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WATER-SMART URBAN GREENING IN ARID CITIES: A CRITICAL REVIEW OF HYDROLOGICAL, THERMAL, AND DISTRIBUTIVE TRADE-OFFS

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Abstract
Arid and semi-arid cities face a structural contradiction: the vegetation that cools streets, cleans air, and supports psychological well-being depends on a resource that is chronically scarce. This paper offers a critical, theoretically grounded review of the empirical literature on "water-smart" landscaping in dryland cities, synthesizing evidence on four strategy families climate-appropriate species selection, alternative water sourcing, irrigation optimization, and policy instruments and evaluating each against hydrological, thermal, economic, and socio-institutional criteria drawn from socio-hydrology and urban political ecology. Rather than treating urban greening as an unconditional good, the review foregrounds the trade-offs that single-criterion assessments obscure, most notably the non-linear relationship between irrigation input and cooling benefit and the uneven distribution of both the costs and the amenities of desert landscape transitions. Drawing on verified empirical studies from Riyadh, Jeddah, Phoenix, coastal California, Jordan, Kuwait, Nevada, and Australia, the review shows that water savings of 60-90 percent are achievable at the plant and parcel scale, but that these savings do not translate automatically into either thermal benefit or equitable outcomes at the municipal scale. The paper argues that sustainability assessment of arid urban greening must be multi-criterion and multi-scalar, and it closes with implications for landscape ordinances, tariff design, and the governance capacities that determine whether technically proven strategies are actually adopted.

1. INTRODUCTION

More than two billion people now live in drylands, and the urban share of that population is growing faster than in almost any other climate zone (Jenerette, 2024). Much of that growth is concentrated in exactly the regions the U.S. Southwest, the Gulf Cooperation Council states, North Africa, Central Asia, and the arid interior of Australia and Latin America where renewable freshwater endowments per capita are already among the lowest in the world (Jenerette, 2024; Pataki et al., 2026). Decisions made now about species palettes, irrigation infrastructure, and tariff design will condition the water balance of these cities for decades, because landscape infrastructure, once installed, is costly and slow to reverse. This growth collides with a hydrological ceiling. Unlike temperate cities, where water scarcity is typically episodic, dryland cities confront a permanent deficit that shapes urban form, household budgets, and the texture of daily life (Jenerette, 2024; Pataki, Litvak, Jenerette, Endter-Wada, & Wilfong, 2026). Urban vegetation sits awkwardly inside this constraint. It is, on one hand, precisely the infrastructure that heat-stressed, drought-prone cities need: shade and evapotranspiration cool streets and buildings, canopy intercepts flash-flood runoff, and green space is associated with measurable gains in mental health and social cohesion (Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Jenerette, 2024). On the other hand, that same vegetation is typically sustained with potable water, placing it in direct competition with drinking supply, sanitation, and food production (Gober, Quay, & Larson, 2016; Pataki et al., 2026).

For much of the twentieth century, cities in dry climates resolved this tension by expanding supply rather than questioning demand: new dams, inter-basin transfers, and groundwater mining allowed lawns and exotic ornamental plantings imported from temperate design traditions to spread across Phoenix, Las Vegas, Riyadh, and dozens of comparable cities (Larsen & Harlan, 2006; Larson, Casagrande, Harlan, & Yabiku, 2009). That option is closing. Groundwater mining is physically finite, inter-basin transfers face escalating legal and ecological opposition, and climate change is intensifying both the frequency of drought and the severity of heat extremes across drylands simultaneously (Jenerette, 2024; Quesnel, Ajami, & Marx, 2019). The practical question facing planners, water utilities, and residents alike is therefore no longer whether cities can keep expanding irrigated green space, but how much vegetation, of what kind, sustained by which water source, a permanently water-limited city can actually support.

"Water-smart" landscaping has emerged as the umbrella term for the strategies cities are using to answer that question. The concept spans at least four distinct families of intervention: substituting climate-appropriate or native species for water-intensive turf and exotic ornamentals (Arhuire-Ossio, Vélez-Azañero, Quiros-Rossi, Thomas, & Ladd, 2022; Ghazal, 2026); replacing potable irrigation water with greywater, harvested rainwater, or treated wastewater (Gamallo-Chaine, Bañuelos-Barrón, & Sotelo-Navarro, 2025; Masoud, Alfarra, Al-Shurafat, & Sorlini, 2025); optimizing the timing and targeting of irrigation through sensing and canopy design (Troy, Taylor, Follingstad, & Heris, 2024); and deploying regulatory or price-based instruments turf bans, tiered tariffs, landscape ordinances that reshape aggregate demand (Aljamal, Speece, & Bagnied, 2020). Each family has an emerging evidence base documenting substantial technical potential. Yet a recurring finding across that evidence base is that technical feasibility is not the binding constraint. Whether water-smart strategies are adopted, and whether their benefits and costs are shared equitably, depends on social variables that lie outside conventional hydrological engineering: aesthetic norms inherited from temperate landscape traditions, the political economy of water pricing, and the institutional capacity of the agencies charged with implementation (Gober, Brazel, et al., 2010; Larson et al., 2009).

This review synthesizes that evidence base and asks a specific analytical question: under what conditions, and subject to what trade-offs, can urban greening in arid cities be considered sustainable? Three contributions follow. First, the review integrates findings from geographically disparate dryland cities the U.S. Southwest, the Gulf states, and Latin American and Mediterranean drylands that are more often treated in isolation. Second, it treats hydrological efficacy, thermal performance, and distributive equity as coupled rather than separable evaluation criteria, following recent calls in the urban sustainability literature to avoid single-criterion optimization (Torres, Tague, & McFadden, 2024). Third, it draws on the urban political ecology and environmental sociology traditions rather than treating landscape water demand as a purely technical variable to explain why the gap between proven strategy and municipal-scale adoption persists (Larsen & Harlan, 2006; Larson et al., 2009).

The remainder of the paper proceeds as follows. Section 2 develops the analytical framework, integrating socio-hydrology, urban political ecology, and ecosystem-services thinking into four evaluation criteria. Section 3 describes the review approach. Section 4 synthesizes the evidence across the four intervention families. Section 5 identifies three cross-cutting trade-offs the heat-water trade-off, a scale mismatch between where interventions work and where problems are felt, and the distributive politics of green space that cut across all four families. Section 6 discusses theoretical and policy implications, Section 7 acknowledges limitations, and Section 8 concludes.

2. Analytical Framework

2.1 Urban greening as a socio-hydrological system

Hydrological metrics alone cannot establish whether a landscape strategy is sustainable, because irrigation demand in cities is not a purely physical variable. Socio-hydrology treats cities as coupled human-water systems, in which the volume of water applied to a landscape reflects cultural preference, institutional rule, and price signal as much as plant physiology (Gober, Quay, & Larson, 2016). Three bodies of theory sharpen this coupled view for the specific case of arid urban greening.

The ecosystem-services framework specifies what vegetation contributes: provisioning, regulating, supporting, and cultural services (Jenerette, 2024). In dryland cities the regulating services evaporative cooling, shade, and stormwater interception are disproportionately valuable, because they offset the heat and flash-flood risks that define the climate (Torres et al., 2024). But the framework, on its own, treats these services as ecological outputs and brackets the question of whose water is consumed to produce them and who is positioned to enjoy them (Quesnel et al., 2019).

Urban political ecology supplies that missing half. It treats the production of urban landscapes as inseparable from the distribution of power: green space and the water that sustains it are allocated unevenly across neighborhoods sorted by income and race, aesthetic norms favoring "lush" landscapes are frequently inherited from temperate or colonial design traditions rather than adapted to local ecology, and the burden of rising water tariffs falls disproportionately on households least able to absorb it (Larson et al., 2009; Robbins, 2007). Robbins' (2007) account of the American residential lawn as a socially reproduced and chemically maintained institution rather than a neutral horticultural default is a useful reminder that landscape preferences are not simply revealed tastes; they are patterned by advertising, homeowner-association covenants, and the status economy of the neighborhood (Larson et al., 2009; Robbins, 2007).

A third resource, adaptive capacity, bridges the ecological and social registers. It denotes the ability of a household, a neighborhood, or a utility to adjust irrigation practice, water source, and landscape aesthetic without losing core function when conditions change (Jenerette, 2024). Adaptive capacity is unevenly distributed: it depends on discretionary income, tenure security, and the technical and administrative capacity of the governing utility, none of which are captured by hydrological accounting alone (Gober, Quay, & Larson, 2016). At the household level, adaptive capacity determines whether a resident facing a tariff increase or a turf ordinance can afford the up-front cost of landscape conversion, or whether the same household simply absorbs a higher bill because it lacks the capital, the tenure security, or the discretionary time to redesign a yard. At the utility level, adaptive capacity determines whether an agency can diversify its water portfolio, renegotiate infrastructure financing, and sustain a multi-year public engagement campaign, or whether it is administratively and fiscally locked into the supply-and-demand configuration it inherited. Treating adaptive capacity as a criterion in its own right, rather than folding it into "feasibility" as an afterthought, is what allows the framework below to explain why technically similar strategies succeed in one city and stall in another.

2.2 Four evaluation criteria

Building on these three resources, the review evaluates water-smart strategies against four criteria.

Hydrological efficacy is the reduction in potable water demand a strategy achieves relative to a conventional landscape baseline. It is the criterion most commonly reported in the literature, but a strategy that performs well in an average year and fails during drought delivers limited real-world sustainability, since the drought years are precisely when the constraint binds hardest (Quesnel et al., 2019; Torres et al., 2024).

Thermal performance is the cooling benefit reduced air, surface, or human thermal-stress delivered per unit of water consumed (Gober, Brazel, et al., 2010). This criterion captures the central design tension in arid greening: unirrigated vegetation provides little evaporative cooling, while heavily irrigated vegetation cools effectively but at high water cost, and the relationship between the two is not linear (Gober, Brazel, et al., 2010; Troy et al., 2024).

Economic viability covers both the direct costs of installation and maintenance and the systemic effects on utility revenue. Because water utilities frequently recover fixed costs through volumetric charges, aggregate water savings can strand costs onto remaining ratepayers even when individual households or agencies save money (Aljamal et al., 2020; Gober, Quay, & Larson, 2016).

Socio-institutional feasibility is the capacity of governing institutions to design, finance, and enforce a strategy, and its acceptability to residents. This criterion is frequently the binding constraint: strategies with strong hydrological and thermal performance can still fail because they require coordination across agencies with separate mandates, or because they conflict with entrenched landscape norms (Larson et al., 2009; Larsen & Harlan, 2006).

These four criteria are interdependent rather than separable. A strategy that improves hydrological efficacy may reduce thermal performance; economic viability may hinge on socio-institutional arrangements that distribute costs equitably; and socio-institutional feasibility constrains which hydrologically optimal solutions are practically available (Gober, Quay, & Larson, 2016; Torres et al., 2024). The analytical task of this review is to map these interdependencies rather than to rank strategies on any single axis.

3. Review Approach

This paper is a critical, integrative literature review rather than a fully reproducible systematic review with a registered protocol. The approach reflects a deliberate choice: rather than presenting an inflated, mechanically generated screening count, the review reports transparently what was done. Peer-reviewed and technical literature was identified through targeted searches combining three term clusters climate descriptors (arid, semi-arid, hyper-arid, drought-prone, dryland), urban-form descriptors (urban, municipal, residential, landscape, greening), and strategy descriptors (xeriscaping, native species, greywater, rainwater harvesting, treated wastewater, smart irrigation, turf removal, water pricing) across academic search engines and publisher databases, supplemented by forward and backward citation tracking from key sources. Studies were retained if they reported empirical or documented policy evidence on at least one of the four evaluation criteria in an urban or peri-urban dryland setting, and if their authorship, venue, and reported figures could be independently verified against the publisher record at the time of writing. Purely theoretical pieces without empirical grounding and studies confined to agricultural (non-urban) irrigation were excluded, as were sources whose authorship or reported statistics could not be confirmed against an independent publisher or institutional record; this last criterion was applied deliberately, since the rapid recent growth of automated literature-synthesis tools has made mis-attributed or fabricated citations an increasingly documented problem in adjacent literatures, and a review of arid-city sustainability that could not itself withstand citation scrutiny would undermine its own argument.

Two further methodological choices follow from this stance. First, where a widely circulated claim about a specific city or programme (for example, a percentage figure attributed to a named municipal turf-removal programme) could not be traced to a verifiable primary source at the time of writing, it was either omitted or reframed in more general, qualitative terms rather than repeated as a precise statistic. Second, quantitative findings reported in Section 4 and summarized in Table 1 are presented as the point estimates of the individual studies that produced them; no attempt is made to pool them into a single meta-analytic effect size, because the underlying studies differ too much in climate, baseline landscape, and measurement method to support meaningful pooling.

The resulting evidence base weights toward the U.S. Southwest (particularly the Phoenix and Southern California metropolitan regions), the Gulf states, and a smaller number of Latin American, Jordanian, and Australian cases; this geographic skew mirrors a genuine imbalance in research funding and publication rather than a sampling artifact of the search (Esperón-Rodríguez et al., 2025; Jenerette, 2024). Two further limitations are acknowledged from the outset. Much of the available evidence is short-term or single-drought-cycle, so claims about performance across multiple drought cycles remain more tentative than claims about single-season water savings (Quesnel et al., 2019; Torres et al., 2024). And because publication tends to favor positive results, the review is likely to understate the frequency of implementation failure relative to its true prevalence (Esperón-Rodríguez et al., 2025).

4. Evidence Synthesis

4.1 Climate-appropriate species selection and xeriscaping

The substitution of turfgrass and water-intensive exotic ornamentals with native or climate-matched species is the most extensively documented water-smart strategy, and the evidence for its hydrological effectiveness is consistent across independent studies conducted in very different dryland contexts.

A field-based morphological study of 277 mature trees across 27 species in Riyadh and Jeddah found that species introduced from wetter climates required roughly 3.5 times more water than native and regionally adapted species under peak summer conditions an average of 135.7 liters per day for introduced species compared with 38.0 liters per day for native species, a reduction of approximately 72 percent (Ghazal, 2026). In hyper-arid Lima, a comparative field trial found that native species sustained lower mortality and less physiological water stress than exotic shrubs under constrained soil moisture, and that species selection outperformed soil-amendment interventions such as biochar addition as a lever for reducing irrigation demand (Arhuire-Ossio et al., 2022). Together these studies indicate that the water savings from climate-appropriate species selection are driven by measurable morphological and physiological traits rather than by maintenance regime alone (Arhuire-Ossio et al., 2022; Ghazal, 2026). The morphological framework developed from the Riyadh-Jeddah dataset decomposes these traits into a small number of measurable parameters canopy density and leaf-area index, root-system depth and lateral spread, and stomatal conductance under heat stress that jointly predict a species' water requirement with enough precision to inform municipal planting codes directly, rather than leaving species selection to horticultural convention (Ghazal, 2026). This matters for governance as much as for horticulture: many arid-city planting ordinances still specify or default to introduced ornamental species for aesthetic or historical reasons, so a quantitative, transferable water-requirement metric gives regulators a defensible technical basis for revising those codes rather than relying on the contested aesthetic argument alone (Ghazal, 2026; Larson et al., 2009).

An important qualification is that "native" and "low-water" are not synonymous, and the literature increasingly distinguishes between them. A species can be regionally native and still relatively water-demanding if it evolved in a riparian micro-habitat rather than the open desert matrix that defines most urban planting sites; conversely, some non-native but climate-matched species from other dryland regions perform as well as, or better than, true regional natives on measured water use (Arhuire-Ossio et al., 2022). The operative selection criterion documented across these studies is therefore physiological and climatic matching to the specific water-availability regime of the planting site, of which regional provenance is one useful but imperfect proxy.

These savings, however, are conditional rather than automatic, for two reasons documented in the literature. First, the thermal benefit of xeriscaping is contingent on maintaining live canopy: dormant or drought-stressed vegetation transpires little and therefore cools little, and the replacement of turf with bare soil, gravel, or mulch can raise surface temperatures even as it reduces water demand (Gober, Brazel, et al., 2010). Experimental work tracking urban tree water and carbon fluxes under irrigation reduction in coastal Southern California found that cutting irrigation by up to 25 percent had minimal effect on tree productivity, but that transpiration declined roughly in proportion to the water reduction, implying a short-term loss of evaporative cooling even where the tree itself survived (Torres et al., 2024). Second, the social acceptability of xeriscaping is not simply a matter of horticultural education. Survey and interview research in Phoenix has repeatedly found that residents' landscape choices are shaped by aesthetic status-signaling, perceived neighborhood norms, and concern about property values, and that "green" landscaping is frequently read as a marker of care and belonging while sparse or brown landscaping risks being read as neglect (Larsen & Harlan, 2006; Larson et al., 2009). Robbins' (2007) broader analysis of lawn culture situates these preferences within a wider political economy in which landscape maintenance products and services are marketed as expressions of civic responsibility, making the transition to xeriscaped aesthetics a cultural project as much as a horticultural one.

Table 1 summarizes the quantitative findings reported across the reviewed intervention families, together with their original sources; the figures are point estimates from individual studies rather than a pooled meta-analytic estimate, and they are not directly comparable across contexts because they were derived using different baselines and methods.

Table 1. Documented quantitative outcomes by strategy family, as reported in the original studies.

Strategy family	Documented intervention	Reported outcome	Setting	Source
Species selection	Native vs. introduced street trees (277 trees, 27 species)	Introduced species require ~3.5× more water; native trees use ~72% less	Riyadh & Jeddah, Saudi Arabia	Ghazal (2026)
Species selection	Native vs. exotic shrubs under constrained soil moisture	Native species show lower mortality and water stress; species selection outperforms soil-amendment interventions	Lima, Peru (hyper-arid)	Arhuire-Ossio et al. (2022)
Alternative water sourcing	Household-scale constructed-wetland greywater treatment	70% reduction in water consumption; 85% reduction in peak-season utility cost; 85–96% pollutant removal	Jordan	Masoud et al. (2025)
Alternative water sourcing	Rooftop rainwater harvesting, peri-urban settlement	Annual catchment ~899,000 m³, equal to 2.6% of local demand	Central Mexico	Gamallo-Chaine et al. (2025)
Irrigation optimization	Residential tree-shade effect on irrigation demand	Mature-tree shade measurably reduces	Semi-arid western U.S. city	Troy et al. (2024)

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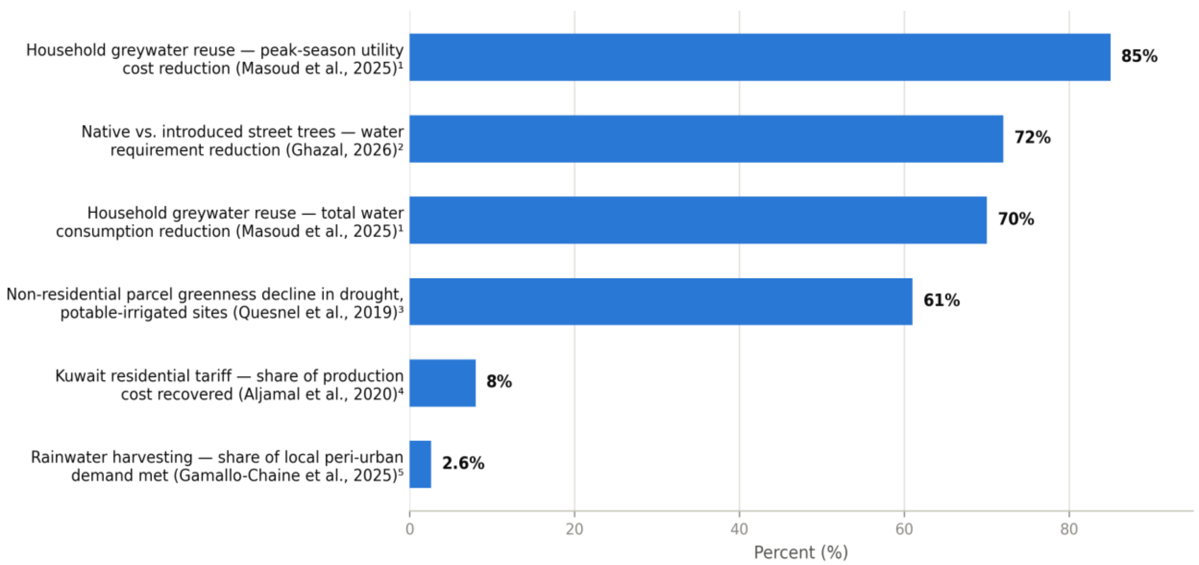
Strategy family	Documented intervention	Reported outcome	Setting	Source
		irrigation demand for underlying vegetation		
Irrigation optimization	Cross-city survey of urban-forest irrigation practice	Semi-arid/arid cities show a "double burden" of highest need and lowest financial/technical capacity	109 cities worldwide	Esperón-Rodríguez et al. (2025)
Policy instruments	Residential water-tariff structure	Tariff recovers ~8% of production cost; among world's highest per-capita consumption	Kuwait City	Aljamal et al. (2020)

Note: figures are point estimates from individual studies using different baselines, locations, and methods; they are not pooled or directly comparable across rows.

Figure 1. Selected quantitative findings from the reviewed literature



Note: point estimates from six individual studies using different baselines, locations, and methods — not a pooled or comparable meta-analytic estimate. [1]Constructed-wetland greywater treatment, Jordan. [2]Field morphology study of 277 trees / 27 species, Riyadh and Jeddah. [3]Four-summer parcel study during California's 2010–2016 drought. [4]Household survey, Kuwait City. [5]Peri-urban catchment study, central Mexico.

4.2 Alternative water sources: greywater, rainwater, and treated wastewater

The second strategy family substitutes non-potable sources for potable water in landscape irrigation. The three principal alternatives differ sharply in reliability, treatment burden, and governance requirements.

Greywater wastewater from showers, baths, and washbasins, excluding toilet and kitchen effluent is comparatively simple to treat to irrigation standard and, unlike rainwater, is generated continuously in proportion to household water use, giving it a reliability advantage in climates with episodic precipitation (Masoud et al., 2025). A field evaluation of household-scale horizontal-flow constructed wetlands treating greywater in Jordan documented removal efficiencies exceeding 85 percent for biochemical oxygen demand, 91 percent for chemical oxygen demand, and 96 percent for total suspended solids, with treated effluent meeting irrigation-quality standards (Masoud et al., 2025). The same study documented a 70 percent reduction in total water consumption at treated sites relative to the prior year, and a roughly 85 percent reduction in utility costs during peak-demand months, indicating that the technology delivers simultaneous environmental and household-economic benefits where it is adopted (Masoud et al., 2025). The principal constraints are not treatment performance but infrastructure and governance: dual plumbing and treatment units impose retrofit costs that are prohibitive for many existing buildings, and jurisdictions vary widely in whether they permit, subsidize, or effectively prohibit greywater reuse (Masoud et al., 2025).

Both greywater and treated-wastewater reuse share a longer-term soil-chemistry risk that is easy to overlook in a strategy evaluated only over one or two irrigation seasons: because arid-zone evapotranspiration concentrates whatever salts and nutrients are dissolved in irrigation water at the soil surface and in the root zone, and because greywater and reclaimed wastewater typically carry higher dissolved-solids loads than potable supply, repeated irrigation with either source over many years can gradually raise soil salinity and alter nutrient balance in ways that are reversible only through periodic leaching with higher-quality water (Masoud et al., 2025). This is not an argument against alternative-source irrigation, but it is a reason why reuse programmes need built-in soil monitoring and periodic freshwater leaching rather than one-time infrastructure substitution.

Rainwater harvesting captures precipitation from roofs and other impervious surfaces for subsequent irrigation use, but its contribution to aggregate municipal supply is fundamentally bounded by the low and variable precipitation that defines arid climates. A study of a peri-urban settlement in central Mexico estimated an annual catchment potential of approximately 899,000 cubic meters, equivalent to only 2.6 percent of local water demand, in an area with a water-scarcity index the authors characterized as severe (Gamallo-Chaine et al., 2025). This finding is consistent with the broader observation that rainwater harvesting typically requires annual rainfall above roughly 500 millimeters to make a material contribution to supply, a threshold that excludes many hyper-arid cities altogether (Gamallo-Chaine et al., 2025). The strategy nonetheless retains value at the parcel and neighborhood scale, particularly where it is paired with stormwater attenuation objectives in cities exposed to flash flooding from short, intense rainfall events a genuine hazard in many drylands despite their overall aridity.

Treated wastewater is, by volume, the most scalable alternative water source in arid cities, because its generation tracks population rather than precipitation and it can draw on existing centralized sewage-collection infrastructure. Large-scale examples include the use of treated sewage effluent to irrigate street trees and parkland in Saudi Arabian projects explicitly designed to reduce dependence on desalinated water. The treatment standard required depends on the end use: restricted irrigation of non-food landscaping can rely on secondary treatment, while unrestricted irrigation requires further reduction of pathogen and nutrient loads, and the long-run sustainability of the practice depends on managing salinity and trace-contaminant accumulation in irrigated soils. The binding constraint on treated-wastewater reuse is capital: centralized treatment and dual-distribution ("purple pipe") networks require substantial up-front investment that is feasible primarily where urban density supports the necessary economies of scale.

4.3 Irrigation optimization and canopy design

The third strategy family concerns not what is planted or which water source is used, but how and where irrigation is delivered. The central empirical finding in this literature is that the relationship between irrigation input and cooling benefit is markedly non-linear. Modeling of the urban heat island in Phoenix found that increasing irrigated vegetation lowers nighttime temperatures, but that the largest temperature reductions occur in the least-vegetated neighborhoods, and that beyond a threshold level of irrigation, additional water yields rapidly diminishing thermal returns (Gober, Brazel, et al., 2010). The direct implication is spatial: a fixed municipal water budget produces more cooling benefit when it is used to establish vegetation in currently bare or sparsely vegetated neighborhoods than when it intensifies irrigation in already-green ones (Gober, Brazel, et al., 2010).

A parallel line of research examines canopy architecture rather than aggregate irrigation volume. Work on residential tree shade in a semi-arid western U.S. city found that shade from mature trees measurably reduces residential irrigation demand for the vegetation beneath them, suggesting that the arrangement and form of the urban forest not only species selection shapes the water efficiency of the landscape as a whole (Troy et al., 2024). This finding reframes irrigation optimization as a design problem that spans plant physiology, spatial layout, and infrastructure, rather than a purely technological problem to be solved with sensors and controllers alone. It also implies that smart-irrigation technologies (soil-moisture sensing, evapotranspiration-based scheduling) are necessary but insufficient on their own: applied to a poorly designed landscape, they optimize delivery to an inherently water-intensive plant palette and spatial arrangement, capping the achievable savings well below what species selection and canopy design together can deliver.

As with xeriscaping, the institutional capacity to deploy these technologies is uneven. Sensor networks, weather stations, and automated controllers require capital investment and ongoing technical maintenance that many municipal parks and water departments particularly in lower-income cities lack, producing a persistent gap between demonstrated technical potential and adoption at scale (Esperón-Rodríguez et al., 2025). A synthesis of urban-forest irrigation practice across a large, geographically diverse set of cities found that irrigation is treated as critical primarily during the establishment period of newly planted trees and during acute heat or drought events, but that cities in semi-arid and arid climate zones face a double burden: they need irrigation most, precisely where the financial and infrastructural capacity to deliver it precisely and efficiently is most constrained (Esperón-Rodríguez et al., 2025). The same synthesis found that promoting drought-tolerant species selection and diversifying water sources functioned as complements to, rather than substitutes for, irrigation-scheduling technology reinforcing the broader argument of this review that the four strategy families are interdependent rather than alternative options to be chosen from a menu (Esperón-Rodríguez et al., 2025).

This capacity gap has a distributive dimension of its own, distinct from the equity questions taken up in Section 5.3. Because precision-irrigation technology is capital-intensive up front and generates savings only over a multi-year payback period, cities and utilities facing near-term fiscal constraints which are disproportionately cities serving lower-income populations are structurally less able to adopt it even where its life-cycle cost is favorable, producing a technology-adoption gradient that tracks municipal fiscal capacity rather than climatic need.

4.4 Policy instruments and governance

The fourth strategy family comprises the regulatory and price-based instruments that shape aggregate landscape water demand: turf-removal mandates and incentives, tiered water pricing, and integrated planning frameworks.

Direct regulation of ornamental turf has become the most visible policy innovation in the U.S. Southwest. In 2022, water agencies across the Colorado River Basin announced a coordinated commitment to reduce non-functional turf grass grass in street medians, office-park entrances, and other decorative, non-recreational applications by 30 percent, building on an initial memorandum signed by five agencies earlier that year and later joined by additional municipal and regional providers (Arizona Municipal Water Users Association [AMWUA], 2022). Nevada has gone further than a voluntary pledge: state legislation (Assembly Bill 356, enacted in 2021) requires the removal of non-functional turf across the Las Vegas Valley by 2027, making it the first U.S. jurisdiction to mandate turf removal in statute rather than merely incentivize it (Nevada Legislature, 2021; Southern Nevada Water

Authority, 2024). The distinction between voluntary incentive programs and binding regulatory mandates matters for both effectiveness and equity: voluntary rebate programs are politically easier to enact but face free-ridership and depend on discretionary participation typically concentrated among higher-income, owner-occupied households, while regulatory mandates are more durable but concentrate compliance costs on the property owners subject to them (Gober, Quay, & Larson, 2016).

Tiered water pricing charging progressively higher marginal rates as consumption rises is intended to signal scarcity and discourage discretionary outdoor use, but the evidence on its effectiveness is mixed and its distributive consequences are significant. Research on North American cities finds that the price elasticity of demand for outdoor irrigation is low in the short run and rises only gradually as households adjust landscaping practices over years (Gober, Quay, & Larson, 2016). The Kuwaiti case illustrates the opposite failure mode: heavy public subsidy keeps the effective residential tariff at only a small fraction of production cost one nationally representative household survey found the prevailing tariff recovered roughly 8 percent of production cost and average household consumption of 3,000 to 4,500 gallons per person per month is correspondingly high by international comparison, with survey respondents showing limited price sensitivity absent tariff reform (Aljamal et al., 2020). Table 2 compares these governance cases directly.

Table 2. Comparison of governance instruments for landscape water demand.

Governance case	Instrument type	Key provision	Source
Colorado River Basin turf pledge	Voluntary inter-utility compact	Coalition of water agencies (from an initial five, later expanded) commits to reduce non-functional turf grass by 30%; announced 2022	Arizona Municipal Water Users Association (2022)
Nevada Assembly Bill 356	Statutory mandate	Requires removal of non-functional turf across the Las Vegas Valley by 2027 the first U.S. statutory (not voluntary) turf-removal mandate	Nevada Legislature (2021); Southern Nevada Water Authority (2024)
Kuwait residential tariff	Price / subsidy policy	Flat, heavily subsidized volumetric tariff recovers roughly 8% of production cost; limited price sensitivity in household survey data	Aljamal, Speece, & Bagnied (2020)
Australian WSUD council guidance	Planning / regulatory guidance	Water-sensitive urban design provisions markedly less developed in arid, semi-arid, and remote council areas than in temperate/tropical areas	Hayden, Brakell, & Senevirathna (2026)

Note: cases selected because their key figures could be verified against a primary legislative, institutional, or peer-reviewed source; they illustrate contrasting instrument types rather than a representative sample of all dryland-city governance responses.

A further complication is structural rather than behavioral: because utilities frequently recover fixed infrastructure costs through volumetric charges, a policy that successfully reduces aggregate consumption can force a compensating increase in the per-unit rate to preserve revenue, a dynamic that falls hardest on low-income households whose consumption was already close to subsistence levels and who have the least discretionary "outdoor" use left to cut (Aljamal et al., 2020; Gober, Quay, & Larson, 2016). Comparable revenue dynamics have been documented for water-sensitive planning more broadly: a climate-comparative review of Australian council stormwater guidelines found that water-sensitive urban design provisions developed originally for temperate, relatively water-abundant contexts were markedly less detailed or entirely absent in guidance issued for arid, semi-arid, and remote council areas compared with guidance for temperate and tropical regions, suggesting that a planning paradigm built for wet climates has not been systematically adapted to dry ones (Hayden, Brakell, & Senevirathna, 2026).

This finding points to a broader institutional-coordination problem that recurs across the governance instruments reviewed here. Water utilities, planning and zoning departments, parks agencies, and public-health regulators typically operate under separate statutory mandates, separate budget cycles, and separate political accountability structures, even though each holds partial authority over landscape water demand. A turf ordinance enacted by a city council can be undermined by a homeowners'-association covenant requiring turf; a greywater-reuse permit issued by a health department can be rendered moot by a plumbing code that has not been updated to allow dual plumbing; and a utility's tiered-pricing structure can be offset by a parks department's continued reliance on flat-rate irrigation contracts. The Colorado River Basin turf pledge and Nevada's statutory mandate are notable in this respect precisely because they represent multi-agency coordination achieved through, respectively, a voluntary inter-utility compact and a single overriding state statute two different institutional routes to the same coordination problem, each with different implications for durability and local political buy-in (AMWUA, 2022; Nevada Legislature, 2021).

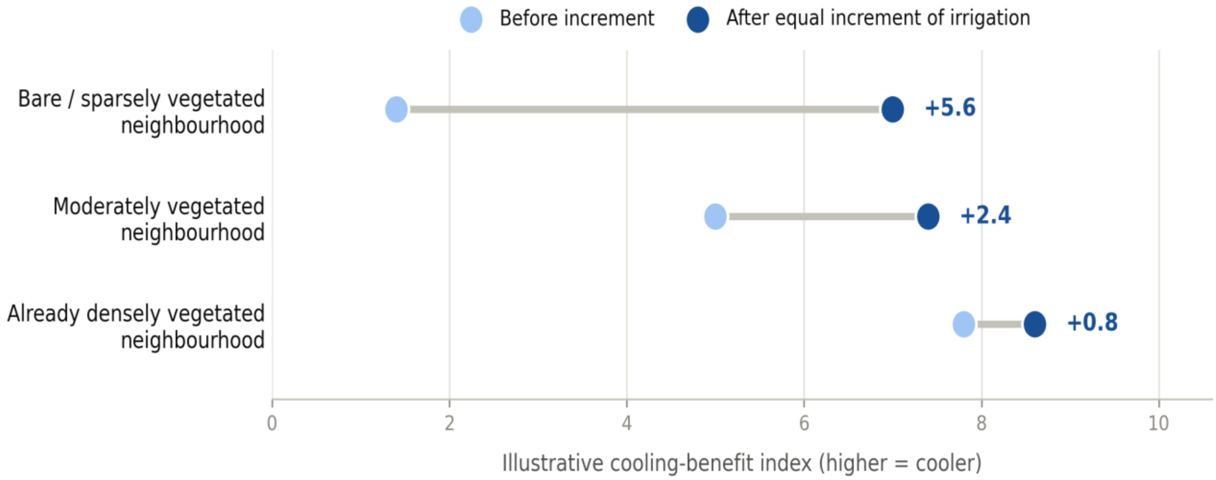
5. Cross-Cutting Trade-Offs

5.1 The heat-water trade-off

The most consequential cross-cutting finding in this review is that water conservation and thermal performance are frequently in tension rather than aligned. Urban vegetation cools through shade, which blocks incoming solar radiation, and through evapotranspiration, which converts sensible heat into latent heat; both mechanisms depend on water, the first indirectly through the maintenance of canopy leaf area and the second directly through the transpiration stream (Torres et al., 2024). Reducing irrigation therefore weakens both cooling mechanisms, though not necessarily in direct proportion to the water saved (Torres et al., 2024).

The relationship is non-linear in a specific and policy-relevant way. Because the largest marginal cooling gains from irrigation occur in currently bare or sparsely vegetated areas, and gains diminish rapidly once a neighborhood is already well vegetated, the spatial allocation of a fixed water budget matters as much as its total volume (Gober, Brazel, et al., 2010). A water-limited city that spreads a modest irrigation budget across previously unvegetated low-income neighborhoods can plausibly achieve more aggregate cooling benefit, at equivalent water cost, than one that concentrates the same volume in already-green, typically higher-income areas (Gober, Brazel, et al., 2010; Harlan et al., 2006). Figure 2 renders this relationship as a paired before/after comparison across three illustrative neighborhood starting conditions bare or sparsely vegetated, moderately vegetated, and already densely vegetated each receiving the same illustrative increment of irrigation; it is a conceptual device for organizing the qualitative findings reported in Gober, Brazel, et al. (2010) and Torres et al. (2024), not a quantitative reproduction of either study's underlying data.

Figure 2. Equal irrigation, unequal cooling gains



Note: a conceptual, illustrative comparison — not measured data — built to organize the qualitative, non-linear relationship reported in Gober, Brazel, et al. (2010) and Torres et al. (2024): the same volume of additional irrigation yields a larger marginal cooling gain in currently bare or sparsely vegetated neighbourhoods than in neighbourhoods that are already densely vegetated.

The practical corollary is that xeriscaping and cooling are not inherently opposed, but achieving both simultaneously is a design problem rather than a default outcome. Canopy architecture specifically, low-branching trees with expansive crowns that maximize shade per unit of transpiration can partially decouple shading from evapotranspirative water demand (Troy et al., 2024). Species and structural diversity in xeriscape design can likewise sustain meaningful shade-based cooling at markedly lower water cost than conventional turf-and-shade-tree landscapes, provided the plant palette is allowed to remain healthy rather than drought-stressed to the point of canopy loss (Torres et al., 2024).

5.2 Scale mismatch

A second recurring tension is between the scale at which the most promising interventions operate and the scale at which the problems they address are experienced. Greywater recycling, rainwater harvesting, and precision irrigation are technically most effective at the parcel, building, or small-district scale, while the problems motivating their adoption aggregate municipal water scarcity and city-wide heat island intensity are phenomena of the city or metropolitan region (Quesnel et al., 2019). Bridging this mismatch requires either an aggregation mechanism that links decentralized household or building-scale action to municipal targets, or centralized infrastructure capable of delivering an alternative water source at genuine scale.

Of the three alternative sources reviewed, treated wastewater offers the most direct route to scale, because it can be layered onto existing centralized sewage-collection infrastructure rather than requiring new decentralized plumbing in every building (a requirement that constrains greywater reuse) or being capped by regional rainfall (a hard limit on rainwater harvesting) (Gamallo-Chaine et al., 2025; Masoud et al., 2025). Cities that have already invested in tertiary treatment and dual-distribution infrastructure are positioned to substitute reclaimed water for potable water in landscape irrigation at a municipal scale that decentralized greywater or rooftop rainwater systems cannot reach on their own (Masoud et al., 2025). This does not make decentralized strategies unimportant they can meaningfully supplement centralized supply at the neighborhood scale, and they carry co-benefits (stormwater attenuation, reduced sewer loading) that centralized wastewater reuse does not but it does mean that municipal-scale water budgets cannot be balanced through parcel-scale interventions alone.

5.3 Equity and distributive effects

The third cross-cutting theme is the distributive politics of water-smart transitions, which are frequently invisible to purely technical evaluation. Turf-removal rebate programs are commonly funded from utility revenue contributed by all ratepayers, yet the direct beneficiaries are disproportionately property owners with large lots to convert typically higher-income, single-family homeowners rather than renters or residents of multifamily housing (Gober, Quay, & Larson, 2016). If aggregate demand reduction subsequently triggers a rate increase to preserve utility revenue, the distributive effect can be regressive: ratepayers who never had a large lawn to remove nonetheless absorb part of the resulting rate increase (Aljamal et al., 2020; Gober, Quay, & Larson, 2016).

Greywater and rainwater harvesting systems present a related but distinct equity profile, because the up-front capital and technical knowledge they require are more accessible to higher-income, owner-occupier households (Masoud et al., 2025). Where wealthier households adopt these systems and reduce their own potable consumption, the fixed costs of the broader water system are spread across a smaller remaining consumption base, which can raise costs for households that cannot afford the initial investment unless municipal programs deliberately subsidize adoption in lower-income neighborhoods, in which case the same technologies can instead reduce both water bills and heat exposure for the residents who need relief the most (Masoud et al., 2025).

This dynamic compounds a longer-standing pattern documented in the environmental-justice literature on desert cities: access to irrigated parks and tree canopy is consistently lower in lower-income and minority neighborhoods, even within cities whose overall water and environmental policies are relatively progressive, and neighborhood microclimates track this distribution closely, with measurably higher heat exposure in less-vegetated, lower-income areas (Harlan et al., 2006). A water-smart transition that is not deliberately designed to counteract this pattern risks reproducing it: green-space investment concentrating in already-vegetated, higher-income areas with the organizational capacity to secure it, while lower-income neighborhoods absorb the conservation mandate turf removal, tariff increases without a compensating share of the cooling and amenity benefits (Harlan et al., 2006; Larson et al., 2009).

5.4 Toward an integrated assessment

The preceding subsections show that each of the four strategy families performs differently against the four evaluation criteria set out in Section 2.2, and that no family dominates on every criterion simultaneously. Table 3 summarizes this pattern as a qualitative synthesis matrix, based on the reviewer's reading of the evidence assembled in Section 4 rather than on any numerical scoring system reported by the original studies themselves; it is offered as an organizing device for planners weighing strategy combinations, not as a precision instrument.

Table 3. Qualitative synthesis matrix: strategy families against the four evaluation criteria.

Strategy family	Hydrological efficacy	Thermal performance	Economic viability	Socio-institutional feasibility
Species selection & xeriscaping	Strong: 50–75% documented reduction	Conditional: depends on maintaining live canopy	Strong: low recurring cost once established	Moderate: constrained by aesthetic norms and codes

Strategy family	Hydrological efficacy	Thermal performance	Economic viability	Socio-institutional feasibility
Alternative water sourcing	Strong: up to 70–85% substitution at parcel scale	Indirect: sustains existing canopy rather than adding cooling	Variable: strong for greywater; capital-intensive for reclaimed water at scale	Variable: permitting regimes differ widely by source and jurisdiction
Irrigation optimization & canopy design	Moderate: optimizes delivery, not underlying plant demand	Strong: directly targets cooling per unit of water	Constrained: high up-front capital and maintenance capacity	Constrained: technical-capacity gap, acute in lower-income cities
Policy instruments (turf rules, pricing, WSUD)	Strong at municipal scale where enforced	Indirect / at-risk if not paired with design standards	Variable: revenue and equity risk under volumetric recovery	Most constrained: cross-agency coordination and political durability

Note: ratings reflect the reviewer's qualitative synthesis of the evidence discussed in Section 4, offered as an organizing device rather than a numerical scoring system reported by the original studies.

Two patterns stand out. First, no single strategy family scores favorably across all four criteria: species selection is strong on hydrological efficacy and economic viability but only conditionally strong on thermal performance, since that depends on maintaining canopy health; alternative water sourcing is strong on hydrological efficacy but variable on economic viability and institutional feasibility depending on which of the three sources is used; irrigation optimization is strong on thermal performance specifically but weak on economic viability where capital and technical capacity are scarce; and policy instruments are potentially strong on hydrological efficacy at the municipal scale but carry the most acute institutional-feasibility and equity risk of the four families. Second, and consistent with the framework developed in Section 2, the criterion that most consistently limits real-world performance across all four families is socio-institutional feasibility rather than hydrological or thermal performance narrowly defined a pattern that argues for prioritizing governance capacity-building alongside, rather than after, technical investment.

The matrix also clarifies why the four strategy families are better understood as complementary components of a single portfolio than as competing options. Species selection and irrigation optimization jointly determine how much water a given landscape configuration needs; alternative water sourcing determines what fraction of that reduced demand can be met without drawing on potable supply; and policy instruments determine whether the resulting configuration is adopted, financed, and sustained at a scale that matters for the municipal water balance. A city that adopts only one family in isolation species selection without addressing the tariff structure that funds its maintenance, say, or a turf ordinance without accompanying investment in alternative water infrastructure is likely to capture only a fraction of the achievable benefit documented in Section 4.

6. Discussion

6.1 Theoretical implications

These findings speak to three ongoing debates in urban sustainability scholarship. First, they complicate any presumption that urban greening is an unconditional good. In arid cities, the ecosystem services vegetation provides are real, but the water consumed to produce them carries an opportunity cost and a distributive incidence that sustainability assessments focused only on canopy cover or green-space area routinely omit (Quesnel et al., 2019; Torres et al., 2024). Second, the evidence underscores the limits of single-scale sustainability assessment. A greywater system that looks unambiguously sustainable at the household scale can have different implications once aggregated to the utility scale, where it affects revenue adequacy and infrastructure planning; conversely, a municipal turf ordinance can have sharply uneven effects at the neighborhood scale (Aljamal et al., 2020; Gober, Quay, & Larson, 2016). Sustainability, on this reading, is not a fixed property of a technology but an emergent property of the configuration of technology, institution, and social relation within which the technology is embedded (Jenerette, 2024). This has a direct methodological corollary for how sustainability is measured: a single-number indicator gallons saved, degrees of cooling, hectares converted will systematically misrepresent outcomes that are genuinely multi-dimensional and scale-dependent, which is precisely why Section 5.4 proposes a qualitative matrix rather than a composite index; collapsing four partly incommensurable criteria into one score would recreate the single-criterion optimization problem this review set out to avoid. Third, the review reinforces the relevance of a properly sociological reading of landscape preference. Aesthetic norms favoring lush, temperate-style greenery are not simply individual tastes to be corrected through information campaigns; they are socially patterned, reproduced through neighborhood-level status competition and, per Robbins (2007), commercially cultivated which is why durable transitions in landscape norms (where they have occurred) have generally required decades of combined drought experience, policy incentive, and a shift in what a well-kept, high-status yard is understood to look like (Larsen & Harlan, 2006; Larson et al., 2009).

6.2 Policy implications

Several actionable implications follow for municipal planners and water utilities. First, cities should develop comprehensive landscape water budgets that account for all major categories of outdoor use parks, street medians, residential yards, institutional and commercial grounds and set enforceable reduction targets, rather than regulating residential turf in isolation while leaving comparably large institutional and commercial demand unaddressed (Gober, Quay, & Larson, 2016). Second, turf-removal and rebate programs should be paired with design standards that specify replacement landscapes retain genuine ecological and aesthetic value structural diversity, flowering species, shade trees appropriately spaced rather than permitting reversion to bare gravel, which both eliminates cooling benefit and undercuts public acceptance of the broader transition (Torres et al., 2024).

Third, investment in alternative water infrastructure should be prioritized according to the scale-mismatch logic developed in Section 5.2: treated wastewater infrastructure for municipal-scale substitution, complemented rather than substituted by greywater and rainwater systems targeted at the parcel and district scale, with regulatory frameworks that actively permit and, where appropriate, subsidize the latter for lower-income households (Masoud et al., 2025). Fourth, tariff reform should be designed jointly with equity safeguards from the outset: a lifeline block of low- or no-cost water for essential domestic use, combined with steeply tiered pricing above that threshold and separate metering of outdoor water use where feasible, can reconcile conservation objectives with protection for low-income households far more directly than either uniform volumetric pricing or heavy blanket subsidy of the kind documented in Kuwait (Aljamal et al., 2020; Gober, Quay, & Larson, 2016). Finally, given the review's recurring finding that socio-institutional capacity not technology is usually the binding constraint, municipalities should invest directly in the administrative and engagement capacity needed to design, finance, and sustain integrated landscape-water governance, including the collaborative capacity to co-design water-smart neighborhoods with residents rather than impose landscape change by ordinance alone (Jenerette, 2024; Larson et al., 2009).

7. Limitations and Future Research

This review has three principal limitations that also indicate where future research is most needed. Geographically, the verifiable evidence base is concentrated in the U.S. Southwest, the Gulf states, and a smaller number of Latin American and Australian cases; dryland cities in Central Asia, the Sahel, and much of South Asia are comparatively under-represented in the peer-reviewed literature, a gap that likely reflects research-funding geography rather than the relative importance of the problem in those regions (Esperón-Rodríguez et al., 2025; Jenerette, 2024). Second, the evidence on long-run performance is thin: most studies document outcomes across a single drought cycle or a period of one to several years, so claims about whether documented water savings and thermal outcomes persist across multiple drought cycles, or as irrigated infrastructure ages, remain more provisional than the strength of the underlying point estimates might suggest (Quesnel et al., 2019; Torres et al., 2024). Third, integrated measurement that couples water-use efficiency directly to cooling benefit within a single study design remains rare; most studies report either hydrological or thermal outcomes, seldom both within the same experimental or observational frame, which is precisely the coupling this review argues is necessary for genuine sustainability assessment (Gober, Brazel, et al., 2010; Troy et al., 2024). Future research that develops a standardized metric of cooling delivered per unit of water consumed, tested longitudinally across multiple drought cycles and explicitly disaggregated by neighborhood income, would directly address all three gaps simultaneously.

A fourth, more methodological limitation concerns this review's own reference base. Restricting inclusion to sources whose authorship and statistics could be independently verified against a publisher or institutional record, as described in Section 3, improves the reliability of the specific claims made here, but it necessarily narrows the review relative to a more exhaustive systematic search that would also capture grey literature, unpublished municipal reports, and non-English-language scholarship on cities outside the Anglophone and Gulf research networks. Readers should therefore treat this review as a rigorously sourced entry point into the literature on water-smart arid urban greening rather than as an exhaustive census of everything that has been written on the topic. Sociologically oriented researchers with access to local-language municipal archives and community-level survey data are well positioned to close the equity and adoption-gap questions raised in Sections 5.3 and 6.2.

8. Conclusion

Water-smart urban greening in arid cities cannot be considered sustainable merely because it increases green cover or reduces water use. Climate-appropriate species selection, alternative water sourcing, irrigation optimization, and policy instruments each offer real potential, but none is sufficient on its own. The evidence shows that plant- and parcel-scale water savings do not automatically translate into municipal-scale cooling or equitable outcomes. The key tensions are the heat-water trade-off, the mismatch between local interventions and city-scale problems, and the uneven distribution of costs and benefits. Sustainable greening therefore requires integrated, multi-criteria, and multi-scalar assessment. Ultimately, arid urban greening is less a purely technical problem than a governance challenge: it depends on institutional capacity, regulatory coordination, equitable tariff design, investment in alternative water infrastructure, and sustained public engagement.

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