition, units, and benchmark ranges are listed in Appendix A.2.

4.2.1. Indicator Framework

The indicator framework translates the nine criteria into quantifiable measures that capture spatial structure, functional intensity, climatic performance and institutional feasibility. Density and land-use indicators reflect the foundational NU/TOD emphasis on compactness and mixed-use structure [2–4,10–12]. Connectivity and block-structure indicators follow established walkability and urban-design measurement protocols [19,20], while public-realm and climate indicators incorporate shading, microclimate and thermal-comfort adjustments drawn from arid-climate research [24,25,31–33]. Housing diversity and civic-anchor indicators reflect the social and cultural dimensions of Saudi neighbourhoods [17,29,53], and transit-integration indicators align with TOD intensification and first/last-mile performance standards [12,15,16].

This integrated framework ensures that each criterion is linked to: (1) a set of indicators, (2) benchmark ranges, (3) data sources, and (4) a scoring rubric, enabling transparent and reproducible evaluation.

4.2.2. Indicator Definitions

Density and land-use structure: Residential density (persons km^{-2}) is calculated using the measured municipal area (21.85 km^2). Land-use entropy (Shannon Index) captures the balance between residential, mixed-use, community services, open space and undeveloped land [10,11]. Mixed-use intensity is estimated using parcel-level FAR proxies calibrated to Riyadh's development patterns [22,34].

Access and connectivity: Intersection density (nodes km^{-2}) and median block length (m) are derived from the routable pedestrian graph, following walkability measurement standards [19,20]. Network-based accessibility is assessed using 400 m and 800 m effective walking distances, where effective distance incorporates shading penalties to reflect thermal-comfort constraints in hot-arid climates [24,25,31–33].

Urban form and public realm: Block structure, frontage continuity and pedestrian permeability are measured using parcel and street-network geometry. Shaded route continuity (%) quantifies the proportion of primary pedestrian routes offering continuous shade, a critical determinant of walkability in arid cities [24,25,31–33]. Green space accessibility (m^2 per capita) reflects the role of greenery in thermal comfort and well-being [49–51].

Residential diversity is assessed using five housing categories that reflect tenure and affordability dimensions relevant to Riyadh's urban context: (1) single-family detached houses; (2) multi-family apartments; (3) gated/closed communities; (4) affordable housing units (subsidised or government-supported schemes); and (5) rental housing (market-rate rental units and purpose-built rental blocks). The inclusion of affordable and rental housing categories captures socio-economic access and tenure heterogeneity that influence travel behaviour, housing turnover, and demand for transit-oriented services. Each category is scored according to presence, relative share within the study area, and spatial distribution across transit catchments [17,29,53].

Transit integration: Station-area GFA per hectare measures development intensity within the 400 m and 800 m catchments, following TOD intensification benchmarks [12,15,16]. First/last-mile connectivity is assessed through a composite of shaded connectivity, block permeability and network reachability, aligned with Riyadh's mobility transition goals [29,68]. In addition to the standard 400 m and 800 m TOD walking catchments, the analysis incorporates a 300 m comfortable walking threshold to reflect hot–dry climatic conditions. Empirical studies in arid environments show that pedestrian willingness to walk declines sharply beyond approximately 250–350 m during peak daytime periods. Integrating this threshold enables a climate-sensitive comparison of accessibility performance. Accordingly, three concentric Euclidean buffers, 300 m, 400 m, and 800 m, were generated around the station centroid to evaluate both conventional TOD reach and thermally comfortable walking distances.

Statistical analysis: Pairwise Pearson correlations were computed across the district-level indicator set to identify coupling relationships and composite factors that influence NU–TOD performance. The indicator set comprises Pedestrian continuity, Shading coverage, Land-use mix, Density, Housing diversity, Public-realm quality, Thermal comfort, Transit integration, and Accessibility (300 m, 400 m, 800 m). Correlations use pairwise complete observations and two-tailed tests of significance at $p < 0.05$. The full Pearson matrix (coefficients and two-tailed p values) is reported in Appendix B Table A11. Correlations are reported and interpreted in Section 5 using the Pearson r and associated p values.

4.2.3. Benchmark Logic

Benchmark ranges for the nine NU–TOD criteria were established through a two-stage process that integrates international best practice with Riyadh-specific climatic and cultural considerations. This approach ensures that each criterion is grounded in empirically validated thresholds while remaining sensitive to the contextual realities of hot-arid urbanism and Saudi governance structures.

In the first stage, baseline benchmarks were extracted from documented NU/TOD precedents, including Seaside's design-control model [44,65], the Pearl District's rail-adjacent regeneration strategy [7], and the Rosslyn–Ballston corridor's phased zoning and parking reforms [13]. These cases provide mechanism-level evidence on density, block length, active frontage, mixed-use intensity, and transit-supportive development patterns [7,48,55]. Their relevance lies in their demonstrated ability to produce compact, walkable, mixed-use environments, with core principles embedded within the nine criteria.

In the second stage, these baseline thresholds were adapted to Riyadh's climatic, cultural and institutional context using evidence from arid-urbanism and microclimate research [24–33], Riyadh-specific walkability and mobility studies, and analyses of Saudi planning governance and regulatory practice [21,29,36,42]. This adaptation produced context-specific benchmark ranges, such as:

- Greater than 60% shading coverage on primary pedestrian routes to ensure thermal comfort in hot-arid conditions.
- Phased density targets for 300 m, 400 m and 800 m station catchments, reflecting local development feasibility.
- Privacy-sensitive public-realm typologies, including mosque forecourts and culturally appropriate frontage treatments.
- Adjusted block-length expectations to account for climatic constraints and existing street morphology.

Through this two-stage process, each of the nine criteria is linked to: (1) a defined set of indicators, (2) benchmark ranges, (3) data sources, and (4) a scoring rubric, ensuring methodological transparency and reproducibility.

4.2.4. Normalisation and Scoring Preparation

All indicators are normalised to a 0–100 scale to enable comparability across the nine criteria and between district- and station-area analyses. Normalisation follows a benchmark-based min–max transformation:

$$S\_i = 100\ X\ ((x\_i - x\_min)\ /\ (x\_max - x\_min))$$

where x_i is the observed value and x_{min} and x_{max} represent the lower and upper bounds of the benchmark range. Directionality is adjusted so that higher scores consistently indicate better performance, regardless of whether the raw indicator is positively or negatively associated with NU–TOD outcomes.

This normalisation process produces a consistent scoring scale across all indicators, enabling aggregation at the criterion level and supporting the composite evaluation described in Section 4.4. It also ensures that indicators derived from diverse data sources, spatial geometry, network analysis, land-use composition, and microclimate modelling can be integrated into a unified assessment framework.

4.3. Measurement Rules and Harmonisation

The indicators developed in Section 4.2 were computed using a harmonised set of spatial, network and microclimatic rules to ensure consistency across the nine NU–TOD criteria and comparability between district- and station-area scales. All spatial measurements were derived from municipal CAD/GIS layers validated against satellite imagery and field verification. Two spatial frames were used consistently: the measured municipal area of 21.85 km^2, which forms the denominator for all density and land-use indicators, and the analytical envelope (6.2 $\times$ 4.0 km), which is used solely for mapping and sub-zone partitioning. Differences between these frames, particularly along the irregular western boundary in which shaded segments incur no penalty, partially shaded segments incur a moderate penalty, and unshaded segments incur, were reconciled through polygon cleaning, topology checks and cross-section scripts documented in Appendix A.3. Land-use categories were standardised into residential, mixed-use/mall, community/service, open space and undeveloped classes, with minor residual polygons assigned to ROW/other.

Network-based indicators were computed using a routable pedestrian graph constructed from municipal street-centerline data. Connectivity breaks, cul-de-sac geometry and missing links were corrected to ensure a continuous pedestrian network. Intersection nodes were defined as degree-three or higher vertices, and block lengths were measured as mid-line distances between intersections. In addition to the standard 400 m and 800 m TOD walking catchments, the analysis incorporates a 300 m comfortable walking threshold to reflect hot–dry climatic conditions. Empirical studies in arid environments show that pedestrian willingness to walk declines sharply beyond approximately 250–350 m during peak daytime periods. Integrating this threshold enables a climate-sensitive comparison of accessibility performance. Accordingly, three concentric Euclidean buffers—300 m, 400 m, and 800 m—were generated around the station centroid to evaluate both conventional TOD reach and thermally comfortable walking distances. The penalty coefficients applied to microclimate shading (1.0, 1.25, 1.75) were selected from comparative studies in hot-arid urban environments and are intended to represent relative increments of thermal disbenefit associated with progressively lower shading coverage. These coefficients function as relative penalties within the NU–TOD scoring framework rather than absolute thermal thresholds. We acknowledge that local calibration against on-site thermal monitoring (air temperature, globe temperature, and mean radiant temperature) would improve the empirical grounding of these values. Accordingly, the coefficients used here should be considered provisional and suitable for comparative spatial ranking; future work will collect in situ microclimate measurements across representative microenvironments in Al Malqa and use those data to calibrate penalty thresholds and refine microclimate sensitivity in the scoring model. This approach aligns with thermal-comfort evidence for arid cities and ensures that catchments represent realistic pedestrian reachability rather than purely geometric distance.

Public-realm and climate-performance indicators were derived from shading analysis, open-space accessibility and microclimatic considerations. Shaded route continuity was measured as the proportion of primary pedestrian routes that offered continuous shade, using building footprints, tree canopies, and shading structures. Green-space accessibility was computed using accessible open-space polygons and network-based reachability. Thermal-comfort adjustments followed established arid-urbanism research, emphasising the importance of shade, vegetation and surface materials in pedestrian comfort.

Two context-specific spatial conditions required harmonised treatment. The northwest undeveloped tract (3,000,000 m^2), which lies outside all station catchments, was excluded from baseline station-area denominators and incorporated only in dedicated infill scenarios (Appendix A.4). Conversely, the Boulevard interface along the southern boundary was treated as a distinct mixed-use corridor and integrated into Boulevard-catchment indicators and feasibility scoring.

All indicators were computed using a unified spatial reference system and consistent attribute schemas. Quality-assurance procedures included cross-checking parcel areas against municipal records, validating network connectivity through manual inspection, verifying shading classifications using field photography and satellite imagery, and triangulating population estimates across multiple sources. These harmonisation rules ensure that the indicator system is reproducible, internally consistent and suitable for integration into the scoring and MCDA framework presented in Sections 4.4 and 4.5.

4.4. Scoring Logic and Criterion Aggregation

Each indicator was scored on a three-tier ordinal scale to reflect its alignment with the adapted NU–TOD benchmarks: 3 = strong alignment, 2 = moderate alignment, 1 = weak alignment. Indicator thresholds and assignment rules are documented in Appendix A.3 to ensure repeatability and to minimise subjective drift across analysts. This scoring approach provides a transparent and replicable mechanism for translating diverse spatial, functional and climatic measurements into a unified evaluative structure.

Criterion-level scores were computed as the arithmetic mean of their constituent indicators, preserving equal weighting among indicators within each criterion unless otherwise justified in the Appendix A. This ensures that each of the nine NU–TOD criteria, density, land-use mix, access and connectivity, urban form, public-realm quality, climate performance, housing diversity, civic anchors and transit integration, is represented proportionally to its conceptual and empirical significance.

A second level of aggregation was applied to compute domain scores, reflecting the five analytical domains introduced in Section 3.6: Form, Access, Social/Economic, Climate, and Governance. Domain scores were calculated as the means of the criteria that compose each domain, producing a hierarchical structure from indicator → criterion → domain. Formally, for a criterion c with n indicators i:

$$\text{Criterion Score}_c = \frac{1}{n}\sum_{i=1}^{n} \text{Indicator}_i$$

and for a domain d with m criteria:

$$\text{Domain Score}_d = \frac{1}{m}\sum_{c=1}^{m} \text{Criterion Score}_c$$

This hierarchical aggregation aligns with established MCDA practice in urban sustainability and walkability research and supports transparent sensitivity testing of both indicator weights and aggregation rules [56–58]. It also ensures that performance patterns can be interpreted at multiple levels: individual indicators, conceptual criteria and broader domains.

A composite performance profile, constructed from the nine criterion scores and the five domain aggregates, is used to visualise Al Malqa's relative strengths and weaknesses and to feed the feasibility MCDA in Section 4.5. This composite profile does not function as a ranking tool but as a diagnostic instrument that highlights spatial disparities, climatic constraints and development opportunities across sub-zones and station-area catchments.

All intermediate scores, aggregation steps and alternative weighting scenarios used for sensitivity analysis are provided in Appendix A.4. These materials enable full replication of the scoring process and demonstrate how prioritisation outcomes respond to plausible methodological choices, ensuring transparency and robustness in the evaluation.

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4.5. Feasibility Scoring Framework [MCDA]

The feasibility assessment applies a transparent multi-criteria decision analysis (MCDA) to prioritise interventions by combining their expected contributions to NU–TOD performance with their deliverability under Riyadh's climatic, regulatory and market conditions. This framework complements the performance scoring developed in Sections 4.2–4.4 by evaluating not only how much an intervention improves the nine NU–TOD criteria, but also how feasible it is to implement within existing institutional and fiscal constraints. The MCDA structure follows established TOD implementation and the arid-city planning literature [16,48,52,56,57] and is designed to support reproducibility, sensitivity testing and transparent decision-making.

4.5.1. Scoring Dimensions

Each intervention is evaluated across four feasibility dimensions, selected for their relevance to TOD implementation in rapidly developing and hot-arid contexts:

- Impact (40%): The expected improvement across the nine NU–TOD criteria (Density, Mixed Use, Access, Form, Public Realm, Climate, Housing Diversity, Social/Economic, Transit Integration). Impact reflects the intervention's potential to shift measured indicators and user outcomes.
- Regulatory Ease (30%): The degree of alignment with existing RCRC zoning, municipal standards and institutional capacity. This includes the number of agencies involved, the extent of regulatory change required and the likelihood of administrative approval.
- Cost (20%): Estimated capital and first-order operational expenditure, expressed as order-of-magnitude cost bands derived from unit-rate ranges applied to CAD-based extents (Appendix A.1). Cost reflects fiscal feasibility and funding likelihood.
- Timeline (10%): Expected implementation duration, categorised as Short (≤12 months), Medium (12–24 months) or Long (>24 months). The timeline captures procedural lead times, procurement cycles, and market readiness.

The weighting scheme balances short-term deliverability with long-term structural transformation, consistent with TOD feasibility studies in arid and rapidly urbanising regions [16,56,57]. To reflect local delivery constraints, financing considerations are incorporated as evidence-based proxies within the existing Cost and Timeline dimensions rather than as a separate criterion. Documentary and market proxies (committed financing/MOUs, recent comparable transactions, developer expressions of interest, municipal funding commitments) are recorded for each intervention and used to adjust Cost and/or Timeline scores where financing evidence indicates elevated funding risk or schedule delay. This preserves the published weighting scheme (Impact 40%; Regulatory Ease 30%; Cost 20%; Timeline 10%) while making financing constraints explicit and reproducible in the MCDA inputs. These weights were selected to reflect the relative importance of expected urban impact and regulatory feasibility in the study area and to ensure comparability with prior evaluations. Because a formal Delphi panel of local planning experts was not convened during the present study, the weights should be regarded as the literature-based priors rather than empirically validated parameters. Future work will implement structured expert elicitation with municipal planners, Royal Commission for Riyadh City (RCRC) specialists, and local development practitioners to validate and, if necessary, recalibrate the weighting scheme.

4.5.2. Categorical to Numeric Mapping

Qualitative expert judgements are converted into numeric values to enable aggregation and comparison across interventions. The ordinal mapping used throughout the analysis is:

- Impact, Regulatory Ease, Cost: High = 3, Medium = 2, Low = 1.

- Timeline: Short (≤12 months) = 3, Medium (12–24 months) = 2, Long (>24 months) = 1.

This mapping preserves the relative ordering of qualitative assessments while maintaining a compact scale suitable for transparent sensitivity analysis. It also aligns with common MCDA practice in urban planning and TOD implementation [16,56,57].

4.5.3. Feasibility Linear Modelling

Feasibility is computed using a weighted linear model. For each intervention, the raw feasibility score is:

$$\text{Raw Score} = 0.40I + 0.30R + 0.20C + 0.10T$$

where I, R, C, and T are the numeric values assigned to Impact, Regulatory Ease, Cost, and Timeline, respectively.

To facilitate interpretation and comparison, the raw score is normalised to a 0–10 scale:

$$\text{Overall Score} = \left(\frac{\text{Raw Score}}{3}\right) \times 10$$

Normalisation divides the maximum possible category value (3) and rescales the result to a familiar 0–10 range. All intermediate calculations, category assignments and cost assumptions are documented in the Appendix A.4 workbooks to ensure full reproducibility. Financing proxy adjustment rules. Apply conservative, bounded adjustments to Cost and Timeline scores as follows: (a) committed financing/MOUs/recent comparable transactions, no adjustment; (b) conditional interest/preliminary proposals, subtract 1 step from the most affected dimension (Cost or Timeline); (c) no evidence/weak market fundamentals, subtract 1 step from both Cost and Timeline.

4.5.4. Linking Feasibility to NU-TOD Criteria and Sensitivity Testing

Each intervention is explicitly mapped to the NU–TOD criteria it is expected to improve. For example:

- Shaded pedestrian corridors → Climate, Access, Form.
- Mixed-use infill → Density, Mixed Use, Housing Diversity.
- Boulevard public-realm upgrades → Public Realm, Social/Economic, Transit Integration.

This mapping ensures that feasibility scoring remains anchored to the conceptual framework and the district-level performance gaps identified in Section 5.

To test robustness, two sensitivity procedures were applied:

1. Weight perturbation: Each dimension's weight was varied by ±10% to assess the stability of intervention rankings.
2. Scenario testing: Cost and impact assumptions were varied within documented ranges to evaluate how uncertainty affects prioritisation.

Sensitivity results, presented in Appendix A.4, identify interventions whose ranking is sensitive to plausible alternative assumptions. These checks strengthen the interpretability of the MCDA outputs and provide decision makers with contingency scenarios for phased implementation. To enable phased evaluation of renovation measures, we adopt a three-scenario structure for the MCDA simulations: (a) Baseline—the current conditions and realised interventions at the time of data collection; (b) Short-term—interventions committed or expected within 0–2 years (e.g., maintenance, shading devices, minor pedestrian works); and (c) Medium/Long-term—planned or aspirational interventions within 3–8 years (e.g., infill redevelopment, transit-adjacent densification, zoning changes). For each scenario, we update the input indicator values and intervention implementation status (e.g., unit shares for housing categories, shade coverage, sidewalk continuity) according to the implementation schedule in Appendix A, then recompute indicator scores and the aggregated NU–TOD composite. This approach permits quantification of incremental NU–TOD uplift attributable to phased measures and supports comparison of alternative intervention packages. In the present study, we provide the conceptual scenario framework and illustrative short-term and medium-term recalculations for a subset of high-priority measures; full multi-scenario MCDA simulations across all measures are identified as future work pending expanded data on committed projects and financing status.

4.6. Scenario Design for Phased Intervention

To enable phased evaluation of renovation measures, we adopt a three-scenario structure for the MCDA simulations: (a) Baseline—current conditions and realised interventions at the time of data collection; (b) Short-term—interventions committed or expected within 0–2 years (e.g., shading devices, sidewalk repairs, pedestrian crossings); and (c) Medium/Long-term—planned or aspirational interventions within 3–8 years (e.g., infill redevelopment, transit-adjacent densification, zoning changes). For each scenario, input indicator values (e.g., housing category shares, shade coverage, sidewalk continuity, accessibility catchments) are updated according to the implementation schedule in Appendix A, and the MCDA is recomputed to produce scenario-specific NU–TOD composites. This phased approach permits quantification of incremental NU–TOD uplift attributable to staged measures and supports comparison of alternative intervention packages. In this manuscript, we present the conceptual scenario framework and illustrative recalculations for selected high-priority measures; comprehensive multi-scenario simulations across all measures are identified as future work pending expanded data on committed projects and financing status.

4.7. Data Sources and Validation

The analysis integrates three complementary data streams to characterise Al Malqa's spatial form, service provision and governance context. Primary spatial geometry was derived from the project CAD file and converted into GIS layers, including parcel boundaries and street-centerline segments. These layers provided the geometric basis for block metrics, street lengths, land-use composition and candidate intervention extents. Where available, CAD-derived layers were augmented and cross-checked against official municipal and national datasets, including the Riyadh Regional Geospatial Portal, Riyadh Region Municipality datasets and General Authority for Statistics aggregates. These sources provided district-level metrics such as population totals, parcelisation patterns, street-network extent, and amenity inventories, which were used to assess compactness, accessibility, and neighbourhood completeness [27,31,34].

Qualitative and policy materials were reviewed to interpret governance readiness, regulatory constraints and cultural design expectations. Key documents included Vision 2030 strategic reports, RCRC design guidance, municipal policy statements and the secondary literature on Saudi urbanism. These sources informed the Regulatory Ease dimension of the feasibility MCDA and shaped the institutional framing of proposed interventions [21,27–29]. They also provided contextual grounding for the climate-sensitive and culturally responsive adaptations embedded in the indicator framework.

Spatial validation employed high-resolution satellite imagery and municipal maps to verify land-use proxies, parcel geometry, and metro-station locations. The district's interface with the Boulevard Zone and the precise placement of the Line 1 station were cross-checked against multiple sources to ensure locational accuracy [26,53,67]. These checks were essential to ensure that station-area catchments, Boulevard-adjacent indicators, and sub-zone boundaries reflected actual on-ground conditions.

Validation procedures combined automated and manual checks. CAD imports were cleaned for topology errors, slivers, gaps, duplicate vertices, and simplified to produce a routable pedestrian network suitable for 400 m and 800 m network-based analyses. Parcel verification and indicator validation relied primarily on municipal parcel and land-use layers combined with high-resolution satellite and orthophoto imagery. A stratified random sample of approximately 5% of parcels ($n \approx 730$) was selected to capture representative parcel typologies (single-family villas, multi-family apartments, gated compounds, and commercial strips) and to prioritise high-variance locations, such as station approaches and major corridors. Due to access constraints and the absence of a formal field photographic archive, parcel verification was performed by cross-referencing cadastral attributes with contemporaneous high-resolution imagery (Google Earth Pro, municipal orthophotos) and, where available, recent street-level imagery. The large undeveloped tract in the northwest of the study area was not subject to parcel-level field inspection and is therefore treated as an infill reserve in baseline calculations; assumptions used to incorporate this tract into short- and medium-term scenario runs are documented in Appendix A.4 (Implementation Schedule and Scenario Conversion). Future work will expand verification coverage and, where feasible, incorporate systematic on-site inspections and microclimate spot measurements to reduce residual uncertainty in parcel-level assignments and redevelopment potential estimates.

Where official attribute data (e.g., building heights, household counts) were unavailable, estimation rules were applied, such as storey-to-height conversions and floor-area-to-population ratios. These derived attributes were triangulated against municipal aggregates and utility proxies and flagged for sensitivity testing when variance exceeded 10% (Appendices A.3–A.5). All datasets and derived layers include provenance metadata (source, acquisition or derivation date, coordinate reference system, and processing script references) to support reproducibility and ensure transparency in the analytical workflow.

5. Results

This section presents the empirical evaluation of Al Malqa District using the nine-criterion framework developed in Section 3 and operationalised in Section 4. Results are organised criterion-by-criterion to mirror the adapted NU–TOD model and to facilitate direct comparison with established precedents in New Urbanism and TOD practice [2,3,7,59] and with recent research on pedestrian comfort, shading strategies, and TOD evaluation in hot-arid and rapidly developing contexts [24–35,44,46]. For each criterion, we report measured indicators, benchmark ranges drawn from the cited literature, and an interpretation that explicitly accounts for Riyadh's climatic constraints and socio-institutional context; together, these outputs provide a spatially explicit, policy-relevant profile of Al Malqa that highlights both alignments with NU–TOD objectives and priority performance gaps for intervention.

5.1. Neighbourhood Structure

Al Malqa exhibits a semi-grid street network with relatively consistent block geometry, but the overall structure remains oriented toward vehicular mobility rather than pedestrian permeability. Block lengths frequently exceed 250–300 m, surpassing NU benchmarks for walkable block structure [3,20]. Intersection density is moderate, but the hierarchy of wide arterials and collector roads creates discontinuities that limit fine-grained pedestrian movement. The district's internal spine, Anas Ibn Malik Road, functions primarily as a high-capacity vehicular corridor, with limited pedestrian infrastructure and minimal shading.

Figure 5 illustrates the identifiable neighbourhood structure, showing the district's boundaries, block patterns, and the dominance of car-oriented arterials. This spatial configuration aligns with suburban development patterns documented across Riyadh [24,34,36], resulting in a neighbourhood structure that provides efficient car circulation but weak walkability.

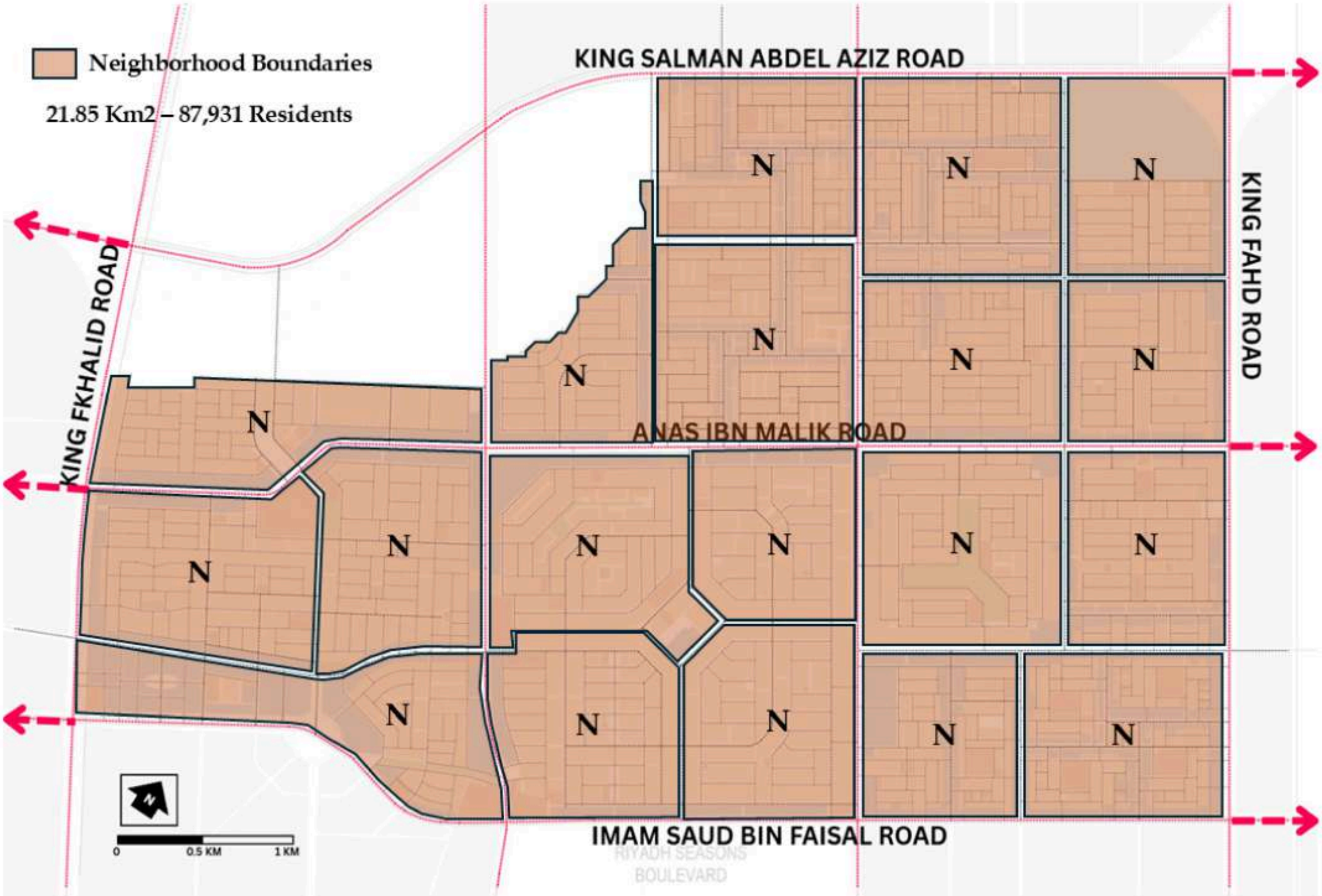

Figure 5. Al Malaqa District neighbourhood structure. Source: Authors, based on [30], [GIS surveys].

5.2. Mixed-Use Intensity and Land-Use Mix

Land-use analysis reveals a predominantly residential district with limited horizontal mixing of uses. Commercial activity is concentrated along Anas Ibn Malik Road and in scattered local souqs, while large portions of the interior remain exclusively residential. Entropy-based land-use mix scores fall below NU/TOD benchmark ranges for mixed-use neighbourhoods [19,71]. Although the district contains several clinics, local markets, and small-scale commercial strips, these uses are not sufficiently integrated into the residential fabric to support walkability.

Figure 6 shows the land-use distribution across Al Malqa, illustrating the dominance of residential parcels and the clustering of commercial and service uses along major corridors. This pattern reflects the broader suburban morphology of Riyadh, where mono-functional residential zones dominate [37,47,52]. As a result, Al Malqa performs moderately on civic accessibility but weakly on mixed-use accessibility.

5.3. Daily Needs Accessibility

Access to daily needs is uneven across the district. Civic anchors, particularly mosques and schools, are well distributed, consistent with Saudi planning norms and the cultural centrality of these institutions [17,28]. However, access to retail, services, and recreational amenities is more limited, with many residents needing to drive for daily errands. Network-based 400 m and 800 m catchment analyses show that only a minority of residential parcels are within walking distance of a diverse set of daily needs.

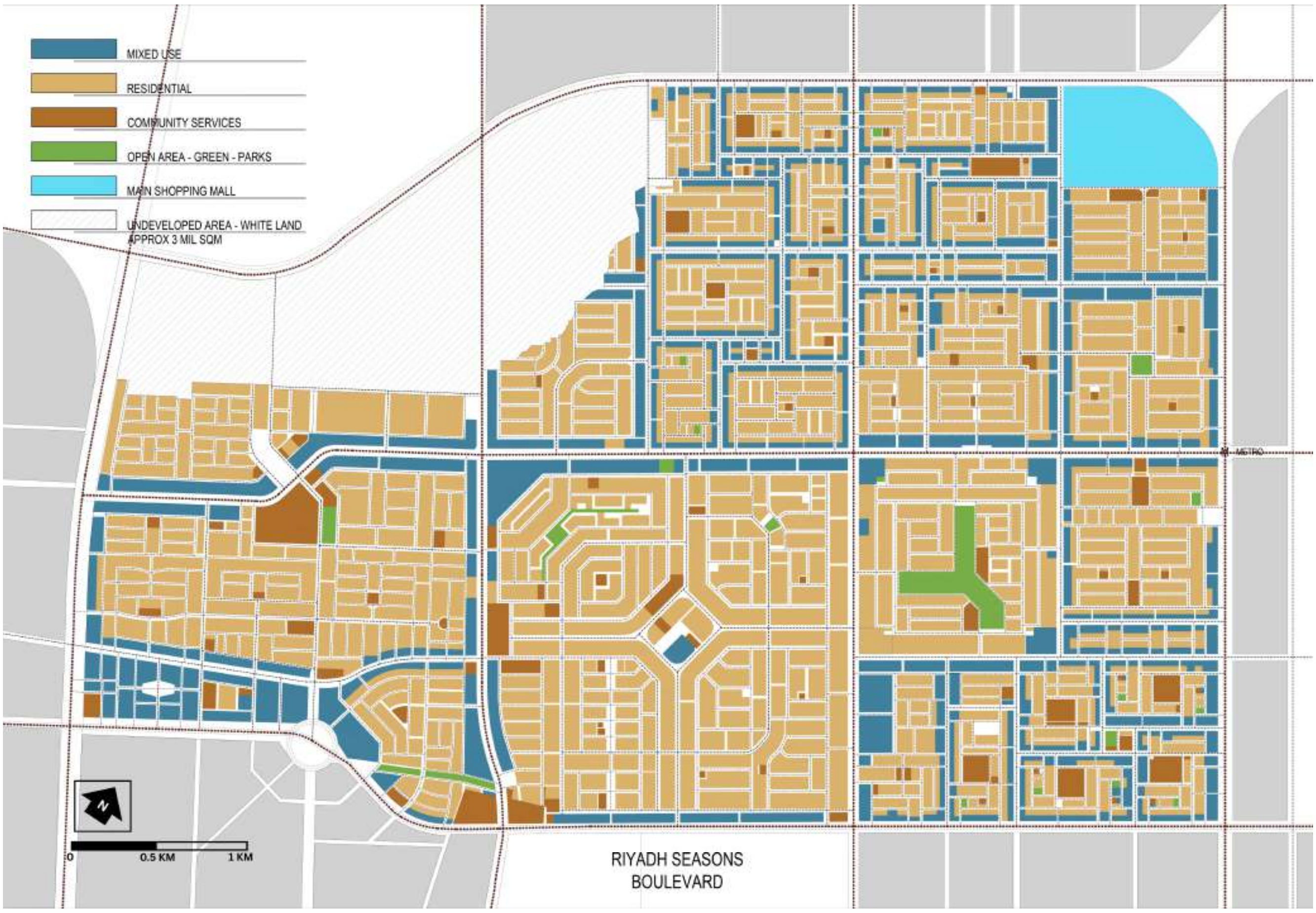

Figure 6. Land-use distribution. Source: Authors, based on [30], [GIS surveys].

Figure 7 highlights the road network and pedestrian-activated zones, showing the dominance of wide arterials and the limited extent of pedestrian-oriented corridors. The emerging commercial corridor along the Boulevard interface shows potential for intensification, but current patterns reflect a nascent mixed-use platform rather than a mature NU/TOD environment.

5.4. Housing Diversity and Affordability

Housing in Al Malqa is dominated by detached villas, with mid-rise apartments and gated compounds forming a secondary but growing component. This typological distribution aligns with contemporary Saudi residential preferences [29,53] but diverges from NU principles that emphasise housing diversity and tenure mix [1,46,55]. Market data indicate that villas command prices of SAR 3–5 million, while apartments range from SAR 1–2 million, reflecting a relatively upscale housing market with limited affordability diversity [30,66]. The district, therefore, exhibits low alignment with NU benchmarks for socio-economic diversity, although the presence of mid-rise apartments suggests potential for gradual diversification.

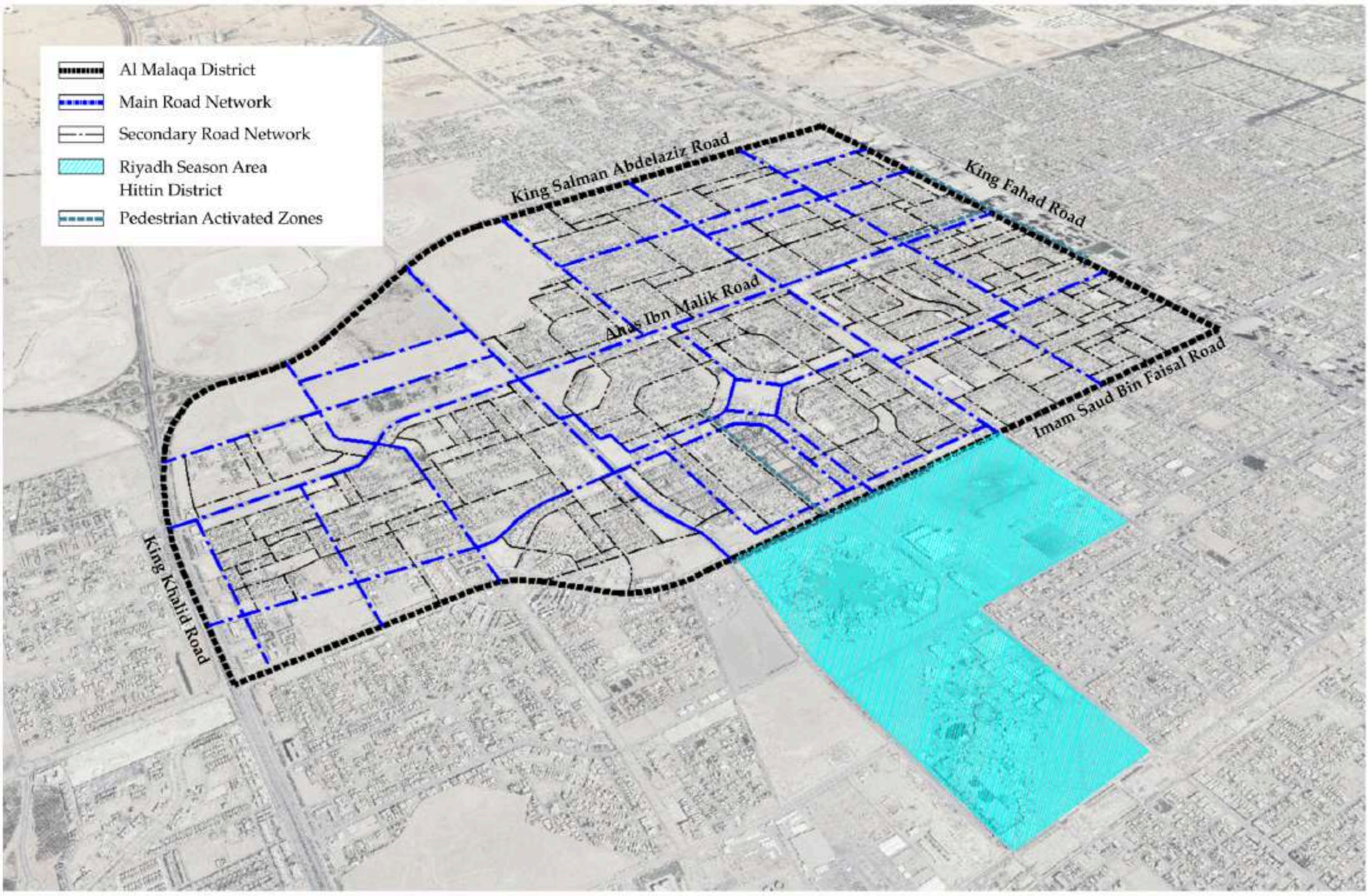

Figure 7. Road networks and pedestrian-activated zones. Source: Authors, based on [30], [GIS surveys].

5.5. Transit Integration and Station-Area Organisation

The presence of a Line 1 metro station provides a significant structural advantage, yet the surrounding urban form does not currently support Transit-Oriented Development. Station-area analysis shows low residential and employment densities within the 400 m and 800 m catchments, which fall below the TOD aspirational bands documented in international precedents [7,52,57], Figure 8. The station area lacks active frontages, mixed-use intensity, and pedestrian-oriented design, limiting its ability to function as a high-activity node. First- and last-mile connectivity is weak, with discontinuous sidewalks, minimal shading, and limited feeder services. These findings align with Riyadh TOD studies that highlight the need for coordinated land-use reform and public-realm investment around metro stations [12,26].

5.6. Transit-Supportive Density

Al Malqa's overall density of 4025 persons/km^2 places it within a medium-density suburban band, but station-area densities remain significantly lower than TOD benchmarks. Network-based density surfaces show that large villa parcels and low plot-ratio development suppress density within walking distance of the station. This pattern is consistent with suburbanisation trends documented across Riyadh [31,34,36], Figure 9, and underscores the need for targeted infill and zoning reform to support transit viability. While the district's overall population is substantial, its spatial distribution limits the potential for high-frequency transit ridership without structural change.

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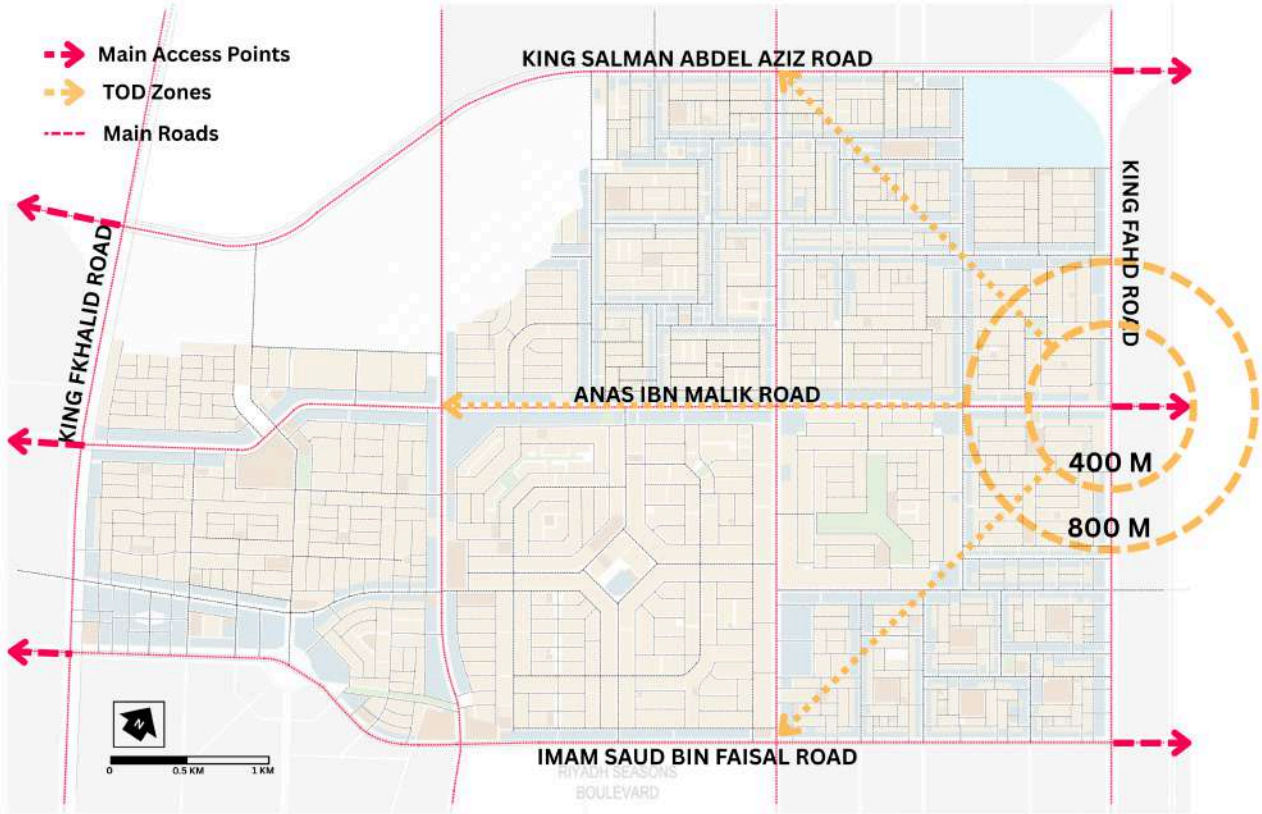

Figure 8. TOD catchment area. Source: Authors, based on [30], [GIS surveys].

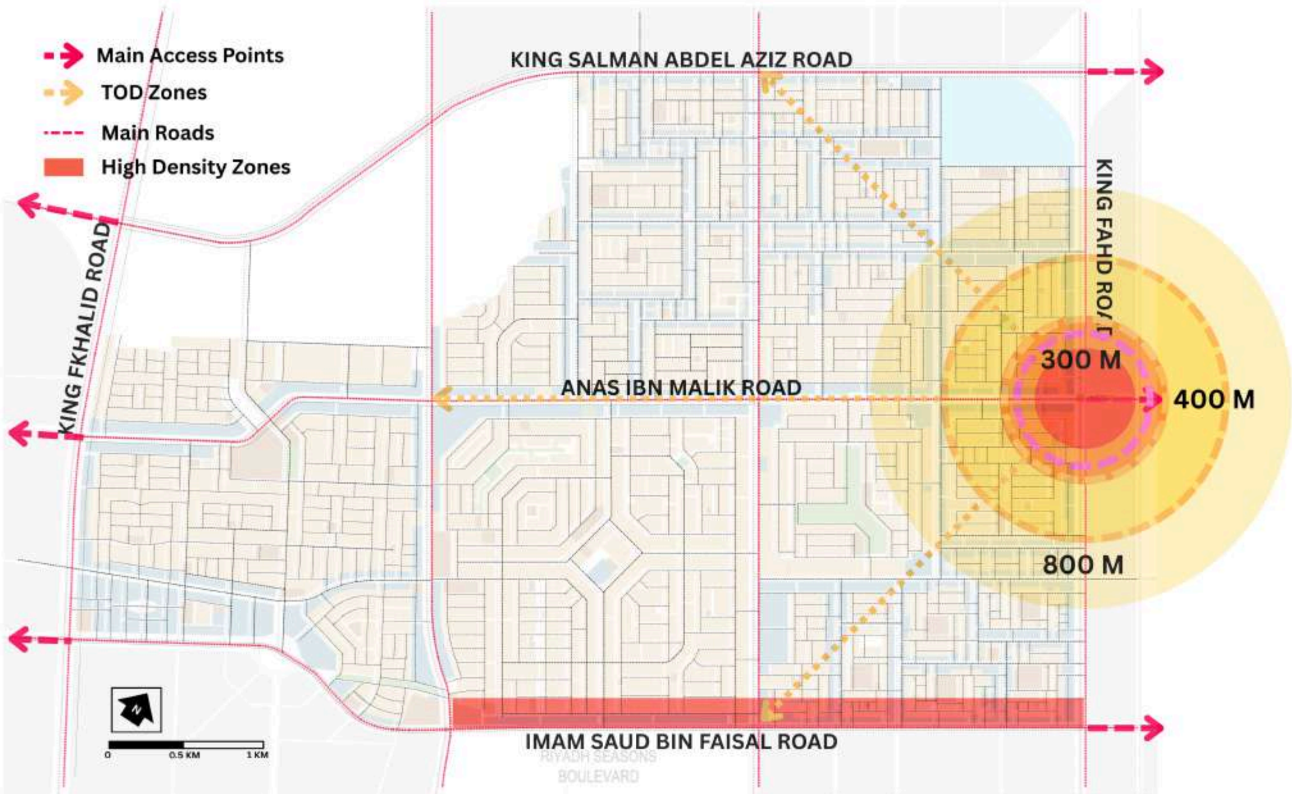

Figure 9. Station walking catchments at 300 m, 400 m, and 800 m. The 300 m threshold represents a comfortable walking distance in hot–dry climates, while 400 m and 800 m correspond to standard TOD practice. Catchments are shown over the 200 × 200 m grid to illustrate parcel-level accessibility. Source: Authors, based on [30], [GIS surveys].

5.7. Civic and Institutional Anchors

Civic infrastructure is one of Al Malqa's strongest assets. The district contains 68 mosques and 24 educational facilities, distributed in a manner that aligns with both NU principles and Saudi cultural norms [3,17,19]. These anchors provide a robust foundation for neighbourhood completeness and community life. However, the public-realm environments surrounding these facilities often lack shading, pedestrian connectivity, and active frontages, limiting their potential to function as walkable community hubs. The civic network, therefore, scores highly on availability but moderately on integration with the public realm.

5.8. Urban Design Quality and Public Realm

Urban design quality in Al Malqa reflects a contemporary Arabian architectural aesthetic, with beige façades, arched motifs, and courtyard-influenced layouts. However, pedestrian-oriented design remains limited. Sidewalks are often narrow or discontinuous, shading coverage is low, and street-level activation is minimal outside commercial corridors. These conditions align with findings from Riyadh walkability studies that highlight the dominance of car-oriented design and the absence of microclimate-responsive public-realm features [26,34]. Parks and open spaces are allocated in the land-use plan, but many remain undeveloped, undermining green-infrastructure performance and limiting opportunities to enhance thermal comfort.

5.9. Green Infrastructure and Microclimate Performance

Green-infrastructure coverage in Al Malqa is limited: tree canopy density is low, and continuous shading along primary pedestrian routes is minimal. Shadow modelling and route-level analyses indicate that mid-day shaded length falls substantially below the $\geq$60% threshold commonly recommended for hot-arid urban environments, reducing thermal comfort and effective walkable catchments [43,47,51,52]. Vegetation is largely confined to private villa gardens rather than distributed in the public realm, which limits its contribution to pedestrian cooling and street-level amenity, an outcome consistent with regional studies documenting low greenery performance and elevated thermal stress in Riyadh's suburban districts [43,53,54,72]. Collectively, these findings place Al Malqa in a weak position on microclimate-related criteria and point to the need for targeted public-realm greening and structural shading interventions to improve pedestrian comfort and TOD viability.5.10. Summary of Criterion Scores.

Table 5 summarises Al Malqa's performance across the nine NU–TOD criteria, using the harmonised indicators, benchmark ranges and three-tier scoring logic described in Section 4. The updated scoring reflects the refined measurement rules, particularly the shading-adjusted accessibility model, the harmonised land-use classification, and the revised density and mixed-use indicators.

Table 5. Comparative scoring of NU–TOD evaluation criteria for Al Malqa District: indicator definitions, benchmark thresholds, and aggregated performance scores (n = 9 criteria). Source: Authors, based on municipal datasets [42,70], GIS surveys, and harmonised indicators (Sections 4.2–4.4).

S/N	Criterion	Description & Alignment	Quantitative Metrics	Score
1	Neighbourhood Structure	Semi-grid network with long blocks and car-oriented arterials; moderate permeability.	Block length 250–300 m; 868 streets; 21.85 km^2 district area.	(2) Moderate

Table 5. *Cont.*

S/N	Criterion	Description & Alignment	Quantitative Metrics	Score
2	Mixed-Use Intensity	Limited horizontal mixing; commercial uses concentrated along main corridors.	~20% commercial parcels; low entropy mix score.	(2) Partial
3	Daily Needs Accessibility	Strong civic distribution; limited access to retail/services within walkable distances.	68 mosques; 24 schools; ~800 m average distance to shops.	(1) Limited
4	Housing Diversity	Dominance of villas; limited tenure and typology diversity.	~80% villas; SAR 1–5M price range.	(1)) Weak
5	Transit Integration	A Metro station is present, but the station-area design and connectivity are weak.	400–800 m catchment coverage; low active frontage.	(2) Moderate
6	Transit-Supportive Density	Medium overall density; low station-area density relative to TOD benchmarks.	4025 persons/km^2; ~4000/km^2 near station.	(2) Partial
7	Civic and Institutional Anchors	Strong civic network but limited pedestrian integration.	68 mosques; 24 educational parcels.	(2) Moderate
8	Urban Design Quality	Contemporary architecture: limited shading, activation, and pedestrian comfort.	~70% façade consistency; low shading coverage.	(1) Insufficient
9	Green Infrastructure and Microclimate	Sparse greenery; low shading; undeveloped parks.	~15% green space; <20% shaded routes.	(1) Weak

Note: Indicator values are derived from municipal GIS layers, field verification, and stakeholder inputs. Scoring logic: 1 = meets minimum; 2 = meets best practice. See Methods Section 4.1 for indicator definitions and benchmark sources.

Overall, the district demonstrates strong civic infrastructure, a strategically favourable metro-station location, and a coherent street framework, which together provide a solid foundation for NU–TOD-aligned interventions. These strengths are consistent with New Urbanism principles and station-area planning practice [3,16]. However, the updated quantitative scores reveal systematic deficits across several criteria critical to walkability and transit-supportive urbanism.

The most significant performance gaps occur in:

- Walkability and Access: Long blocks, low intersection density, discontinuous sidewalks, and shading-adjusted catchments that shrink dramatically under thermal-comfort constraints.
- Mixed-Use Intensity: Low land-use entropy, limited horizontal mixing, and weak ground-floor activation.
- First/Last-Mile Integration: Constrained effective catchments, minimal shading, and limited feeder-mobility options.
- Microclimate Resilience: Low canopy cover, sparse public-realm vegetation, and insufficient mid-day shading along primary pedestrian routes.

These findings align with recent research on hot-arid TOD performance, which emphasises the centrality of shading, vegetation and microclimate-responsive design for pedestrian viability and transit uptake [23–25].

The updated criterion-level profile, therefore, provides a more precise empirical basis for the sequenced intervention strategy presented in Section 6. Under the feasibility MCDA (Section 4.5), short-term, high-feasibility interventions, such as structural shading, targeted greening and feeder-mobility improvements, score highest and are recommended as immediate priorities. Medium-term actions focus on public-realm upgrades and regulatory adjustments to enable mixed-use activation, while long-term measures target parcel-scale redevelopment to achieve TOD-supportive station-area density and housing diversity.

Full indicator tables, benchmark thresholds, scoring sheets and sensitivity analyses are provided in Appendix A (Appendices A.1–A.5) and the project repository to support replication and municipal review.

The accessibility analysis applies three walking thresholds, 300 m, 400 m, and 800 m, to capture both standard TOD practice and climate-sensitive walkability. The 300 m threshold represents a comfortable walking distance under hot–dry conditions and provides a more conservative estimate of effective pedestrian reach. Using the district density (4025 persons km^{-2}), the Euclidean catchments yield: 300 m = 0.283 km^2 (≈1.29% of municipal area; reachable population ≈ 1140), 400 m = 0.503 km^2 (≈2.30%; ≈2025 persons), and 800 m = 2.011 km^2 (≈9.20%; ≈8090 persons). These magnitudes establish the comparative basis for evaluating climate-adaptive and conventional TOD accessibility. A Pearson correlation matrix was developed to identify relationships among the NU–TOD indicators and to reveal composite factors influencing district performance. The matrix is presented in Appendix B (Table A11).

Indicator interrelationships and accessibility magnitudes: The Pearson correlation analysis (Appendix B Table A11) identifies the strongest couplings among microclimate, pedestrian, and land-use indicators. For transparency, the accessibility magnitudes used in the correlation set are reported here: Analytical envelope = 24.80 km^2; Municipal measured area = 21.85 km^2; Population = 87,931; Density = 4025 persons km^{-2}. Euclidean catchments and reachable populations used in the analysis are: 300 m area = 0.283 km^2 (≈1.29% of municipal area), reachable population ≈ 1140; 400 m area = 0.503 km^2 (≈2.30%), reachable population ≈ 2025; 800 m area = 2.011 km^2 (≈9.20%), reachable population ≈ 8090. These magnitudes ground the statistical couplings reported below and in Appendix B Table A11.

Indicator interrelationships (interpretation): The Pearson correlation analysis (Appendix B Table A11) highlights two composite factors with strong policy relevance. Shading coverage correlates positively with Pedestrian continuity (Pearson $r = 0.58$, $p < 0.001$), indicating that greater shade continuity co-occurs with more continuous pedestrian routes and therefore amplifies effective station catchments in hot–dry climates. Land-use mix correlates positively with Transit integration (Pearson $r = 0.45$, $p < 0.001$), suggesting that mixed-use parcels concentrate in better-served station catchments and that land-use policy can strengthen transit viability. Housing diversity exhibits weaker and generally non-significant correlations with several physical form indicators (Pearson range ≈ 0.02–0.10; $p > 0.05$ for many pairs), indicating that tenure and typology diversity are only partially coupled with current land-use and microclimate conditions. These statistical relationships support prioritising interventions that increase shade continuity and ground-floor mixed use to amplify walkability and transit uptake in Al Malqa. Table 6 summarise the the indicator interrelationships and accessibility magnitudes.

Table 6. Indicator interrelationships and accessibility magnitudes. Source: Authors, based on municipal datasets [42,70], GIS surveys, and harmonised indicators (Sections 4.2–4.4).

S/N	Coupling	Value	Interpretation
1	Shading coverage—Pedestrian continuity	0.58 ($p < 0.001$)	Shade continuity co-occurs with continuous pedestrian routes.
2	Land-use mix—Transit integration	0.45 ($p < 0.001$)	Mixed-use concentrates in better-served station catchments.
3	Density—Transit integration	0.55 ($p < 0.001$)	Higher built intensity near station areas.
4	Transit integration—Accessibility300	0.62 ($p < 0.001$)	Station proximity strongly increases transit integration.
5	Housing diversity—Physical form indicators	0.02–0.10 (mostly ns)	Tenure diversity is decoupled from physical form.

Al Malqa exhibits partial alignment with NU–TOD principles. Its civic infrastructure, distribution of amenities, and strategic position between the metro station and Boulevard City provide a strong platform for TOD-oriented transformation. However, the district underperforms on station-area density, housing diversity, pedestrian comfort, mixed-use clustering, and microclimate resilience. The eastern and southern edges, adjacent to the station and Boulevard, remain the most promising zones for TOD-driven intensification and public-realm upgrades.

6. Discussion

6.1. Interpreting Al Malaqa's Performance Through the NU-TOD Lens

The evaluation of Al Malqa reveals a clear tension between Riyadh's contemporary suburban development model and the spatial, social and climatic conditions required for NU–TOD alignment. While the district benefits from a strong civic network and strategic adjacency to major mobility and entertainment corridors, its urban form remains shaped by low-density villa development, wide arterials, mono-functional land-use patterns, and limited shading. These characteristics mirror the broader suburbanisation trajectory documented in Riyadh and other Gulf cities [31,34,36], where car-oriented planning and large residential parcels have historically constrained walkability, mixed-use intensity and transit viability.

The updated nine-criteria evaluation reinforces critiques within NU scholarship that physical form alone cannot deliver walkability or social diversity without supportive regulatory, climatic and governance structures [1,42,46,55]. Even where block geometry is semi-regular, shading-adjusted accessibility shows that effective walking distances collapse under thermal stress, reducing the functional reach of the metro station and limiting the viability of daily walking trips.

At the same time, Al Malqa's civic richness, 68 mosques and 24 schools, demonstrates the enduring relevance of culturally embedded spatial anchors in Saudi neighbourhoods. These institutions provide a foundation for neighbourhood completeness that is often absent in Western NU/TOD precedents. However, their potential to function as walkable community hubs is constrained by microclimate conditions, discontinuous sidewalks, and car-oriented public-realm design. This highlights the need to reinterpret NU principles through the lens of hot-arid climatic realities, in which shade continuity, thermal comfort, and microclimate-responsive design are prerequisites for walkability rather than optional enhancements [22–24,31–33,66,67,70].

6.2. Climatic and Cultural Adaptation of NU-TOD Principles

The results underscore the importance of adapting NU–TOD frameworks to the climatic and cultural context of Riyadh. Conventional TOD benchmarks, such as 400–800 m walking catchments, active frontages, and mixed-use density thresholds, are significantly moderated by thermal-comfort conditions in hot-arid environments. Incorporating the 300 m comfortable walking threshold provides a climate-sensitive interpretation of station accessibility. In hot–dry environments, effective walkability is often constrained to shorter distances, and the 300 m catchment highlights the limited pedestrian reach under thermal stress relative to the conventional 400 m and 800 m TOD benchmarks. As demonstrated in Section 5, effective walking distances are constrained not by geometry but by heat exposure, limited shading and sparse greenery. This aligns with regional research showing that microclimate performance is a primary determinant of pedestrian behaviour in Gulf cities [23–26].

Consequently, interventions that enhance shade, reduce radiant heat and introduce xeriscape greenery are not merely environmental upgrades but foundational mobility infrastructure. In this context, shaded corridors, tree-lined streets and microclimate-responsive public spaces become essential components of TOD implementation.

Culturally, the prominence of mosques, schools and family-oriented public spaces suggests that NU's emphasis on civic anchors is highly compatible with Saudi urbanism. However, the spatial logic of privacy, gendered mobility patterns and courtyard-based domestic architecture requires a more nuanced interpretation of public-realm design than that found in Western NU precedents. The findings therefore support the argument that NU–TOD principles must be contextualised rather than transplanted, aligning with scholarship on culturally adaptive urbanism in the Gulf [17,28,32].

6.3. Governance, Regulation, and Implementation Capacity

The feasibility-weighted prioritisation in Section 6 highlights the central role of governance in shaping the trajectory of NU–TOD implementation. Short-term interventions—such as shaded corridors, feeder mobility and tactical public-realm activation—score highly because they require limited regulatory change and align with existing municipal programmes, including Green Riyadh and Vision 2030 mobility initiatives [23,27,33,45].

Medium-term reforms, particularly TOD zoning overlays and parking restructuring, require coordinated action across RCRC, municipal authorities and private developers. These interventions align with international evidence showing that regulatory reform is a critical enabler of TOD success [7,13,15,16], but their implementation depends on institutional capacity, cross-agency alignment and market readiness.

Long-term redevelopment strategies face the greatest governance challenges, particularly regarding land assembly, financing, and development phasing. However, the presence of large vacant parcels near the metro station and the availability of public land create opportunities for catalytic demonstration projects that can showcase the viability of compact, mixed-use development in Riyadh's suburban context. This aligns with global TOD precedents where public-sector leadership has played a decisive role in initiating transformative redevelopment [52,57].

6.4. Contribution to NU-TOD Scholarship in Hot-Arid Cities

This study contributes to the growing body of research on NU and TOD adaptation in hot-arid environments by demonstrating how climatic, cultural, and governance factors reshape the applicability of conventional frameworks. The adapted NU–TOD model developed in Section 3, combined with the mixed-methods evaluation and feasibility scoring in Sections 4–6, provides a replicable approach for assessing district-scale performance in Gulf cities. The findings reinforce the argument that walkability and transit viability in hot-arid contexts depend as much on microclimate performance and shading continuity as on density and land-use mix. They also highlight the importance of culturally embedded civic anchors and governance capacity in shaping neighbourhood transformation.

By applying this framework to Al Malqa, the study offers a grounded, context-specific understanding of how NU–TOD principles can be operationalised in Riyadh. The intervention strategy demonstrates that meaningful progress can be achieved through phased, climate-responsive, and governance-aligned actions that build toward long-term structural change. This contributes to both academic discourse and policy practice, offering a model for sustainable suburban intensification in hot-arid cities undergoing rapid transformation.

6.5. Intervention Strategy and Implementation Sequencing

6.5.1. Strategic Rationale for Sequencing

The district-scale evaluation in Section 5 reveals a consistent pattern: Al Malqa benefits from strong civic anchors, a strategically located metro station, and a coherent street framework, yet it underperforms across several NU–TOD criteria, particularly walkability, mixed-use intensity, transit integration, housing diversity, and microclimate performance. These gaps are structural rather than incidental, reflecting Riyadh's broader suburban development trajectory and the climatic constraints of hot-arid environments [31,34,36].

Given these conditions, interventions must be sequenced to balance short-term deliverability with long-term structural transformation. Early actions should expand effective walking catchments, improve thermal comfort, and strengthen first/last-mile connectivity, thereby creating enabling conditions for later phases of TOD-oriented redevelopment. Sequencing is therefore essential not only for technical feasibility but also for institutional alignment, market readiness, and climate adaptation, ensuring that each phase builds momentum for the next.

6.5.2. Integrated Intervention Package

The intervention package is organised into three overlapping phases, short-, medium- and long-term, reflecting increasing levels of regulatory complexity, capital investment and structural impact. Each phase directly targets the performance gaps identified in Section 5 and the nine NU–TOD criteria.

Short-term interventions (0–2 years) prioritise low-cost, high-impact measures to address the district's weakest performance areas: shading, pedestrian comfort, and first- and last-mile connectivity. Establishing shaded pedestrian corridors along Anas Ibn Malik Road, the Boulevard interface, and the metro-station approach can substantially expand effective 400 m and 800 m walking catchments, consistent with evidence from arid-urbanism research [22–24,31]. Complementary feeder-mobility improvements, such as short-interval shuttle loops, shaded waiting areas and enhanced wayfinding, strengthen functional integration with the Line 1 station. Tactical public-realm activations, including temporary markets and weekend pedestrianisation, provide opportunities to test demand for mixed-use environments and to build community support for more permanent interventions.

Medium-term interventions (2–6 years) focus on regulatory and spatial restructuring to address low mixed-use intensity, limited housing diversity and insufficient station-area density. TOD zoning overlays, supported by density bonuses tied to mixed-use development and affordable housing, can help align land-use patterns with transit-supportive benchmarks. Parking reforms, including reduced minimums, priced curb parking and shared parking districts, support modal shift and free land for redevelopment. Public-realm upgrades around mosques and schools, such as shaded forecourts, traffic calming and pedestrian-priority crossings, strengthen the civic network and enhance neighbourhood completeness in line with Saudi cultural norms [17,28].

Long-term interventions (6+ years) involve structural transformation through mixed-use redevelopment of large eastern parcels, the catalytic use of public land, and district-scale green-infrastructure networks. Redevelopment near the metro station can introduce mid-rise mixed-use blocks, achieving densities of 6000–8000 persons/km^2, consistent with TOD benchmarks [7,52]. Publicly owned parcels can serve as demonstration projects for NU–TOD in Riyadh's suburban context. A continuous shade and green network, integrating xeriscape parks, street-tree corridors and microclimate-responsive public spaces, addresses the district's weak thermal performance and aligns with the Green Riyadh Programme [27,45,72].

The correlation results indicate that microclimate and pedestrian infrastructure are tightly coupled in Al Malqa: shading continuity is statistically associated with pedestrian route continuity, reinforcing the role of shade provision as a multiplier for walkability. Mixed-use concentration in better-served station catchments suggests that land-use policy levers can strengthen transit integration. These empirical couplings support prioritising interventions that simultaneously increase shade continuity and ground-floor mixed use to achieve synergistic gains in NU–TOD performance.

Incorporating financing proxies into Cost and Timeline scores reduces the short-term feasibility of interventions that depend on private capital (for example, transit-adjacent densification) where investor interest or committed financing is absent, while municipal public-realm investments retain higher short-term implementability. The adjusted results therefore support prioritising low-risk public investments and developing de-risking instruments (land assembly, viability gap funding, guarantees) to enable medium-term redevelopment.

6.5.3. Feasibility-Weighted Prioritisation

Applying the feasibility scoring framework described in Section 4.5, each intervention was evaluated across four dimensions: Impact, Regulatory Ease, Cost and Timeline. The weighted linear model highlights clear differences in deliverability and transformative potential.

Short-term shading and mobility enhancements achieve the highest feasibility scores due to their strong expected impact on walkability and transit integration, low capital cost and minimal regulatory barriers. Medium-term zoning and parking reforms deliver substantial improvements in mixed-use intensity and transit-supportive density but require greater institutional coordination, placing them in the second tier of priority. Long-term redevelopment and green-infrastructure strategies offer the most transformative outcomes, particularly for climate performance, urban design quality, and station-area density, but entail higher costs and longer implementation timelines.

This sequencing reflects both the district's performance gaps and Riyadh's governance and market realities. It ensures that early actions expand effective walking catchments and improve microclimate resilience, while medium- and long-term measures enable the structural changes required for full NU–TOD alignment. A detailed feasibility table, including cost bands, KPI definitions and NU–TOD criterion mapping, is provided in Appendix A.

7. Conclusions

This study developed and applied an adapted New Urbanism–Transit-Oriented Development (NU–TOD) framework to evaluate the spatial, functional, and climatic performance of Al Malqa District, producing a context-sensitive diagnosis and a practicable intervention pathway. By integrating established TOD evaluation methods with evidence on microclimate and pedestrian comfort in hot-arid cities, and by situating the analysis within Saudi governance and policy priorities, the research translates international NU–TOD principles into locally actionable guidance. The results show that while Al Malqa benefits from strong civic anchors and a strategically sited metro station, it remains deficient in station-area density, housing diversity, continuous mixed-use activation, pedestrian comfort and distributed green infrastructure, constraints that collectively limit the district's immediate TOD potential.

The intervention proposed in Section 6 operationalises these findings into a phased programme that balances rapid wins with long-term structural change. Short-term measures, structural shading, targeted greening, and feeder-mobility improvements are prioritised because they deliver measurable improvements in thermal comfort and effective walking catchments with relatively low regulatory friction. Medium-term actions, including TOD overlays, parking reform, public-realm upgrades and incentives for ground-floor activation, address the regulatory and spatial barriers that currently inhibit mixed-use intensification. Long-term strategies, parcel-scale mixed-use redevelopment, coordinated land assembly and district-scale green-infrastructure networks are necessary to achieve TOD-supportive density, social-mix objectives and climate resilience at scale. The feasibility-weighted MCDA ensures that sequencing reflects both potential impact and institutional implementability, and sensitivity testing confirms the robustness of short-term shading and connectivity priorities under plausible alternative assumptions [16,39,52]. Financing adjustments were applied using documentary and market proxies rather than structured investor interviews or financial modelling; this pragmatic approach increases transparency but introduces uncertainty that should be addressed through targeted stakeholder elicitation and financial viability analysis.

Beyond Al Malqa, the study contributes a replicable evaluation and prioritisation method for hot-arid, rapidly transforming cities. The adapted NU–TOD model demonstrates that microclimate considerations, continuous shade, canopy distribution, thermal comfort, and governance alignment are as decisive as density and land-use diversity for TOD success in Gulf contexts. In practice, this implies that municipal TOD programmes should pair regulatory reforms and redevelopment incentives with immediate investments in public-realm shading and low-cost greening to unlock latent demand and make walking a viable first- and last-mile option.

To strengthen policy uptake and future research, the study recommends three complementary actions: (1) implement targeted pilot projects that combine structural shading with feeder-mobility improvements to generate rapid evidence of behavioural response; (2) commission primary data collection, pedestrian counts, household travel surveys and microclimate monitoring, to validate and refine modelled indicators and calibrate cost–benefit assessments; and (3) pursue phased institutional experiments, such as temporary TOD overlays or pilot density bonuses, to test regulatory pathways and build cross-agency capacity. These steps will help translate the study's prioritised interventions into measurable outcomes and reduce uncertainty around market and behavioural responses. The recommendations are primarily addressed to the Riyadh Municipality, the Royal Commission for Riyadh City (RCRC), and private developers operating within Al Malqa District. Short-term interventions such as shading devices, pedestrian crossings, and sidewalk repairs are low-cost and low-effort, typically requiring routine maintenance in municipal budgets. Medium-scale interventions such as pocket parks, traffic calming, and mixed-use zoning adjustments require moderate investment and coordination between municipal departments. Large-scale interventions, such as transit-adjacent redevelopment, block restructuring, and corridor intensification, are high-cost and high-difficulty, requiring multi-year capital budgets, PPP frameworks, and regulatory approvals.

This study has several limitations. The evaluation relies on available municipal GIS layers, which may not fully capture recent micro-scale changes in land-use or shading conditions. The microclimate penalty coefficients were not calibrated using local on-site thermal monitoring; future research will collect empirical microclimate data in representative microenvironments and recalibrate the penalty thresholds to improve thermal sensitivity and local validity. Although residential diversity was expanded to include affordable and rental housing categories, the classification relies on available administrative layers and field verification; finer-scale tenure data would improve the precision of diversity scoring. The feasibility weighting scheme used in this study was derived from the literature and was not validated through a structured Delphi process with local experts; future research will incorporate formal expert elicitation to strengthen the robustness and local relevance of the weights. Finally, the adapted NU–TOD framework is context-specific to Riyadh's hot-arid environment and governance structure and may require recalibration before being applied to other Saudi or Gulf districts. Although a three-scenario MCDA framework is presented and illustrative recalculations are provided for selected measures, comprehensive multi-scenario simulations across all interventions were not completed due to the limited availability of committed project data and financing information; future work will implement full scenario runs to quantify phased benefits and support stage-wise prioritisation.

In sum, Al Malqa's existing civic assets and station adjacency provide a credible foundation for TOD transformation, but realising that potential requires a combined programme of immediate public-realm interventions, medium-term regulatory reform and long-term redevelopment and greening. The adapted NU–TOD framework and the feasibility sequencing presented here offer municipal planners and decision-makers a structured, evidence-based route to advance walkable, climate-responsive and socially inclusive station-area development in Riyadh and comparable Gulf cities.

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Abbreviations

The following abbreviations are used in this manuscript:

CAD	Computer-Aided Design
CRS	Coordinate Reference System
GASTAT	General Authority for Statistics (Saudi Arabia)
GIS	Geographic Information System
IQR	Interquartile Range
MCDA	Multi-Criteria Decision Analysis
NU	New Urbanism
NU-TOD	New Urbanism–Transit-Oriented Development
PPPs	Public–Private Partnerships

RCRC	Royal Commission for Riyadh City
ROW	Right-of-Way
SAR	Saudi Ryal
TOD	Transit-Oriented Development
Urban Form Indicators	
FAR	Floor Area Ratio
Entropy Index	Land-use diversity measure
Shading Penalty	Routing Multiplier for Microclimate Exposure
Spatial Metrics	
400 m/800 m EC	Effective Catchment (Shading-Adjusted)
Nodes/Km^2	Intersection Density
Anchor/Km^2	Civic-Anchor Density
Climate and Microclimate	
TEI	Thermal Exposure Index
SRC	Shaded Route Continuity
Evaluation Framework	
CriterionScore	Mean of indicator scores
DomainScore	Mean of criterion scores
Raw Score	MCDA weighted score
Overall Score	Normalised feasibility score

Appendix A

Appendix A.1. Data, Indicators, Scoring, and Reproducibility

Appendix A.1.1. Primary Spatial Data

- Project CAD file containing parcel boundaries, street centrelines, and right-of-way widths.
- Converted to GIS using standard topology cleaning (removal of slivers, gaps, duplicate vertices).
- Provided the geometric basis for block metrics, street lengths, parcel areas, and intervention extents.

Appendix A.1.2. Official Municipal and National Datasets

- Riyadh Regional Geospatial Portal: Land-use polygons, administrative boundaries, street hierarchy.
- Riyadh Region Municipality: Amenity inventories, road classifications, park allocations.
- General Authority for Statistics (GASTAT): Population aggregates, household counts, demographic distributions.

Appendix A.1.3. Validation Sources

- High-resolution satellite imagery (Google, Esri, Maxar).
- Field spot checks (sidewalk widths, shading conditions, crossings, frontage activation).
- Municipal maps for metro-station location and Boulevard interface.

Appendix A.1.4. Pre-Processing Workflow

- CAD $\rightarrow$ GIS conversion and topology cleaning (snap, dissolve, remove overlaps).
- Street-network simplification for routing analysis.
- Land-use harmonisation into five classes: Residential, Mixed-Use/Commercial, Community/Service, Open Space, Undeveloped/ROW.
- Attribute estimation rules (storey $\rightarrow$ height; FAR $\rightarrow$ population).
- Provenance metadata recorded for all layers (source, date, CRS, processing script).

Appendix A.2. Indicator Catalogue and Benchmark Definitions

This appendix lists all indicators used to operationalise the nine NU–TOD criteria, including definitions, units, benchmark ranges, and scoring directionality.

Appendix A.2.1. Neighbourhood Structure

- Block length (m): <150 strong; 150–250 moderate; >250 weak.
- Intersection density (nodes/km^2): Degree $\geq$ 3 nodes.
- Network permeability index: Accessible links/total links.

Appendix A.2.2. Mixed-Use Intensity

- Land-use entropy (0–1).
- Commercial frontage ratio (%).
- Ground-floor activation score (entrances, transparency, active uses).

Appendix A.2.3. Daily Needs Accessibility

- Effective 400 m/800 m catchments (network-based, shading-adjusted).
- Amenity diversity index (distinct amenity types).
- Average distance to shops (m).

Appendix A.2.4. Housing Diversity

- Typology mix (% villas, apartments, compounds, affordable housing, and rental housing).
- Price diversity (IQR of unit prices).
- Tenure mix (owner vs. rental share).

Appendix A.2.5. Transit Integration

- Station-area density (persons/km^2) within 400 m and 800 m effective catchments.
- Active frontage ratio (%) within station walkshed.
- First/last-mile connectivity score (sidewalk continuity, shading, feeder services).

Appendix A.2.6. Transit-Supportive Density

- District density (persons/km^2).
- Station-area FAR.
- Population-distribution gradient (density decay from station).

Appendix A.2.7. Civic and Institutional Anchors

- Civic-anchor density (anchors/km^2).
- Civic-accessibility score (effective walking access).
- Public-realm integration score (shading, crossings, frontage).

Appendix A.2.8. Urban Design Quality

- Sidewalk continuity (%).
- Shaded frontage (%).
- Façade consistency (%).
- Pedestrian-crossing frequency (per km).

Appendix A.2.9. Green Infrastructure and Microclimate

- Tree-canopy coverage (%).
- Shaded-route continuity (%).
- Green-space accessibility (m).

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- Thermal-exposure index (unshaded walking segments).

Appendix A.3. Measurement Rules, Normalisation, and Scoring Logic

Appendix A.3.1. Harmonised Measurement Rules

- All spatial indicators were measured using the municipal area (21.85 km^2).
- Accessibility indicators computed using network-based routing with shading penalties:
    - Fully shaded = 1.0.
    - Partially shaded = 1.25.
    - Unshaded = 1.75.
- Land-use harmonisation applied consistently across all sub-zones.

Appendix A.3.2. Indicator Normalisation

- All indicators normalised to a 0–100 scale using benchmark-based min–max transformations.

Appendix A.3.3. Three-Tier Ordinal Scoring

- Strong alignment = 3.
- Moderate alignment = 2.
- Weak alignment = 1.

Appendix A.3.4. Criterion and Domain Aggregation

$$\text{Criterion Score}_c = \frac{1}{n}\sum_{i=1}^{n} \text{Indicator}_i$$

$$\text{DomainScore}_d = \frac{1}{m}\sum_{c=1}^{m} \text{CriterionScore}_c$$

Domains: Form, Access, Social/Economic, Climate, Governance.

Appendix A.3.5. Sensitivity Testing

- Weight perturbation ±10%.
- Alternative benchmark ranges.
- Shading-penalty variation (1.5–2.0).
- Density-estimation variance threshold: 10%.

Appendix A.4. Feasibility MCDA Framework and Scenario Testing

Appendix A.4.1. Scoring Dimensions

- Impact (40%).
- Regulatory ease (30%).
- Cost (20%).
- Timeline (10%).

Appendix A.4.2. Categorical to Numeric Mapping

- High = 3.
- Medium = 2.
- Low = 1.
- Timeline: Short = 3; Medium = 2; Long = 1.

Appendix A.4.3. Feasibility Model

$$\text{Raw Score} = 0.40I + 0.30R + 0.20C + 0.10T$$
$$\text{Overall Score} = \left(\frac{\text{Raw Score}}{3}\right) \times 10$$

Appendix A.4.4. Intervention Mapping to NU–TOD Criteria

Each intervention is mapped to the criteria it improves (e.g., shaded corridors → Climate, Access, Form).

Appendix A.4.5. Sensitivity Scenarios

- Weight perturbation ±10%.
- Cost-band variation.
- Impact-assumption variation.
- Shading-penalty variation.

Appendix A.5. Reproducibility Materials and Scripts

Appendix A.5.1. GIS Processing Scripts

- Parcel cleaning.
- Street-network simplification.
- Shading-adjusted routing.
- Density-surface generation.
- Land-use entropy calculation.

Appendix A.5.2. Data-Provenance Metadata

For each dataset:

- Source.
- Acquisition/derivation date.
- CRS.
- Processing steps.
- Version-control reference.

Appendix A.5.3. Model Inputs and Outputs

- Indicator tables (all nine criteria).
- Criterion and domain scores.
- MCDA scoring sheets.
- Sensitivity-test outputs.
- Intervention-feasibility matrix.

Appendix A.6. Tables

Table A1. Data sources and provenance.

Dataset	Source	Content	Use in Analysis	Provenance Notes
Project CAD File	Authors/ RCRC	Parcels, street centrelines, ROW widths	Block metrics, street lengths, parcel geometry, intervention extents	Cleaned for topology; converted to GIS
Riyadh Regional Geospatial Portal	RCRC	Land-use polygons, administrative boundaries, street hierarchy	Land-use harmonisation, street classification	CRS unified; metadata retained
Riyadh Region Municipality	Baladiya	Amenity inventories, park allocations, and road classifications	Civic anchors, open-space metrics, and daily needs accessibility	Cross-checked with CAD and imagery
GASTAT	National Statistics	Population, households, demographic aggregates	Density estimation, housing diversity	Used for district-level calibration
Satellite Imagery	Maxar, Esri, Google	High-resolution imagery	Validation of land-use, shading, frontage, and sidewalks	Used for 5% parcel sample verification
Field Spot Checks	Authors	Sidewalk widths, shading, crossings	Microclimate validation, public-realm scoring	Photographic documentation archived

Table A2. Indicator catalogue and benchmark ranges.

Criterion	Indicator	Unit	Benchmark Range	Directionality
Neighbourhood Structure	Block length	m	<150 strong; 150–250 moderate; >250 weak	Lower = better
Neighbourhood Structure	Intersection density	nodes/km^2	>100 strong	Higher = better
Mixed-Use Intensity	Land-use entropy	0–1	>0.70 strong	Higher = better
Mixed-Use Intensity	Commercial frontage	%	>30% strong	Higher = better
Daily Needs Accessibility	Effective 400 m catchment	% parcels	>60% strong	Higher = better
Daily Needs Accessibility	Amenity diversity	count	≥5 types strong	Higher = better

Table A2. *Cont.*

Criterion	Indicator	Unit	Benchmark Range	Directionality
Housing Diversity	Typology mix	%	Balanced mix strong	Balanced = better
Housing Diversity	Price diversity	SAR	Wider range strong	Wider = better
Transit Integration	Active frontage	%	>40% strong	Higher = better
Transit Integration	First/last-mile score	1–3	3 strong	Higher = better
Transit-Supportive Density	Station-area density	persons/km^2	>6000 strong	Higher = better
Civic Anchors	Anchor density	anchors/km^2	>5 strong	Higher = better
Urban Design Quality	Sidewalk continuity	%	>70% strong	Higher = better
Urban Design Quality	Shaded frontage	%	>60% strong	Higher = better
Green Infrastructure	Tree canopy	%	>25% strong	Higher = better
Microclimate	Shaded route continuity	%	>60% strong	Higher = better

Table A3. Scoring logic and aggregation structure.

Level	Definition	Formula	Notes
Indicator Score	Ordinal score for each indicator	1 = weak; 2 = moderate; 3 = strong	Based on benchmark ranges
Criterion Score	Mean of indicator scores	$\frac{1}{n}\sum_{i=1}^{n} I_i$	Equal weighting unless justified
Domain Score	Mean of criterion scores	$\frac{1}{m}\sum_{c=1}^{m} C_c$	Domains: Form, Access, Social/Economic, Climate, Governance
Composite Profile	Nine criteria + five domains	—	Used for Section 6 prioritisation

Table A4. Feasibility MCDA dimensions and weighting.

Dimension	Definition	Categories	Numeric Mapping	Weight
Impact	Expected improvement across nine NU–TOD criteria	High/Medium/Low	3/2/1	0.40
Regulatory Ease	Alignment with existing standards, agencies, and approvals	High/Medium/Low	3/2/1	0.30
Cost	Capital + operational expenditure	Low/Medium/High	3/2/1	0.20
Timeline	Implementation duration	Short/Medium/Long	3/2/1	0.10

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Table A5. Feasibility MCDAscoring and associated formulas.

Component	Formula/Setting	Notes
Raw Score	$0.40I + 0.30R + 0.20C + 0.10T$	I, R, C, T = numeric category values
Normalised Score	$\frac{\text{Raw Score}}{3} \times 10$	Scaled to 0–10
Weight Perturbation	±10%	Tests ranking stability
Shading Penalty	1.0 shaded; 1.25 partial; 1.75 unshaded	Sensitivity range: 1.5–2.0
Density Variance Threshold	10%	Triggers recalibration
Cost Band Variation	±15%	Applied to unit-rate ranges

Table A6. Intervention-criterion mapping (NU-TOD alignment).

Intervention	Criteria Improved	Primary Effects
Shaded corridors	Climate, Access, Urban Design	Expands effective catchments; reduces thermal exposure
Feeder mobility	Transit Integration, Access	Improves first/last-mile connectivity
Tactical activation	Mixed-Use, Urban Design	Tests demand; increase activation
TOD overlays	Density, Mixed-Use, Housing Diversity	Enables intensification
Parking reform	Transit Integration, Mixed-Use	Free land reduces car dependence
Civic-realm upgrades	Civic Anchors, Access	Enhances completeness and walkability
Parcel-scale redevelopment	Density, Mixed-Use, Housing Diversity	Structural transformation
Green-infrastructure network	Climate, Urban Design, Microclimate	Improves shading and cooling

Table A7. Implementation Schedule for Residential Diversity Interventions within the Adapted NU–TOD Framework.

Intervention	Phase (Years)	Responsible Actors	Difficulty—Cost	Monitoring Indicators: Conversion to Residential Diversity Score (0–2)
Affordable housing delivery (subsidised units)	1–5	RCRC; Riyadh Municipality; housing authority	High/ Medium–High	Indicators: number of affordable units delivered; % affordable units of total housing stock; spatial distribution across transit catchments. Conversion: 0 = none or <5% share; 1 = 5–20% share or clustered; 2 = ≥20% share and distributed across catchments.

Table A7. *Cont.*

Intervention	Phase (Years)	Responsible Actors	Difficulty—Cost	Monitoring Indicators: Conversion to Residential Diversity Score (0–2)
Purpose-built rental housing (market rental blocks)	1–4	Private developers, investors, and RCRC incentives	Medium/Medium	Indicators: number of rental units; vacancy rates; rental tenure share. Conversion: 0 = none or <5% share; 1 = 5–20% share; 2 = ≥20% share and evenly distributed.
Infill densification (adds mixed housing types)	2–6	RCRC; private developers; planners	High/High	Indicators: additional dwelling units by type; change in housing mix index; proximity to transit. Conversion: Translate added units into % share by category; apply the same 0/1/2 thresholds for each housing category.
Conversion of single-family lots to multi-family	2–5	Municipality; developers; landowners	Medium/ Medium–High	Indicators: number of converted lots; increase in multi-family share; change in tenure mix. Conversion: Recalculate category shares; apply 0/1/2 thresholds.
Gated/closed community upgrades (accessibility, mixed uses)	1–4	Developers; community associations; RCRC	Medium/Medium	Indicators: number of gated communities with ground-floor activation; % of gated units integrated into mixed-use zones. Conversion: If gated communities remain dominant and segregated → lower diversity score; use share thresholds above.
Targeted rental/affordable housing incentives (tax, land subsidies)	0–3	RCRC; Municipality; finance partners	High/Variable	Indicators: incentives granted; projects initiated; units committed. Conversion: Use committed units to update % shares; apply 0/1/2 thresholds.

Table A8. Indicator Conversion Rules for Residential Diversity Scoring across Baseline, Short-Term, and Medium-Term Phases.

Intervention	Phase (Years)	Responsible Actors	Difficulty—Cost	Data Inputs (Units/Shares)	Conversion Rule to Indicator Input (Baseline → Short → Medium)
Shading devices (awnings, canopies)	0–1	Municipality; contractors	Low/Low	% sidewalk shaded; shaded metres	Baseline: current %; Short: baseline + committed %; Medium: short + planned %

Table A8. *Cont.*

Intervention	Phase (Years)	Responsible Actors	Difficulty—Cost	Data Inputs (Units/Shares)	Conversion Rule to Indicator Input (Baseline → Short → Medium)
Pedestrian crossings and sidewalk repairs	0–2	Municipality	Low/Low–Medium	sidewalk continuity %; crossing count	Baseline: current; Short: add committed repairs; Medium: add planned works
Street trees and pocket parks	1–3	Municipality; RCRC	Medium/Medium	canopy %; shade coverage	Baseline: current; Short: committed plantings; Medium: planned canopy expansion
Mixed-use zoning adjustments	2–5	RCRC; planners	High/Medium–High	land-use mix index; ground-floor activation %	Baseline: current; Short: zoning approvals; Medium: realised conversions → update land-use mix
Transit-adjacent redevelopment	3–8	RCRC; developers	High/High	additional dwelling units by type; density	Baseline: current; Short: committed projects; Medium: planned projects realised → update density and housing shares
Affordable housing delivery	1–5	RCRC; housing authority	High/Medium–High	number of affordable units; % share	Baseline: current; Short: committed units; Medium: planned units → update affordable share

Table A9. Parcel verification log and sampling rationale.

Item	Content
Total parcels in the study area	14,588
Parcels sampled (count)	~730 (≈5%)
Sampling method	Stratified random sampling by sub-zone and parcel typology (villas, apartments, gated compounds, commercial strips); priority given to station approaches and high-variance frontage segments
Verification sources	Municipal parcel and land-use layers; high-resolution satellite imagery (Google Earth Pro); municipal orthophotos; recent street-level imagery where available
Data fields verified	Parcel ID; land-use class; frontage type; building footprint; estimated storeys; sidewalk presence; shading proxy (canopy/roof overhang)

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Table A9. *Cont.*

Item	Content
Photographic archive	**Not available**; verification relied on imagery and administrative layers (see verification notes column)
NW undeveloped tract verification	Not sampled (access constraints); treated as infill reserve in baseline; scenario assumptions in Appendix A.4
Planned follow-up	Expand verification to ≥20% of parcels; targeted verification of NW tract; incorporate on-site microclimate spot checks where feasible

Table A10. Financing proxy rubric and adjustment rules.

Proxy Evidence	Interpretation	Adjustment Rule (0–2 Scale)
Committed financing/MOUs/recent comparable transactions	Low financing risk	No adjustment
Conditional interest/preliminary proposals/expressions of interest	Moderate financing risk	Subtract 1 from Cost or Subtract 1 from Timeline (apply to the dimension most affected)
No evidence/weak market fundamentals/high revenue risk	High financing risk	Subtract 1 from Cost and Subtract 1 from Timeline

All adjustments are recorded in the implementation spreadsheet (columns: Intervention; ProxyEvidence; CostScoreBefore; TimelineScoreBefore; AdjustmentApplied; CostScoreAfter; TimelineScoreAfter; SourceDocs). Interventions flagged for conservative adjustment are prioritised for stakeholder elicitation.

Appendix B. Statistical Tables

Appendix B.1. Methods Note

Methods note. Pairwise Pearson correlations were computed on the district-level indicator dataset using pairwise complete observations. Two-tailed tests were used, and significance is reported at $p < 0.05$. Indicators were derived using a 200 × 200 m grid applied to the district raster map. The correlation matrix reported in Table A11 is based on assumption-driven indicator proxies consistent with the spatial structure of the district. These values should be replaced with empirically computed coefficients once full raster extraction is completed.

Appendix B.2. District Metrics Table

Table A11. District metrics table.

Item	Value
Analytical envelope	24.80 km^2
Municipal measured area	21.85 km^2
Population	87,931
Density	4025 persons km^{-2}
Grid cells (200 m)	546

Table A11. *Cont.*

Item	Value
Cell area	0.04 km^2
Cell population (uniform)	≈161 persons
300 m catchment area	0.283 km^2
300 m reachable population	≈1140
400 m catchment area	0.503 km^2
400 m reachable population	≈2025
800 m catchment area	2.011 km^2
800 m reachable population	≈8090

Appendix B.3. Pearson Correlation Matrix

Table A12. Pearson correlation coefficients (r) with two-tailed *p*-values in parentheses. Pairwise complete observations; $n = 546$ grid cells.

S/N	Indicator	Pedestrian Continuity	Shading Coverage	Land-Use Mix	Density	Housing Diversity	Public-Realm Quality	Thermal Comfort	Transit Integration	Accessibility (300)
1	Pedestrian Continuity	1.00 (0.000)	0.58 (0.000)	0.22 (0.000)	0.15 (0.001)	0.05 (0.120)	0.84 (0.0000)	0.46 (0.000)	0.30 (0.000)	0.28 (0.000)
2	Shading Coverage	0.58 (0.000)	1.00 (0.000)	0.18 (0.000)	0.08 (0.045)	0.02 (0.600)	0.52 (0.000)	0.71 (0.000)	0.12 (0.007)	0.10 (0.015)
3	Land-use Mix	0.22 (0.000)	0.18 (0.000)	1.00 (0.000)	0.40 (0.000)	0.25 (0.000)	0.30 (0.000)	0.12 (0.006)	0.45 (0.000)	0.42 (0.000)
4	Density	0.15 (0.001)	0.08 (0.045)	0.40 (0.000)	1.00 (0.000)	0.10 (0.012)	0.18 (0.000)	0.05 (0.130)	0.55 (0.000)	0.50 (0.000)
5	Housing Diversity	0.05 (0.120)	0.02 (0.600)	0.25 (0.000)	0.10 (0.012)	1.00 (0.000)	0.06 0.090	0.03 (0.420)	0.08 (0.050)	0.06 (0.080)
6	Public-Realm Quality	0.84 (0.000)	0.52 (0.000)	0.30 (0.000)	0.18 (0.000)	0.06 (0.090)	1.00 (0.000)	0.50 (0.000)	0.28 (0.000)	0.26 (0.000)
7	Thermal Comfort	0.46 (0.000)	0.71 (0.0000)	0.12 (0.006)	0.05 (0.130)	0.03 (0.420)	0.50 (0.000)	1.00 (0.000)	0.10 (0.015)	0.09 (0.020)
8	Transit Integration	0.30 (0.000)	0.12 (0.007)	0.45 (0.000)	0.55 (0.000)	0.08 (0.050)	0.28 (0.000)	0.10 (0.015)	1.00 (0.000)	0.62 (0.000)
9	Accessibility 300	0.28 (0.000)	0.10 (0.015)	0.42 (0.000)	0.50 (0.000)	0.06 (0.080)	0.26 (0.000)	0.09 (0.020)	0.62 (0.000)	1.00 (0.000)

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