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Article

Climate-Resilient Schoolyards: Comparative Strategies and Priorities for Urban Climate Adaptation

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Abstract

Schools are increasingly recognised as critical public infrastructure for climate adaptation, particularly in heat-vulnerable and park-poor neighbourhoods. This study examines climate-resilient schoolyards as urban cooling systems, social spaces and educational landscapes. We conduct a comparative review of nine international programmes for schoolyard transformation (Paris, Barcelona, Madrid, Milan, Rotterdam, Los Angeles, New York, Melbourne and Santiago de Chile), drawing on municipal plans, reports and implementation guidelines. We examine programmes' design strategies, governance configurations and monitoring approaches, and synthesise them through a CAME (Correct, Adapt, Maintain, Explore) framework. Building on this analysis, we develop a Multicriteria Analysis (MCA) structure to prioritise interventions according to four families of criteria: environmental and climatic performance, social and educational equity, urban integration and accessibility, and feasibility and co-benefits. Results highlight a recurrent toolkit of measures—depaving, tree planting, cool and permeable surfaces, nature-based drainage systems, BIPV shade canopies and sensor-based monitoring—that can reduce surface temperatures by around 10–12 °C while improving thermal comfort, biodiversity and community use beyond school hours. We argue that climate-resilient schoolyards should be planned as networks of essential public infrastructure and that the combined CAME–MCA framework offers a robust, transferable decision-support tool for local governments and school authorities.

Keywords: climate-resilient schoolyards; urban climate adaptation; nature-based solutions; thermal comfort; environmental justice; public space and infrastructure; CAME strategies; multicriteria analysis (MCA); child-friendly cities

1. Introduction

Cities worldwide are experiencing increasing frequency, duration, and intensity of heatwaves, alongside growing exposure to air pollution and hydrometeorological extremes. These trends are particularly critical for children, who spend a large share of their time in educational facilities and whose thermoregulation, cognitive performance, and overall health are especially vulnerable to high temperatures and degraded environmental conditions. While a substantial body of research has advanced passive design and life-cycle-based approaches for buildings in Mediterranean and semi-arid climates—showing, for instance, how early-stage passive strategies and optimized insulation can significantly reduce energy demand and associated impacts [1,2]—outdoor school environments such as schoolyards have only recently begun to receive comparable analytical attention. Emerging work on the thermal environment of urban schoolyards reveals that conventional paved playgrounds can reach extreme surface temperatures, whereas increased vegetation cover and shade can markedly improve children's thermal comfort and reduce heat stress perception.

These findings underline the need to treat schoolyards as critical microclimates rather than residual outdoor spaces.

At the same time, a growing evidence base links green schoolyards with multiple health and educational co-benefits. Systematic reviews and empirical studies show that schoolyard greening is associated with increased physical activity, improved socioemotional health, better attention and perceived restorativeness, and more diverse patterns of play among children [4–6].

Green schoolyards are increasingly framed as a specific form of nature-based intervention, deliberately designed to expose all children—including those in socially or environmentally disadvantaged neighbourhoods—to everyday contact with nature, thereby contributing to health equity and long-term environmental attitudes [4–6].

More recently, schoolyards have been conceptualised as nature-based solutions (NBS) that serve simultaneously as climate adaptation infrastructure, everyday public space, and ecological steppingstones. Reviews and conceptual work emphasize that schoolyard greening can contribute to urban cooling, stormwater management, carbon sequestration, and biodiversity support, while also strengthening human–nature relationships, environmental learning, and social cohesion [3,7–9].

This multifunctional framing aligns schoolyard interventions with broader agendas on green infrastructure, ecosystem services, and just climate adaptation in dense urban contexts.

In Europe and beyond, several pioneering programmes have operationalised this vision at scale, treating schools as laboratories and anchors for urban resilience. The OASIS programme in Paris has transformed dozens of asphalted schoolyards into “cool oases” that provide shade, permeable surfaces, and accessible green space for both pupils and local communities, explicitly framed as a just adaptation measure to heatwaves [7].

Similarly, the “Climate Shelters” project in Barcelona combines green, blue, and grey measures (vegetation, water elements, shading structures, and material changes) to adapt schoolyards and buildings to climate change, under a robust mixed-method evaluation protocol [7].

Comparative work on nature-based climate solutions in European schools further highlights that these initiatives can catalyse wider social-ecological transformations, linking school communities, municipal climate strategies, and metropolitan-scale resilience planning [8].

Alongside health and climate benefits, recent ecological network studies demonstrate that schoolyards can play a strategic role in urban biodiversity conservation. Large-scale spatial modelling across several European cities shows that greening schoolyards can densify ecological networks for tree-dependent species and improve functional connectivity, particularly in highly built-up, vegetation-poor urban cores [9,10]. Although connectivity gains per individual school may be modest, the dense and evenly distributed pattern of school locations means that, collectively, schoolyards can significantly enhance urban green infrastructure, with co-benefits for thermal regulation, recreation, and environmental education.

Despite this rapidly expanding body of evidence, important gaps remain. Existing studies tend to focus on single outcomes (e.g., health, thermal comfort, or biodiversity) and on individual pilot projects, with limited comparative analysis across programmes and cities [4–7,9]. Moreover, local governments and educational authorities still lack robust, actionable frameworks to prioritise interventions and scale up climate-resilient schoolyards as an integrated network of essential public infrastructures. There is thus a need for methodological approaches that (i) synthesise international experiences in climate-resilient schoolyards, (ii) translate lessons into strategic CAME (Correct, Adapt, Maintain, Explore) recommendations, and (iii) support multicriteria prioritisation that jointly considers environmental, social, and urban-planning criteria.

Responding to these gaps, this paper examines climate-resilient schoolyards as essential public infrastructure for urban adaptation. First, it presents a comparative analysis of leading international programmes for schoolyard transformation in Europe, North America, Latin America, and Oceania. Second, it develops a CAME matrix to identify transferable strategies for local administrations and educational institutions. Third, it proposes a Multicriteria Analysis framework to prioritise interventions according to climate resilience, environmental performance, social equity, and spatial integration. Building on this integrated perspective, the paper concludes with recommendations for

designing networks of climate-resilient schoolyards as priority infrastructures within urban sustainability, mitigation, and adaptation policies.

2. Materials and Methods

2.1. Research Design

This study follows a comparative multiple case-study design centred on international programmes that have implemented climate-resilient schoolyards at scale. The approach combines:

- (1) structured document analysis;
- (2) qualitative cross-case comparison;
- (3) coding of strategies into a **CAME (Correct, Adapt, Maintain, Explore)** matrix; and
- (4) the development of a **Multicriteria Analysis (MCA)** framework for prioritising interventions.

The aim is to identify transferable patterns in design, governance and decision-making rather than to produce exhaustive evaluations of individual programmes.

2.2. Case Selection

Cases were selected through purposive sampling according to four criteria:

1. The initiative explicitly targets **schoolyards or outdoor school spaces** as a main focus of intervention.
2. Climate adaptation, environmental performance or nature-based solutions (e.g., cooling, stormwater management, biodiversity) are stated objectives.
3. The programme has reached at least a **pilot or early scaling phase** (i.e., more than one school and/or multi-year implementation).
4. Sufficient **public documentation in English or Spanish** is available (policy documents, technical reports, academic publications, project websites).

Applying these criteria led to nine programmes in Europe, North America, Latin America and Oceania (Paris, Barcelona, Madrid, Milan, Rotterdam, Los Angeles, New York, Melbourne and Santiago de Chile). In this paper, each “case” refers to the programme as a whole, not to individual schools.

2.3. Data Collection

Data were collected between [month year] and [month year] from four main types of sources:

- **Policy and technical documents:** climate adaptation plans, educational and green-infrastructure strategies, design guidelines and evaluation reports produced by municipal or regional authorities.
- **Scientific and grey literature:** peer-reviewed papers, project deliverables and research reports related to schoolyard greening, climate shelters and nature-based solutions.
- **Programme websites and repositories:** descriptions of objectives, design catalogues, maps, images, monitoring dashboards and communication materials.
- **Open datasets (where available):** spatial data on school locations, land cover, land-surface temperature and socio-demographic indicators published in municipal or project portals.

All documents were downloaded or archived locally. The initial corpus comprised approximately [N] documents; after screening for relevance and completeness, [N₁] documents were retained for detailed analysis. Materials that mentioned schoolyards only tangentially or lacked concrete information on interventions or governance were excluded.

2.4. Document Coding and Cross-Case Comparison

Document analysis was structured in three steps:

1. **Exploratory reading and initial coding.** A subset of documents from three leading programmes (Paris, Barcelona and New York) was read in depth to identify recurrent themes related to drivers, design strategies, governance, monitoring and outcomes.
2. **Codebook development.** Preliminary codes were refined into a codebook with explicit definitions and examples, grouped into higher-level families such as “Design Measures”, “Governance and Participation”, “Monitoring and Evaluation” and “Urban Integration”.
3. **Systematic coding and synthesis.** The codebook was applied to all retained documents. For each programme, a case-summary sheet was produced, capturing context, key interventions, governance arrangements and reported impacts (thermal, social, ecological, etc.).

A cross-case comparison was then performed to identify convergences and divergences across programmes. This step provided the empirical basis for constructing the CAME matrix and informing the design of the MCA framework.

2.5. Construction of the CAME Matrix

All strategies identified during coding were classified into the four CAME categories:

- **Correct:** actions that remediate existing deficits or vulnerabilities (e.g., removal of extensive asphalt, introduction of basic shade and vegetation, minimum green-cover targets).
- **Adapt:** measures designed to address current and future climate risks (e.g., nature-based drainage, drought-tolerant plant palettes, flexible shading, sensor-based monitoring).
- **Maintain:** actions that ensure the durability and care of effective interventions (e.g., maintenance protocols, budget lines, stewardship programmes, formalisation of shared-use agreements).
- **Explore:** innovative or experimental approaches in design, technology or governance (e.g., BIPV canopies, participatory data collection, new co-management models).

Each measure was assigned to at least one category according to its principal stated intention. Ambiguous cases were discussed among the authors until a consensus classification was reached. The resulting CAME matrix synthesises, for each programme, the dominant strategic profile and the balance between corrective, adaptive, maintenance and exploratory actions.

2.6. Development of the Multicriteria Analysis (MCA) Framework

The MCA framework was developed as a generic decision-support tool for prioritising schoolyards and intervention packages. It is not calibrated to a specific city, but is structured so that local authorities can adapt it to their data and policy priorities.

The development process included:

1. **Definition of criteria families.** Drawing on the literature on climate-resilient public space, nature-based solutions and environmental justice, and on insights from the case studies, four criteria families were defined:
 - *Environmental and climatic performance* (e.g., cooling potential, stormwater management, biodiversity contribution);
 - *Social and educational equity* (e.g., socio-economic vulnerability, green-space deficit, school population);
 - *Urban integration and accessibility* (e.g., public transport access, potential as neighbourhood climate refuge, connection to green-blue networks);
 - *Feasibility and co-benefits* (e.g., depavable surface, readiness of the school community, synergies with planned renovations or energy retrofits).
2. **Selection of indicators.** For each criterion, one or more indicators were proposed, favouring variables that can typically be obtained from municipal GIS databases or open statistical sources (for example, percentage of impervious surface, land-surface temperature anomaly, distance to nearest public park, or socio-economic deprivation index).

3. **Scoring scheme.** A five-point ordinal scale (1–5) was defined for each indicator, where 1 represents low priority/benefit and 5 represents very high priority/benefit. Thresholds can be adapted locally (e.g., based on quantiles of city-wide distributions).
4. **Weighting and aggregation.** The framework allows for adjustable weights for each criterion family to reflect local policy goals (e.g., greater weight for social equity in climate-justice oriented programmes). The weighted sum of indicator scores yields a composite index that can be used to rank schoolyards or compare alternative intervention scenarios.

3. Results

3.1. Programme Typologies and Underlying Drivers

The cross-case analysis confirms that climate-resilient schoolyard initiatives emerge in very heterogeneous urban and institutional contexts, yet they cluster around a limited set of underlying drivers. Previous work on nature-based climate solutions in schools and on the greening of schoolyards as urban infrastructure has also highlighted this diversity of contexts and rationales [8,9,11–13].

First, **heat-equity programmes** conceive schoolyards as climate-shelter infrastructure for overheated and park-poor neighbourhoods. The OASIS programme in Paris and the Climate Shelters project in Barcelona explicitly target schools located in highly sealed, heat-exposed areas with limited access to green public space, and open the transformed schoolyards to the wider community as neighbourhood climate refuges [7,12–15]. In both cases, school selection is guided by social vulnerability indices, heat-exposure maps and green-space deficits, with the explicit aim of reducing unequal exposure to environmental risks. Similar logics underpin Community Schoolyards and Green Community Schoolyards initiatives in several U.S. cities, where schoolyard greening is framed as a response to both heat stress and park inequities [17,18].

Second, **water-resilience programmes** are primarily driven by stormwater management and flood-risk reduction. Rotterdam's Green-Blue Schoolyards address combined sewer overflows and pluvial flooding by treating schoolyards as micro-basins that retain, infiltrate or temporarily store rainwater, while also providing natural play areas and outdoor learning spaces [8,16,17]. In New York, Community Schoolyards incorporate rain gardens, bioswales and permeable sports fields as part of the city's green-infrastructure strategy, with substantial stormwater-capture estimates [17,18]. Here, cooling and recreational benefits are acknowledged, but are typically framed as co-benefits rather than primary objectives.

Third, **education-community programmes** originate in agendas of outdoor learning, child-friendly cities or open-school policies. Examples include renaturalised schoolyards in Madrid, "Scuole Aperte" in Milan and "Patios Verdes/Patio Vivo" in Santiago de Chile, many of which are documented in European and Latin American NBS projects such as COOLSCHOOLS and in studies of green schoolyard governance [8,11,19,20]. In these initiatives, climate adaptation is progressively layered onto existing educational and community frameworks rather than constituting the initial impetus, with a strong emphasis on participation, pedagogical innovation and community use.

Across all typologies, schoolyards are gradually reframed from residual institutional courtyards into **multi-functional public infrastructures**. Recent research on schoolyard greening as nature-based solution and green infrastructure shows how these spaces are being reimagined as climate refuges, neighbourhood parks and "green classrooms" that combine adaptation, biodiversity, health and educational functions [9–11,20–22]. This evolution aligns with broader debates on the upscaling of green infrastructure and on the role of green schoolyards in urban resilience and environmental justice [11,19,22].

3.2. Design Measures: A Convergent Toolkit Under Divergent Conditions

Despite marked differences in climate, urban morphology and governance, the programmes converge on a relatively stable repertoire of physical interventions:

- Depaving and soil restoration. All programmes prioritise the reduction of sealed asphalt surfaces, replacing them with permeable pavements, stabilised gravel, mulch or planting beds. In several cities, depaving targets are quantified (e.g., minimum percentages of unsealed surface), often aligned with local stormwater or heat-mitigation objectives.
- Vegetation and shade provision. Systematic tree planting is ubiquitous, frequently combined with layered vegetation (shrubs, meadows, groundcovers) to create more complex habitats. Shade is provided through canopy trees, pergolas, tensile structures and, in a small number of pilot cases, building-integrated photovoltaic (BIPV) canopies that couple shading with on-site renewable energy production.
- Nature-based water management. Rain gardens, bioswales, permeable play surfaces and small retention basins are widely used in Rotterdam, Melbourne and New York, where schoolyards are integrated into broader sponge-city or water-sensitive urban design strategies. In Mediterranean contexts, smaller-scale infiltration and drainage features are preferred due to heritage constraints, limited space or water-scarcity considerations.
- Cool and reflective materials. In areas where complete renaturalisation is not feasible (e.g., heavily used sports courts or accessible circulation routes), high-albedo and/or porous materials are used to reduce radiative load and improve thermal comfort, particularly in dense, heat-stressed urban fabrics.

Where quantitative evaluation is available, environmental performance is consistently positive and non-trivial. In Paris OASIS and Barcelona Climate Shelters, measurements report surface temperature reductions of approximately 10–12 °C between conventional asphalt zones and renaturalised areas during extreme heat events, accompanied by improvements in subjective thermal comfort and reduced heat-stress perception among pupils. Microclimate studies in schoolyards corroborate these findings, emphasising the role of tree canopy and evapotranspiration in moderating radiant heat loads. Ecological assessments in European projects show increased arthropod diversity and measurable gains in modelled connectivity for tree-dependent species when paved schoolyards are partially converted into vegetated patches.

These converging results suggest that a compact combination of depaving, vegetation and shade, water-sensitive design and selective use of cool materials constitutes a robust and transferable design toolkit for climate-resilient schoolyards across diverse climatic and socio-spatial contexts.

3.3. Social Use, Health and Educational Dimensions

Beyond physical performance, the analysed programmes report consistent social, health and educational effects, although the depth of monitoring varies.

Greened schoolyards are associated with more diversified and inclusive patterns of play, higher levels of physical activity and perceived restorativeness, in line with findings from intervention studies and systematic reviews. Teachers in several programmes report more evenly distributed use of space, fewer conflicts and new opportunities for quiet play, exploration and informal learning, particularly for younger children and for girls, who gain access to alternative play settings compared with traditional large asphalt courts dominated by ball games.

In cities where transformed schoolyards are opened beyond school hours, neighbourhood-use patterns change significantly. In Paris, Barcelona and New York, for example, schoolyards act as “neighbourhood living rooms”, providing shaded, green public space within walking distance for residents who previously lacked such amenities. This extended use reinforces the interpretation of schoolyards as essential public infrastructure but introduces additional governance challenges related to cleaning, security and the coordination of school and community activities.

From an educational perspective, many programmes develop pedagogical resources and teacher-training modules to integrate the transformed yards into everyday teaching—particularly in

environmental education, health promotion and STEM subjects. However, the extent to which these resources become structurally embedded in curricula differs: in some contexts they remain optional or project-based, whereas in others they are institutionalised through school improvement plans or local curriculum frameworks.

3.4. Governance and Participation: From Experiments to Networked Infrastructure

The governance analysis shows that climate-resilient schoolyard initiatives often begin as interdepartmental or cross-sectoral experiments, typically involving environment, education and planning departments, as well as non-profit partners. Only in some cities are they subsequently consolidated into stable, networked infrastructures.

In Paris and Barcelona, schoolyard transformation is anchored in city-wide climate and health strategies and supported by dedicated funding lines and formal collaboration agreements between departments. This institutional embedding facilitates scaling from pilot schools to larger networks and supports the development of technical guidelines and design catalogues. In New York and Los Angeles, partnerships between school districts, parks departments and non-profit organisations (such as community land trusts or environmental NGOs) play a central role in co-design, financing and maintenance.

Participation mechanisms range from deep co-design processes—involving iterative workshops and model-making with children, teachers and families—to more limited consultative approaches. Where co-design is systematic, it is reported to enhance local ownership, align spatial interventions with everyday practices and reveal otherwise overlooked needs (e.g., gendered patterns of use, sensory sensitivities, informal routes). However, such processes require specialised facilitation and additional time, which not all administrations can sustain at scale.

Across cases, stakeholders consistently identify maintenance and long-term stewardship as structurally fragile dimensions. Responsibility for irrigation, pruning or repair of play elements is often fragmented across departments, and budget allocations may be short-term or project-based. Programmes that formalise shared-use agreements and secure dedicated maintenance budgets are better positioned to preserve climate and social benefits over time; where this is not the case, there is recurrent concern about vegetation loss, infrastructural degradation and pressures to re-asphalt.

3.5. Strategic Patterns Revealed by the CAME Matrix

Classifying programme actions into the CAME framework reveals strategic patterns that are less visible in purely descriptive accounts.

- Correct measures are ubiquitous and form the backbone of most programmes. These include the removal of extensive asphalt, provision of minimum levels of shade and vegetation, replacement of unsafe equipment and correction of drainage problems. Correct actions are politically salient and highly visible, which facilitates their adoption, but they primarily address legacies of underinvestment and poor design rather than future climate conditions.
- Adapt measures constitute a more explicitly climate-oriented layer, encompassing nature-based drainage systems, drought-tolerant planting palettes, microclimate-sensitive layouts and, in some cases, sensor-based environmental monitoring. Heat-equity programmes typically display a dense cluster of Adapt strategies tightly linked to municipal adaptation plans, whereas education–community programmes incorporate such measures more incrementally.
- Maintain strategies—maintenance protocols, dedicated budgets, stewardship schemes involving schools and community organisations—are recognised as essential but remain the least consistently articulated pillar. Their relative weakness in many programmes is perceived by practitioners as a major risk to the long-term effectiveness of schoolyard transformations, potentially eroding achieved climate and social benefits.

- Explore strategies are concentrated in a subset of pilot or flagship schools and include BIPV canopies, experimental water–play elements that double as stormwater devices, advanced sensor networks or novel co-governance models. These pilots operate as laboratories for innovation, but their translation into routine practice depends on institutional learning, risk tolerance and the capacity to absorb higher upfront costs.

Overall, the CAME analysis suggests that most cities are currently in a “Correct + Adapt consolidation” phase, with Maintain and Explore dimensions emerging but not yet fully integrated into programmatic logics and budget cycles. Strengthening maintenance capacities and selectively scaling successful exploratory elements appear as key conditions for consolidating climate-resilient schoolyards as long-term infrastructure rather than as one-off projects.

3.6. Cross-Case Validation of the MCA Criteria

As described in Section 2.6, the proposed MCA framework is organised around four criteria families—environmental and climatic performance, social and educational equity, urban integration and accessibility, and feasibility and co-benefits—synthesised in Table 1. These families were initially derived from the literature on climate-resilient public space, nature-based solutions and environmental justice, and then shaped by insights from the case-study corpus.

Table 1. Multicriteria Analysis (MCA) criteria families for prioritising climate-resilient schoolyard interventions, derived from the literature and the comparative case-study analysis (Sections 2.6 and 3.6).

Criteria family	Guiding question	Core dimensions	Example indicators	Strategic implications
Environmental and climatic performance	To what extent can the intervention deliver measurable climate- and ecosystem-service benefits?	- Reduction of heat exposure - Stormwater management and infiltration - Biodiversity and ecological connectivity	- % impervious surface - Land Surface Temperature (LST) anomaly - Potential increase in tree-canopy cover - Area suitable for nature-based drainage (rain gardens, swales, etc.)	Ensures that projects deliver tangible climate-adaptation and ecosystem-service gains (cooling, flood mitigation, biodiversity) and helps identify sites with the highest adaptation potential.
	Who benefits from the intervention, and does it reduce existing inequalities in health, exposure and access?	- Socio-economic vulnerability - Access to quality green space - Exposure to environmental hazards - Educational opportunities and needs	- Socio-economic deprivation index - Green-space deficit within walking distance - % pupils eligible for social support/free meals - School population size/density	Anchors prioritisation in climate justice and children’s rights, directing resources to schools where interventions can most effectively reduce exposure gaps and improve health and learning conditions.
Urban integration and accessibility	How does the schoolyard function within wider networks of public space, mobility and	- Role as neighbourhood climate refuge - Spatial position in green-blue networks -	- Distance to nearest park/public open space - Public-transport accessibility (stops within a defined radius) - Resident population within walking distance - Location relative to	Connects schoolyard projects to wider green-blue and mobility strategies, prioritising sites

	green-blue infrastructure?	Walkability and everyday accessibility	existing/planned green-blue corridors	that can act as key nodes in networks of cool, accessible public spaces and ecological corridors.
Feasibility and co-benefits	Under which institutional, economic and social conditions can the intervention be implemented and sustained over time?	- Technical feasibility and site capacity - Alignment with ongoing or planned works - Expected costs and maintenance needs - Institutional readiness and partnerships	- Area available for depaving/renaturalisation - Presence of planned renovations/energy retrofits in buildings - Estimated implementation and maintenance costs - Degree of engagement of school leadership and community partners	Keeps the MCA grounded in real implementation conditions, helping identify “high-impact, high-feasibility” projects and signalling where additional resources or capacity building will be required.

Table 2 summarises the relative emphasis placed on each of these four criteria families across the nine schoolyard programmes, using a simple high/medium/low (H/M/L) coding derived from document analysis. This mapping allows us to (i) distinguish different strategic profiles and (ii) assess to what extent existing initiatives already align with, or partially anticipate, the proposed MCA logic.

Table 2. Relative emphasis of MCA criteria families across selected schoolyard programmes (H = high, M = medium, L = low), based on document analysis.

Programme / City	Environmental & climatic performance	Social & educational equity	Urban integration & accessibility	Feasibility & co-benefits
OASIS Schoolyards, Paris	H – strong focus on cooling, depaving, NBS and microclimate monitoring	H – priority to vulnerable areas and schools with low access to green space	H – schoolyards as part of a city-wide network of climate refuges	M – dedicated funding and agreements, but maintenance and coordination remain challenging
Climate Shelters in Schools, Barcelona	H – combined green/blue/grey measures and mixed-method environmental evaluation	H – explicit targeting of socially vulnerable and heat-exposed neighbourhoods	M–H – schoolyards integrated into broader climate-shelter and health strategies	M – project-based funding and strong technical support, with emerging questions on long-term maintenance
Renaturalised Schoolyards, Madrid	M – significant greening and depaving, but less systematic performance monitoring	M – equity considerations present but less central than in Barcelona or NYC	M – links to city adaptation and education policies, with variable neighbourhood roles	M – support through municipal and EU projects, with constraints on scaling and maintenance capacity
Scuole Aperte, Milan	L–M – environmental improvements present but not the primary driver	H – emphasis on open schools, social use and educational/community projects	H – schoolyards framed as civic hubs and local public spaces	M – strong social coalitions, but climate-specific funding and maintenance arrangements less developed

Green-Blue Schoolyards / Adaptation Playgrounds, Rotterdam	H – clear focus on NBS for stormwater, cooling and resilience	M – child-friendly and play-oriented, with partial equity framing	H – integrated into city-wide climate adaptation and water strategies	M – technically robust, with typical constraints on long-term stewardship and cross-department coordination
LA Cool Schools / Green Schoolyards, Los Angeles	H – greening and shade as response to extreme heat and sealed playgrounds	H – focus on heat-vulnerable, park-poor communities	M – contributions to local park networks and neighbourhood cooling	M-L – fragmented funding and governance, with uneven implementation and maintenance capacity
Community Schoolyards / Schoolyards to Playgrounds, New York City	M-H – greening and permeable surfaces linked to stormwater and heat mitigation	H – explicit prioritisation of underserved communities with limited park access	H – schoolyards function as public parks and neighbourhood open spaces	M – strong NGO-city partnerships, but dependence on project funding and shared responsibilities
Green Schoolyards Victoria, Melbourne	M-H – integration of greening and climate-related initiatives in schools	M – educational and health benefits recognised, with partial focus on disadvantage	M – connections to wider green and education programmes, varying by locality	M-H – embedded in state-level programmes, with relatively stable support but uneven local capacity
Patios Verdes / Patio Vivo, Santiago de Chile	M – renaturalisation and microclimate improvement, with limited systematic monitoring	H – strong orientation towards educational innovation and socio-emotional wellbeing	M – schoolyards as local community references, with emerging links to wider green infrastructure	M-L – NGO-led model with constrained budgets and reliance on school/community engagement for continuity

3.6.1. Environmental and Climatic Performance

The first criteria family addresses the capacity of schoolyard interventions to deliver **measurable climate-adaptation and ecosystem-service benefits**. Empirical evidence from monitored programmes such as OASIS Paris and Barcelona Climate Shelters shows that combinations of depaving, vegetation and shade can reduce surface temperatures by approximately 10–12 °C during heat events and improve perceived thermal comfort among pupils. In parallel, microclimate studies and ecological assessments in greened schoolyards highlight gains in evapotranspiration, stormwater infiltration, biodiversity and functional connectivity.

As reflected in Table 2, heat–equity and water–resilience programmes—OASIS Paris, Barcelona Climate Shelters, Rotterdam’s green–blue schoolyards, and several initiatives in Los Angeles, New York and Melbourne—place a **high emphasis** (H) on environmental and climatic performance, often supported by explicit targets or monitoring protocols. In contrast, education–community programmes (e.g., Milan, Santiago de Chile) still tend to assign a **medium** (M) weight to this family, with environmental benefits recognised but less systematically quantified.

This pattern empirically reinforces the centrality of the environmental–climatic performance family in the MCA (Table 1). Indicators such as percentage of impervious surface, land-surface temperature anomaly, potential for increased tree canopy and suitability for nature-based drainage are not abstract constructs but metrics already present—explicitly or implicitly—in many of the analysed programmes.

3.6.2. Social and Educational Equity

The second criteria family responds to the question of **who benefits** from climate-resilient schoolyards and whether interventions help reduce existing inequalities in exposure, access and

health/educational outcomes. Several programmes explicitly target schools in socio-economically disadvantaged, park-poor and heat-exposed neighbourhoods, using deprivation indices, green-space deficits and other equity-related indicators to guide selection.

This logic is particularly evident in Barcelona Climate Shelters, LA Cool Schools and Community Schoolyards in New York, all of which score **high** (H) on social and educational equity in Table 2. By contrast, programmes such as Madrid renaturalised schoolyards or Green Schoolyards Victoria incorporate equity considerations more partially, resulting in **medium** (M) emphasis, while others (e.g., some water-focused pilots) show only implicit or indirect attention to equity.

The cross-case analysis therefore supports a strong equity orientation in the MCA (Table 1). Indicators such as socio-economic deprivation indices, green-space deficit within walking distance, percentage of pupils eligible for social support and school population density provide a robust basis for assigning higher priority to schools where climate-resilient schoolyards can function as **levers of climate justice and health equity**.

3.6.3. Urban Integration and Accessibility

The third criteria family recognises that schoolyards operate as **nodes within wider urban systems** of public space, mobility and green-blue infrastructure, rather than as isolated institutional courtyards. In several cities, transformed schoolyards are formally designated as neighbourhood parks or climate refuges and are mapped within networks of cool public spaces or ecological corridors.

Table 2 shows that programmes such as OASIS Paris, Barcelona Climate Shelters, Community Schoolyards in New York and Scuole Aperte in Milan place **high** (H) emphasis on urban integration and accessibility, framing schoolyards as neighbourhood “living rooms” or civic hubs. Others, such as Madrid, Rotterdam, Melbourne or Santiago, exhibit **medium** (M) emphasis, acknowledging the neighbourhood role of schoolyards but with more variable integration into city-wide networks.

This empirical pattern validates the inclusion of urban integration and accessibility in the MCA (Table 1). Indicators like distance to the nearest public park or open space, public-transport accessibility, resident population within walking distance and location relative to existing or planned green-blue corridors are closely aligned with how leading programmes justify and communicate their schoolyard networks.

3.6.4. Feasibility and Co-Benefits

The fourth criteria family concerns the **institutional, economic and social conditions** under which schoolyard interventions can be implemented and sustained over time. Across all cases, recurring constraints include limited municipal budgets, fragmented responsibilities between departments (education, environment, parks, public works) and uncertain long-term maintenance arrangements. At the same time, several programmes exploit **co-benefits and windows of opportunity**, such as coupling schoolyard transformation with building renovations, energy retrofits or curriculum reforms, thus improving cost-effectiveness and institutional buy-in.

In Table 2, few programmes reach a clearly **high** (H) emphasis on feasibility and co-benefits; most remain at **medium** (M) levels, reflecting partial but incomplete institutionalisation of long-term maintenance and cross-department coordination. NGO-led or project-based models (e.g., LA Cool Schools, Patios Verdes) tend to fall in the **medium-low** (M-L) range, with strong social engagement but constrained budgets and dependence on short-term funding cycles.

These observations confirm that feasibility and co-benefits must be incorporated explicitly in the MCA (Table 1). Indicators such as area available for depaving, alignment with planned works, estimated implementation and maintenance costs, and degree of engagement of school leadership and community partners are essential to identify “high-impact, high-feasibility” projects and to signal where additional resources or capacity-building efforts will be required.

3.6.5. Strategic Implications of the Four Criteria Families

Taken together, the evidence summarised in Tables 1 and 2 indicates that the four MCA criteria families are **not arbitrary analytical categories**, but synthetic expressions of how leading climate-resilient schoolyard programmes already operate in practice.

- The **environmental and climatic performance** family ensures that projects deliver tangible adaptation and ecosystem-service benefits.
- The **social and educational equity** family grounds prioritisation in climate justice and children's rights.
- The **urban integration and accessibility** family links individual school interventions to city-wide strategies for green-blue infrastructure and walkable, cool public-space networks.
- The **feasibility and co-benefits** family keeps the MCA anchored in real implementation conditions, increasing the likelihood that selected projects will be both deliverable and sustainable.

By making these four dimensions explicit and operational, the MCA framework supports a shift from opportunistic or politically driven selection of schoolyard projects towards **transparent, criteria-based prioritisation** of climate-resilient schoolyard networks as essential public infrastructure within urban adaptation policies.

4. Discussion

This study set out from the hypothesis that schoolyards can and should be treated as **essential public infrastructures for urban climate adaptation**, rather than as residual playgrounds or purely educational spaces. The comparative analysis of nine international programmes, combined with the CAME-MCA framework, provides support for this reframing while also revealing important tensions, blind spots and opportunities for future work.

4.1. From Green "Projects" to Climate Infrastructure

Our results confirm that climate-resilient schoolyards can deliver **non-trivial environmental benefits**, particularly in terms of surface-temperature reduction, stormwater management and biodiversity support, when depaving, vegetation and shade are implemented consistently at scale. These findings are strongly consonant with microclimatic and health evidence from intervention studies on green schoolyards and other nature-based solutions [3–7,9,10]. In this sense, schoolyards can be read as a specific, spatially dense expression of green infrastructure: they are already distributed throughout the urban fabric, embedded in neighbourhoods, and relatively well served by basic utilities.

However, treating schoolyards as **infrastructure** rather than as a collection of isolated projects implies a shift in governance and planning. Infrastructure is expected to be reliable, long-lived and subject to systematic maintenance. Yet, as the CAME analysis shows, most programmes are still dominated by **Correct** and **Adapt** actions (e.g., depaving, shading, NBS for heat and water), while **Maintain** and **Explore** dimensions remain comparatively weak. This imbalance risks creating "green one-offs": visually transformative pilot projects whose performance and quality may degrade over time in the absence of robust stewardship, echoing concerns raised in broader debates on the long-term governance of nature-based solutions.

The CAME matrix thus helps to make explicit that a truly infrastructural approach would require at least three shifts: (i) consolidating maintenance capacities and stable budget lines; (ii) institutionalising shared responsibilities between education, environment and public-works departments; and (iii) embedding exploratory pilots (e.g., BIPV canopies, advanced monitoring, co-governance models) within learning loops that can inform standards and design guidelines rather than remaining as isolated experiments.

4.2. Equity, Justice and the Spatial Politics of Schoolyards

The programmes examined illustrate that climate-resilient schoolyards can be powerful tools for **climate and environmental justice**, but only when equity is made explicit as a selection criterion and design principle. Heat-equity initiatives such as Barcelona's Climate Shelters and Community Schoolyards in New York systematically target schools in socio-economically disadvantaged, park-poor and heat-exposed neighbourhoods, thereby aligning with emerging frameworks that link nature-based solutions to distributive and recognitional justice.

At the same time, several programmes with strong educational or water-management agendas display only **medium** emphasis on equity, and some rely on opportunistic selection (e.g., availability of motivated staff or existing project networks) rather than on vulnerability and exposure metrics. In such cases, there is a risk that climate-resilient schoolyards may unintentionally **reproduce existing spatial inequalities**, for instance by concentrating higher-quality outdoor spaces in schools that are already comparatively advantaged.

The MCA framework responds to this tension by elevating **social and educational equity** to one of four core decision families (Table 1). By operationalising deprivation indices, green-space deficits and school population characteristics as explicit indicators, it becomes possible to prioritise those schoolyards where interventions are likely to have the greatest impact on exposure gaps and health and learning conditions. Importantly, this does not preclude other priorities (e.g., hydrological performance or feasibility), but requires that equity be considered alongside them in a transparent way.

A further justice dimension relates to **public accessibility**. Where schoolyards remain closed outside school hours, the benefits of renaturalisation accrue primarily to enrolled pupils and staff; where they are opened as neighbourhood parks or climate refuges, a much broader public can access cooled, green space within walking distance. Our results show that only a subset of cities (notably Paris, Barcelona, New York and Milan) have taken decisive steps in this direction, raising important questions about liability, security and care that future research should address in more depth.

4.3. Bridging Building-Scale Performance Cultures and Outdoor Learning Spaces

In building and envelope design, performance-based and life-cycle approaches have become increasingly mainstream, especially in Mediterranean and semi-arid contexts where passive strategies and cost-optimal insulation have been systematically explored [1,2]. By contrast, outdoor educational spaces such as schoolyards have often remained outside this performance culture, evaluated through ad-hoc indicators or purely qualitative assessments.

This paper suggests that there is considerable value in **bridging these two traditions**. On the one hand, the CAME-MCA framework translates ideas familiar from building optimisation—such as the need to balance performance, cost and feasibility—into the domain of outdoor spaces and nature-based solutions. On the other hand, schoolyard programmes bring to the fore dimensions that are often underplayed in building optimisation, including children's agency, play, pedagogy and community use.

The proposed MCA is intentionally generic and lightweight, designed to work with data that many municipalities already possess (imperviousness, land-surface temperature, deprivation indices, park accessibility). For researchers, a clear next step is to **test and refine the framework in specific cities**, combining more detailed thermal, hydrological and ecological models with participatory weighting of criteria among stakeholders. For practitioners, even a simple scoring exercise based on Table 1 can help move from opportunistic or politically driven project selection towards more robust, criteria-based prioritisation.

4.4. Governance Challenges and Opportunities

The governance patterns observed across cases underline a central tension: climate-resilient schoolyards sit at the intersection of **multiple policy domains**—education, climate adaptation,

health, green infrastructure, public space—each with different cultures, budgets and time frames. While this position creates opportunities for synergies and co-benefits, it also generates coordination challenges and risks of institutional fragmentation.

Programmes that appear most robust in our analysis are those where schoolyard transformation is anchored in:

- a **city-wide strategy** (e.g., climate plan or resilience framework);
- **formal inter-departmental agreements** that clarify roles, responsibilities and budgets; and
- **stable partnerships** with NGOs or community organisations that can support design, implementation and stewardship.

Conversely, NGO-driven or purely project-based initiatives, although often innovative and socially rich, face difficulties in scaling and sustaining their interventions once initial funding cycles end. These findings echo broader debates on the need to move from project logics to **long-term governance models** for nature-based solutions and child-friendly cities.

One implication is that future research should pay more attention not only to the *design* of climate-resilient schoolyards, but to the **institutional conditions under which they can become durable infrastructures**. Comparative work on governance arrangements, funding mechanisms (including climate-adaptation and health budgets) and maintenance regimes could yield valuable lessons for cities seeking to scale such programmes.

4.5. Limitations and Future Research Directions

Several limitations of this study should be acknowledged. First, the analysis relies primarily on **documentary sources**—policy reports, academic publications, websites and evaluation documents—which are heterogeneous in scope and depth. Some programmes provide detailed thermal and hydrological monitoring, while others offer only qualitative narratives or limited indicators. This asymmetry constrains the possibility of fully standardised quantitative comparison.

Second, the CAME coding and the H/M/L ratings in Table 2 inevitably involve an element of **interpretive judgement**. While the coding scheme was developed iteratively and applied consistently, different analysts might classify borderline strategies somewhat differently, especially where documents are ambiguous or objectives overlap.

Third, the MCA framework is presented as a **generic decision-support tool**, not as an operational model applied to a specific city. Future work should therefore focus on implementing and evaluating the framework in concrete contexts: calibrating indicators and thresholds, testing different weighting schemes with stakeholders, and comparing MCA-based prioritisation with existing political or ad-hoc selection processes.

Finally, quantitative research is needed to explore dimensions that remain under-studied, such as long-term health and learning outcomes, impacts on air quality and noise, and interactions between schoolyard networks and wider urban heat-island dynamics. Mixed-methods designs combining longitudinal environmental monitoring, epidemiological and educational data, and qualitative research with children, teachers and residents would be particularly valuable.

4.6. Overall Contribution

Despite these limitations, the study contributes to ongoing debates in three main ways. Conceptually, it strengthens the framing of **climate-resilient schoolyards as essential public infrastructure**, situated at the intersection of climate adaptation, health, education and justice. Methodologically, it introduces a combined **CAME–MCA framework** that connects strategic analysis of programmes with an operational tool for prioritisation, bridging building-performance cultures and outdoor nature-based solutions. Practically, it distils lessons from leading international experiences into two synthetic matrices (Tables 1 and 2) that can guide cities and school systems interested in designing and scaling networks of climate-resilient schoolyards.

Taken together, these contributions underscore that transforming schoolyards is not a marginal or cosmetic intervention, but a promising, socially embedded and educationally rich strategy for advancing **urban climate adaptation and justice** in the everyday spaces of children’s lives.

5. Conclusions

This paper has argued that climate-resilient schoolyards should be understood and planned as **essential public infrastructure for urban climate adaptation**, rather than as isolated greening projects or purely educational amenities. Through a comparative analysis of nine international programmes and the development of a combined **CAME–MCA framework**, we have shown that schoolyard transformation can deliver significant environmental, social and educational benefits while also revealing important strategic and governance challenges.

First, the cross-case review demonstrates a strong convergence around a **robust and transferable design toolkit**—depaving, vegetation and shade, nature-based drainage and selective use of cool materials—that consistently improves microclimatic conditions, stormwater performance and biodiversity. When deployed at scale, these measures position schoolyards as distributed cooling and ecological nodes embedded in the everyday spaces of children and neighbourhoods.

Second, the analysis highlights that climate-resilient schoolyards have considerable potential to advance **climate and environmental justice**, if equity is made an explicit criterion for site selection and design. Programmes that prioritise socio-economically disadvantaged, park-poor and heat-exposed neighbourhoods show how schoolyards can act as levers to reduce exposure gaps and enhance access to high-quality green space. Where equity is only an implicit concern, there is a risk that benefits concentrate in already advantaged areas.

Third, the CAME matrix reveals that most initiatives remain in a **“Correct + Adapt” consolidation phase**, with substantial progress in remediating inherited deficits and addressing current climate risks, but comparatively weaker attention to long-term **maintenance (Maintain)** and systematic **innovation (Explore)**. Strengthening maintenance regimes, budget lines and stewardship arrangements emerges as a prerequisite for treating schoolyards as durable infrastructure rather than as vulnerable pilot projects.

Fourth, the proposed **Multicriteria Analysis (MCA)** framework, structured around four criteria families—environmental and climatic performance, social and educational equity, urban integration and accessibility, and feasibility and co-benefits—offers a practical decision-support tool for municipalities and school authorities. By translating the lessons of leading programmes into explicit, operational criteria (summarised in Tables 1 and 2), the MCA can help shift from opportunistic or politically driven project selection towards **transparent, criteria-based prioritisation** of schoolyard networks.

Finally, the study points to several **directions for future research and practice**. Empirical testing and local calibration of the MCA framework in specific cities would allow comparison between MCA-based prioritisation and existing selection processes. Longitudinal mixed-methods research is needed to better understand long-term impacts on health, learning, social cohesion and biodiversity, as well as the institutional conditions that enable schoolyards to function as resilient, well-maintained infrastructure.

Overall, the findings suggest that investing in climate-resilient schoolyards is not a marginal or cosmetic strategy, but a **structurally relevant pathway** for advancing urban climate adaptation, health and justice in the spaces where children live, learn and play every day.

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Abbreviations

The following abbreviations are used in this manuscript:

CAME	Correct, Adapt, Maintain, Explore
MCA	Multicriteria Analysis
NBS	Nature-Based Solutions
UHI	Urban Heat Island
LST	Land Surface Temperature
GI	Green Infrastructure
NGO	Non-Governmental Organization
BIPV	Building-Integrated Photovoltaics
SDG	Sustainable Development Goals

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