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# A multi-criteria decision analysis framework for assessing the environmental vulnerability of urban playgrounds: A case study of Iași, Romania

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## Abstract

Urban playgrounds are important in many ways for children's well-being, yet their environmental conditions remain rarely assessed in an integrated manner, particularly in post-socialist cities. This study evaluates the environmental vulnerability of 214 playgrounds in Iași Municipality, Romania, using a geospatial Multi-Criteria Decision Analysis (MCDA) framework incorporating four indicators: land surface temperature (LST), vegetation density (NDVI), noise exposure, and air quality (AQI). Indicator values were extracted within 25-meter playground buffers, normalized, and combined into a composite vulnerability index with PCA-derived weights. Results reveal marked spatial variability, with scores ranging from 6 to 87 on a 0–100 scale. Moderate vulnerability is the most prevalent condition, characterizing 46.7% of sites, while high and very high vulnerability (18.7%) concentrate in dense, traffic-exposed neighborhoods with elevated thermal stress and limited vegetation. Lower vulnerability is associated with higher elevations and proximity to green infrastructure. The findings demonstrate that formal playground distribution does not guarantee spatial environmental equity, with children in post-socialist high-density neighborhoods facing systematically worse outdoor conditions. The proposed framework is transferable and supports evidence-based planning interventions aimed at improving the environmental quality and resilience of child-oriented urban spaces.

**Keywords:** Environmental vulnerability, spatial analysis, remote sensing, post-socialist cities, urban sustainability

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## 1. Introduction

Urban playgrounds serve as multifunctional spaces that support children's physical, cognitive, and social development while enhancing community well-being and urban livability (Carroll et al., 2017; Vecellio et al., 2022). Their importance extends beyond recreation; playgrounds are key contributors to environmental services such as microclimate regulation, noise mitigation, and air purification (Nowak et al., 2006; Vanos et al., 2017). In densely built cities, they also function as some of the few publicly accessible green infrastructures, particularly for vulnerable population groups such as children, the elderly, or low-income households (Refshauge et al., 2013; Rugel et al., 2017). Beyond recreation, playgrounds occupy a prominent place in public-space governance and planning debates (Horton & Kraftl, 2018) and have been the subject of numerous studies assessing their availability and spatial distribution in urban areas (Smoyer-Tomic et al., 2004). Research on playground safety similarly emphasizes supervision, age-appropriate design, surfacing and material choices as determinants of injury risk (Sansakorn et al., 2022; Suminski et al., 2015; Vollman et al., 2009). However, playgrounds in post-socialist Eastern European cities, characterized by transitional governance structures and rapid, often uncoordinated urbanization processes, face environmental stressors that compromise not only their functionality, but accessibility as well (Kentelky et al., 2024). Research has shown that urban heat, inadequate vegetation cover, and high noise exposure significantly reduce outdoor recreational spaces' usability and thermal safety (Lehnert et al., 2024; Pfautsch et al., 2022). Moreover, these environmental risks are often spatially uneven, leading to unequal access to safe and healthy play environments, and raising concerns about social and environmental equity (Bănică et al., 2023; Sheridan et al., 2019).

In Eastern European cities, playgrounds are often distributed according to past urban planning logic rather than current environmental conditions or demographic needs (Csomós et al., 2020). As such, some neighborhoods – especially older and high-density ones – tend to be more exposed to high surface temperatures, air pollution, and limited green infrastructure (Ignatieva et al., 2020; Sfică et al., 2018). These disparities underscore the need for localized assessment of playground quality and vulnerability to better inform urban policy and investment in green infrastructure.

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Building on the well-documented benefits of outdoor play for children's physical, cognitive and social development and for community cohesion, there is growing evidence that specific environmental stressors – notably noise (Vanos et al., 2017), heat waves (Lehnert et al., 2024), air pollution, lack of shade and vegetation, and harmful surface materials (Pfautsch et al., 2022) – reduce playground usability and can create direct health risks for children. At the same time, multi-scale vulnerability frameworks emphasize that these hazards are spatially uneven across cities and interact with social factors to produce inequitable access to safe play spaces (Wu & Liu, 2022).

Therefore, this study aims to assess the environmental vulnerability of urban playgrounds in Iaşi Municipality, a second-tier post-socialist city in Romania, through an integrated spatial analysis framework. The primary objective is to identify spatial patterns of environmental risk across the municipal playground network by examining four key environmental indicators: vegetation availability, thermal exposure, noise pollution, and air pollution through topographic context. By generating composite vulnerability scores and examining their correlation with neighborhood-level population density and green space availability, the research seeks to reveal areas of environmental inequity where children face compounded exposure to adverse conditions during outdoor play. Ultimately, the study intends to provide an evidence base for prioritizing intervention zones and informing the strategic integration of nature-based solutions (NBS) into playground design and rehabilitation policies, thereby supporting the transition toward more equitable, climate-resilient, and health-promoting urban play infrastructure in post-socialist urban contexts.

## 2. Theoretical background

The studies on the environmental quality of urban playgrounds have increasingly emerged as a focal point within broader discussions on subjects such as sustainable urban planning, environmental justice, and children's well-being. A growing body of literature highlights the vulnerability of playgrounds to environmental stressors, particularly in cities where rapid urbanization and insufficient green infrastructure intersect. These spaces, vital for children's development and urban resilience, are often overlooked in urban policy frameworks, especially in post-socialist contexts like Romania. This literature review synthesizes recent academic contributions that examine playgrounds as recreational spaces and critical components of urban environmental quality and equity. Urban vulnerability and environmental inequity are central to understanding playgrounds' spatial distribution and environmental quality. Frantzeskaki et al. (2019) argue that urban areas differ significantly in their exposure and capacity to adapt to environmental stressors such as heat, pollution, and noise, often reflecting social and infrastructural inequality patterns. Sheridan et al. (2019) specifically address disparities in $NO_2$ exposure across parks and playgrounds in Greater London, emphasizing how environmental burdens disproportionately affect marginalized communities. These inequities are not incidental but embedded within broader urban development patterns and infrastructure investments.

In Eastern European cities, where urban planning frameworks continue to undergo institutional transformation following the post-socialist transition, these disparities are frequently amplified by fragmented governance structures, weak inter-sectoral coordination, and the persistence of path-dependent planning practices (Hirt, 2013) that prioritize infrastructure development over environmental equity and public health considerations (Sarabi et al., 2022). Empirical studies show a strong relationship between urban morphology and playground thermal discomfort. Lehnert et al. (2024) provide detailed analyses of how different surface materials and the presence or absence of shading significantly alter heat exposure in Central European playgrounds. Their study finds that surface temperatures during hot summer days can exceed safety thresholds for children's physical activity. Similarly, Carlstein et al. (2023) demonstrate that playgrounds with mature tree canopy cover in Melbourne significantly enhance the city's overall thermal comfort, reinforcing the need for climate-sensitive playground design. These findings are further supported by Pfautsch et al. (2022), which highlight the significance of both surface material selection and shade provision in prolonging playtime and reducing the risk of injuries. Such research emphasizes the necessity of incorporating microclimatic factors into playground design, especially in the context of climate change. Noise pollution is another relevant, but underexplored, stressor in playground environments. While urban noise is generally considered in transportation and residential planning, its effects on play spaces remain insufficiently addressed. Some studies, such as Nowak et al. (2006), suggest that tree cover and vegetative buffers can significantly reduce ambient noise levels. This ecological function of green infrastructure aligns with the broader concept of ecosystem services that playgrounds can provide, including air purification, stormwater mitigation, and habitat provision. However, the effectiveness of these services depends greatly on the spatial configuration, vegetation density and surface of the area of the playground site.

The multifunctional role of playgrounds extends beyond ecological services; Barton et al. (2014) and Refshauge et al. (2013) highlight the co-benefits of green playgrounds in enhancing children's physical activity, mental well-being, and social inclusion. These spaces can act as nodes of community interaction and intergenerational exchange, especially when embedded in accessible and safe urban environments. Yet, children's use of playgrounds is critically mediated by environmental comfort conditions, particularly temperature and shade availability (Huang et al., 2021; Vanos et al., 2017). In hotter climates or during heatwave events, inadequately shaded playgrounds become effectively unusable, exacerbating disparities in access to safe outdoor play environments (Barton et al., 2014; Refshauge et al., 2013). Recent thermal assessments document this vulnerability: Rasmussen et al. (2023) revealed significant spatial variability in thermal stress across playground sites in Gothenburg, Sweden, while Walters and Pfautsch (2025) developed the Heat-Safe Play Index (H-SPI) as a practical evaluation framework for playground thermal safety.

Nature-based solutions (NBS) – strategies leveraging ecological processes to address urban challenges including extreme temperatures, air pollution, and stormwater management (Ignatieva et al., 2020; Somarakis et al., 2019) – offer effective interventions for improving playground environmental performance through native tree planting, permeable materials, and topographical features like bioswales (Maghlakelidze, 2018). However, NBS remain underutilized in Eastern European cities due to institutional inertia, budgetary constraints, and fragmented planning, with playgrounds often treated as 'aesthetic add-ons' rather than environmental infrastructure (Bănică et al., 2023). Addressing this implementation gap requires systematic assessment of existing playground environmental conditions and the development of evidence-based design guidelines that prioritize children's thermal comfort and air quality exposure alongside recreational functionality.

The interplay between playgrounds and urban sustainability is gaining momentum in academic and policy discourses; as urban areas continue to densify and climate change accelerates, ensuring that playgrounds offer safe and stimulating environments and protection from environmental stressors becomes essential. This requires moving beyond traditional design approaches and embracing transdisciplinary strategies that combine

environmental science, urban planning, and public health. Spatially explicit analyses, such as those conducted using GIS and remote sensing tools, are increasingly valuable in identifying high-risk playgrounds and guiding targeted interventions.

## 3. Study area and context

### 3.1 Urban overview of Iași city

Iaşi Municipality, located in northeastern Romania (Fig. 1), is the country's second-largest city by population, with 389,494 registered residents according to the most recent official statistics (INS, 2024; Foşalău et al., 2025). It represents an important academic, cultural, and economic center and covers both densely urbanized areas and peripheral residential developments, resulting in heterogeneous land-use patterns and pronounced spatial disparities in access to infrastructure, green spaces, and environmental quality (Sfică et al., 2018).

The city's urban morphology reflects successive development phases shaped by distinct planning paradigms. The historical core, situated on the upper terraces of the Bahlui River, maintains relatively lower residential density but intense urban activity due to Iaşi's pronounced monocentric structure. Socialist-era neighborhoods, primarily developed on the lower terraces of the Bahlui River, concentrate the highest population densities while retaining comparatively favorable environmental conditions, owing to state-planned provision of green spaces, playgrounds, and regulated building densities. Despite ideological criticism, these planning approaches often ensured broader access to public amenities than subsequent development phases. In contrast, post-socialist residential expansion at the urban periphery – typically developed along major arterial roads and within formerly rural settlements – proceeds largely without coherent planning frameworks, maximizing built coverage at the expense of public facilities and green infrastructure, though remnants of undeveloped natural areas persist. Former industrial zones undergoing private-sector regeneration further intensify spatial pressures through high-density redevelopment that prioritizes profitability over resident needs, particularly regarding green space provision. Mixed-use areas incorporating historical, administrative, educational, or medical facilities generally offer superior environmental conditions but restrict public access.

### 3.2 Systemic vulnerabilities in the urban ecosystem of Iași

Iaşi Municipality exemplifies the complex environmental challenges facing post-socialist urban centers, characterized by systemic vulnerabilities that profoundly affect public recreational infrastructure, particularly children's playgrounds. The city's pronounced continental climate, coupled with intensive (peri) urban expansion, has generated significant surface urban heat island (SUHI) effects, with LST exceeding 35 °C in densely built areas during summer periods (Sfică & Ţopa, 2023). Concurrent air quality deterioration, evidenced by elevated particulate matter concentrations (PM10 and PM2.5) that frequently exceed European regulatory thresholds, positions Iaşi among Romania's most polluted urban centers (Burghelea et al., 2024; Drăgoi et al., 2025). These environmental stressors create acute exposure risks for children in outdoor recreational spaces, where prolonged activity periods coincide with inadequate natural buffering systems.

The spatial manifestation of these vulnerabilities reflects broader patterns of chaotic urban expansion and socio-environmental inequity that emerged following Romania's post-1990 transition period. Accelerated suburbanization and fragmented development patterns have resulted in a heterogeneous urban fabric lacking functional zoning and green infrastructure integration (Foşalău et al., 2025; Ursu et al., 2016). Air pollution hotspots demonstrate pronounced spatial overlap with socio-economically disadvantaged neighborhoods, including Păcurari, Canta, and Dacia districts. At the same time, access to quality green spaces exhibits significant disparities between centrally planned socialist-era zones and rapidly expanding peri-urban areas. Despite achieving the nationally-required 26.15 $m^2$/capita green space threshold (Law no. 24/2007; Săgeată et al., 2025), accessibility analysis reveals that only 25% of residents live within five minutes of urban green spaces (Roşu & Corodescu, 2013) – a figure that, while dating from 2013, remains a defensible and arguably conservative estimate of current conditions, given that only one significant green space

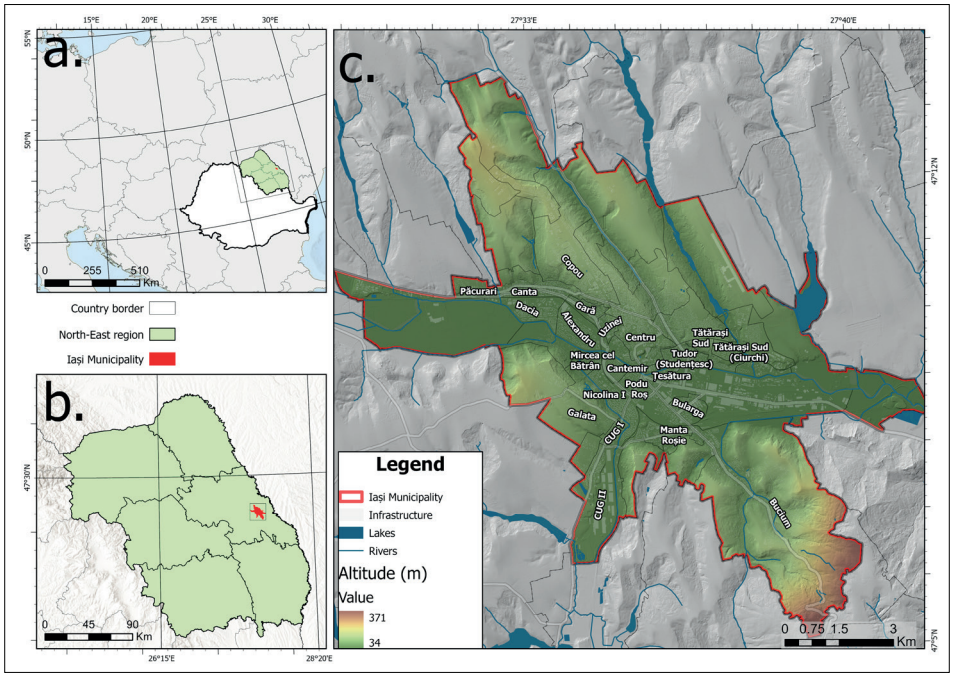



*Fig. 1: Location of the study area at different spatial scales: (a) position of the North-East Region within Romania; (b) location of Iaşi Municipality within the North-East region; (c) topography, hydrography, infrastructure and neighborhoods distribution of Iaşi Municipality Source: Authors' elaboration using spatial datasets from Eurostat, OpenStreetMap (OSM), and ANCPI (National Agency for Cadastre and Land Registration)*

addition has occurred since (the C.A. Rosseti park at the city's northern periphery), and that the structural drivers of limited accessibility – monocentric urban form, high-density post-socialist residential blocks, and continued peripheral densification without corresponding green space provision – have persisted or intensified in the intervening years (Badiu et al., 2019; Foşalău et al., 2025). These conditions create pronounced environmental justice concerns for the primary users of these spaces – namely children and the elderly, whose physiological sensitivity renders them disproportionately susceptible to thermal stress, noise exposure, and degraded air quality.

This configuration of thermal stress, air quality degradation, and inequitable green space distribution provides the contextual foundation for systematic playgrounds vulnerability assessment. Integrating vegetation density, through the Normalized Difference Vegetation Index (NDVI), land surface temperature (LST), noise levels, and air quality metrics into composite vulnerability indices responds directly to documented environmental stressors affecting children's outdoor recreational environments.

This transitional urban structure, characterized by heterogeneous environmental quality across development periods, provides a critical context for examining playground distribution and environmental performance within a city where market-driven densification increasingly compromises quality of life relative to the spatial standards established under centralized socialist planning.

## 4. Research design

This study adopts a geospatially explicit, indicator-based methodology within a Multi-Criteria Decision Analysis (MCDA) framework to evaluate the environmental vulnerability of playgrounds within the administrative boundaries of Iaşi Municipality. The approach integrates spatial statistics, remote sensing, and GIS-based evaluations to map environmental stressors acting upon the 214 urban playgrounds. The objective is to produce a spatially differentiated and statistically-validated vulnerability index that reflects localized exposure to key environmental risks relevant to child-friendly public spaces. In this study, environmental vulnerability is conceptualized as cumulative spatial exposure resulting from the overlap of multiple environmental stressors rather than as a measure of social sensitivity or adaptive capacity.

### *4.1 Data acquisition*

The core of the methodological framework is structured around four key indicators selected for their empirical relevance to playground sustainability: LST, NDVI, noise exposure, and direct air quality (AQI). In addition, population density data were integrated in order to estimate the number of potential playground users. Population density was used as a contextual variable to characterize potential exposure intensity, rather than as a component of the composite vulnerability index, which focuses exclusively on environmental stressors. This demographic variable provides an essential contextual layer for assessing environmental exposure and the intensity of human use, allowing the vulnerability model to account for ecological and social dimensions of playground sustainability. Table 1 describes the data sources for the aforementioned parameters and the methods used for processing and harmonization within the GIS environment. Playground locations were digitized from municipal databases and cross-validated through satellite imagery interpretation and in-situ verifications. Each playground was associated with a 25-meter circular buffer to spatially extract contextual environmental information; the 25-meter buffer was chosen to represent the immediate micro-environment experienced by children during play activities, balancing spatial specificity with the resolution of remote sensing inputs.

NDVI was quantified using Sentinel-2 MSI Level L2A imagery for the summer of 2024, using a set of cloud-free scenes from early June to late August. The scenes have been already pre-processed (atmospherically corrected by the European Space Agency (ESA) so that potential clouds and cloud shadows can be removed). A seasonal median composite that represents peak vegetation conditions was then generated for the entire study area, from which the NDVI was calculated by computing bands 4 (Red) and 8 (NIR). NDVI values were later normalized and inverted post-scaling so that reduced greenness corresponds

| Parameter | Data type | Source / provider | Spatial resolution | Acquisition date | Processing / notes |
|---|---|---|---|---|---|
| NDVI | Raster (Sentinel-2) | Copernicus Data Space Ecosystem | 10 m | 23 June 2024<br>28 June 2024<br>8 July 2024<br>13 July 2024<br>28 July 2024<br>7 August 2024 | Atmospherically corrected with Sen2Cor<br>Cloud & cloud shadow removal using SCL<br>Compilation into composite raster<br>NDVI = (B8 − B4) / (B8 + B4); normalized and inverted |
| LST | Raster (Landsat 4, 5, 7 and 8) | USGS Earth Explorer | 30 m | July (1984–2022) | Load TOA BT*<br>Load SR* data<br>Load ASTER GED* Dataset<br>Mask clouds<br>Compute NDVI<br>Compute FVC*<br>Compute TIR* Emissivity<br>Compute LST (SMW* algorithm)<br>Gap-filling with DINEOF* |
| Noise pollution | Raster (Municipality map) | Iaşi Municipality | ~1:5,000 | 2023–2024 | Digitized and calibrated with in-situ observations |
| Air pollution | Raster (EBK Regression) | AQICN | 100 m | Multiple | Regression based on high-resolution digital elevation model, population density, traffic and air quality data |
| Playground locations | Vector (points) | Iaşi Municipality + digitizing | – | 2025 | Validated through field visits and satellite imagery |
| Population | Raster (GHS-POP 2020) | European Commission, JRC (Global Human Settlement Layer) | 100 m | 2020 | Extracted by mask to study area and aligned with other raster datasets |

*Tab. 1: Overview of spatial datasets and preprocessing steps used in the study*
*Notes: * TOA BT = Top-of-Atmosphere Brightness Temperature; SR = Surface Reflectance; GED = Global Emissivity Dataset; FVC = Fractional Vegetation Cover; TIR = Thermal Infrared; SMW = Statistical Mono-Window*
*Source: Authors' elaboration based on the datasets and sources specified in the table*

to higher vulnerability scores. NDVI was selected as an indicator of vegetation availability due to its widespread use as a proxy for urban greenness and its demonstrated relevance for children's health and outdoor activity, including associations with increased physical activity and reduced environmental health risks in green play environments (Grigsby-Toussaint et al., 2011; Bao et al., 2021). Although NDVI does not fully capture qualitative aspects of vegetation, such as spatial configuration, accessibility, or perceptual experience, particularly in small or fragmented play spaces (Teeuwen et al., 2024), it provides a consistent, open-source and spatially explicit measure of vegetation presence suitable for integrated vulnerability assessment at the city scale.

LST was estimated from thermal infrared bands of Landsat 8, using radiometric calibration and emissivity correction procedures. Given the urban heat island effect's substantial impact on children's thermal comfort and health, LST was weighted accordingly in the composite index.

Further, high spatial resolution LST data (30 m spatial resolution) spanning over a significant period of 39 years (1984 to 2022) provided by the Landsat series (4, 5, 7, 8) was integrated in this study. To obtain Warm Season LST, we utilized a comprehensive code repository (quality controlled) provided by Ermida et al. (2020). In order to fill gaps in Landsat LST data due to cloud cover and sensor errors, this study employed the Data Interpolating Empirical Orthogonal Functions (DINEOF) method, initially proposed by Beckers and Rixen (2003) and successfully applied in Sea Surface Temperature reconstruction (Alvera-Azcárate et al., 2011; Sirjacobs et al., 2011). The efficiency of the DINEOF method is evident in its widespread applications across various fields (Amihaesei et al., 2023; Cheval et al., 2020), enabling precise thermal characterization of playground locations and their immediate surroundings – a prerequisite for assessing children's thermal exposure during outdoor play activities. Similar with Creţu et al. (2025) in this study the DINEOF gap-filling method was applied to 97 LST images available from 1984 to 2022 during the July month, having 1% to 50% missing data over the analyzed cities, using the 'Raster Time Series Analysis' library (Filipponi, 2019) developed in R (R Core Team, 2021).

Noise exposure data were obtained by georeferencing and digitizing the official noise pollution map of Iaşi Municipality, which was developed using Predictor software (version 2023) during September 2023. The noise map employs calculation methods specified in Annex 2 of Law 121/2019 (Romania) and applies the CNOSSOS-EU algorithm for three primary noise sources: road traffic, railway traffic (including tramways), and industrial activities. Noise exposure is expressed as Lden (day–evening–night equivalent sound level), measured in dB(A), consistent with European environmental noise standards, and the original noise map has a spatial resolution of 10 m. Spatial noise level classes were extracted through systematic digitization of the georeferenced map, enabling precise characterization of acoustic conditions at playground locations. As urban noise constitutes a chronic yet frequently underestimated environmental stressor affecting children's outdoor play behavior and developmental outcomes, its integration captures the acoustic dimension of environmental discomfort critical to comprehensive playground quality assessment. Although digitization of modelled noise contours introduces minor spatial uncertainty, this limitation is considered negligible relative to the exposure classes applied and does not affect the comparative assessment of playground vulnerability across the study area.

Air pollution data for each playground was retrieved from an estimation performed on the entire study area, based on the Empirical Bayesian Kriging Regression Prediction (EBK Regression Prediction). This analysis was done in ArcGIS Pro 3.6 and it represents a geostatistical method that combines regression-based trend modeling with spatial interpolation of residuals, enabling the integration of a number of predictors alongside the spatial autocorrelation structure of the dependent variable. As input measurements, AQI data were obtained from the AQICN network, comprising 36 monitoring points distributed throughout Iaşi, each providing standardized composite air pollution index values aggregated over available measurement periods of up to 1,000 days. Three spatial predictors were incorporated: elevation, derived from a high-resolution LiDAR digital elevation model provided by the Prut-Bârlad Basin Water Authority; population density, from the Global Human Settlement Layer (GHSL); and traffic intensity, based on strategic noise mapping data provided by the City Hall of Iaşi. Prior to modeling, all raster layers were reprojected to a common coordinate reference system, resampled to a matching cell size, and spatially snapped to ensure a correct overlay. As stated above, population data was used in order to capture the social dimension. Cell-based population values were extracted from a Global Human Settlements Layer (GHS-L) raster depicting population sum. Specifically, the analysis employed the GHS-POP 2020 dataset, a 100-meter resolution raster expressing the total population count per cell.

### 4.2 Methods

Following spatial data analysis practices established in the geographical sciences (Demšar et al., 2013), a MCDA approach was implemented, where a weighting scheme was developed through the application of a statistical dimension-reduction technique, namely Principal Component Analysis (PCA), conducted using R (R Core Team, 2021) using the *factoextra* package. PCA is a multivariate statistical method that transforms a set of potentially correlated variables into a smaller number of uncorrelated components, known as principal components (PCs), which explain the maximum variance within the dataset (Karamizadeh et al., 2013). By examining the loadings of each original variable on the first few PCs (Fig. 2), it becomes possible to identify which variables contribute most significantly to the overall structure of the dataset. All indicators were min–max normalized prior to PCA. Weights were derived from the first principal component (PC1), which captured the dominant variance across playground conditions; PC1 loadings were converted to positive values and normalized to sum to one, ensuring proportional, interpretable contributions to the vulnerability index. In this study, PCA served as a data-driven tool to assess the underlying inter-relationships among environmental indicators and to determine their relative importance in explaining spatial variability across playgrounds, rather than as a dimensionality-reduction step for predictive modeling. The first principal component (PC1) captured the dominant share of the

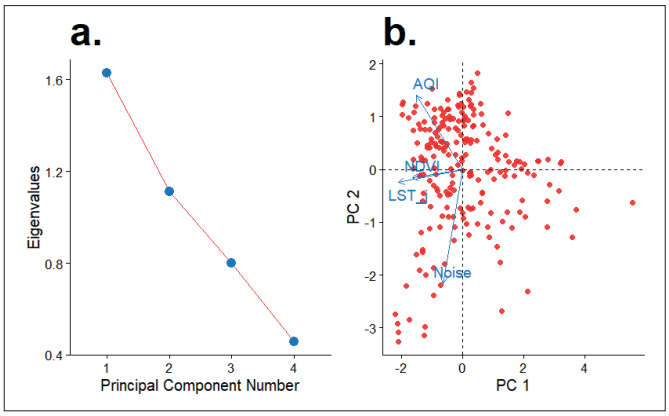



*Fig. 2: Principal Component Analysis (PCA) of environmental indicators: (a) eigenvalue scree plot; (b) PC1–PC2 biplot showing variable loadings and distribution*
*Source: Authors' calculations; data analysis and visualization performed in RStudio*

dataset's variance (40.7%), whilst the second principal component (PC2) accounted for an additional 27.8%. This analysis revealed that July season LST, NDVI, and AQI exhibited the highest contributions to PC1 (44.9%, 27.6%, and 23.4%, respectively), confirming their synergistic and dominant role in influencing playground-level environmental conditions. Conversely, noise emerged as an independent stressor, dominating PC2 with a 69.3% contribution. This statistical insight substantiated the decision for assigning greater weights to the thermal and air quality variables in the upcoming composite vulnerability index. Moreover, the use of PCA helped reduce subjectivity in the weighting process, by providing with an objective validation for the chosen indicator structure and, respectively, hierarchy, thus enhancing the methodological robustness of the study. This weighting scheme also reflects empirical findings in the literature, which highlight that mainly thermal regulation and vegetation availability have a disproportionate impact on the usability and safety of urban playgrounds (Carlstein et al., 2023; Vanos et al., 2017).

The final vulnerability model applied the following weights: LST (july) – 44.9%, NDVI – 27.6%, AQI – 23.4%, and noise – 4.1%.

The formula for calculating the composite vulnerability index is, as follows:

$$\text{Vulnerability score} = 0.449 \times \text{LST july}_{norm} + 0.276 \times \text{NDVI}_{inv} + \\ + 0.234 \times \text{AQI}_{norm} + 0.041 \times \text{Noise}_{norm}$$

Prior to the score calculation, all four indicators were subjected to min-max normalization to ensure comparability. After the weighing, the composite vulnerability scores were scaled on a 0–100 continuum and classified into five ordinal categories based on the empirical distribution of scores, representing increasing relative levels of environmental vulnerability. The categories are: very low (0–40), low (41–50), moderate (51–70), high (71–85), and very high (86–100). Furthermore, a Pearson correlation matrix was produced to explore inter-variable dependencies, revealing both positive and negative associations between the selected factors. For instance, LST and NDVI showed a moderately negative correlation, consistent with the theoretical expectations, while LST and altitude demonstrated a stronger inverse relationship, reinforcing the environmental logic underpinning the vulnerability model. These findings provided an additional layer of confidence in the indicator selection and helped ensure minimal redundancy in the composite index.

All spatial data processing and cartographic operations were performed using ArcGIS Pro 3.6 software. Final maps were designed to visualize environmental vulnerability across playgrounds through both continuous gradient representations and discrete categorical classifications, enabling comprehensive spatial interpretation of exposure patterns.

## 5. Results

As of 2025, Iaşi Municipality hosts 214 official urban playgrounds, dispersed across its neighborhoods, which vary widely in terms of size, design, and environmental conditions. The broad statistical distribution of these physical and environmental parameters is summarized in Table 2. While some playgrounds are embedded within large parks, urban green spaces or green corridors, others are located adjacent to busy roads, in-between housing blocks, or in areas deficient in natural shade.

The spatial distribution of these playgrounds reveals structural inequalities deeply rooted in the city's socialist planning heritage and subsequent unregulated urban expansion. Nearly half are concentrated in dense, high-rise estates built during the socialist period – such as Nicolina, Alexandru cel Bun, and Tătăraşi – where public play spaces were originally incorporated into modernist residential layouts (Bănică et al., 2023). However, these sites now face physical degradation, limited vegetation, and high exposure to traffic noise, air pollution and heat. In contrast, newer suburban developments like Valea Adâncă, Bucium, and Galata lack municipal playgrounds altogether, illustrating a fragmentation of planning responsibilities after 1990. This duality between inherited and emergent urban morphologies mirrors findings from other post-socialist contexts, where transitions to market-driven development have weakened the integrative logic of public space provision (Sandu, 2024). A comprehensive summary of these environmental and socio-demographic indicators aggregated at neighborhood level is provided in Table 3. Similar patterns have been observed in Romania's capital, Bucharest, where the retreat of state planning produced spatial disparities in access to recreational infrastructure (Mionel & Neguţ, 2011), and in Serbia's Novi Sad, where new residential districts failed to incorporate adequate public play amenities (Lakićević et al., 2025).

### 5.1 Environmental factors

Evaluating playgrounds' environmental vulnerability necessitates an integrated analysis of biophysical conditions influencing comfort, safety and usability. In line with the methodology presented in the previous chapter of this paper, the results are structured around the four core indicators that the composite vulnerability model is based on – LST, NDVI, noise pollution and air quality – together with their statistical interrelationships and contribution to the composite vulnerability index.

The following subsections present these results thematically, highlighting spatial variability in microclimatic conditions, vegetation structure, acoustic exposure, and air pollution, as well as their combined effects on playground vulnerability across the study area.

#### 5.1.1 UHI and climate risk

The analysis of LST highlights major influences of the SUHI effect over microclimatic conditions inside the playgrounds of Iaşi Municipality. The July mean LST (1984–2022) shows that the placement of playgrounds in highly urbanized sectors – characterized by dense high-rise residential structures, a raised degree of impervious areas and reduced vegetation continuity – all determine a significant heat accumulation, with direct implications over children's thermal comfort and heat stress exposure.

The LST distribution map (Fig. 3) confirms the presence of pronounced thermal hotspots in neighborhoods such as Păcurari, Canta, Dacia, Tudor Vladimirescu and Gară, where warm-

| Indicator/Parameter | Min | Max | Mean | Median | Standard Deviation |
|---|---|---|---|---|---|
| Vulnerability score | 5.85 | 87.08 | 51.32 | 51.96 | 13.19 |
| Multiannual LST (°C) | 15.96 | 21.07 | 19.02 | 19.11 | 0.75 |
| July LST (°C) | 28.49 | 37.64 | 34.79 | 34.89 | 1.29 |
| Vegetation Density (NDVI) | 0.08 | 0.59 | 0.33 | 0.33 | 0.12 |
| Air Quality Index (AQI) | 50.35 | 72.32 | 63.75 | 64.29 | 4.20 |
| Noise exposure (dB) | 55.00 | 85.00 | 59.78 | 55.00 | 7.09 |
| Playground surface ($m^2$) | 137.00 | 3,163.00 | 339.62 | 270.00 | 311.27 |

*Tab. 2: Descriptive statistics of environmental parameters for the analyzed urban playgrounds*
*Source: Authors' calculations*

| Neighborhood | Number of playgrounds | Number of potential local users of playgrounds | Surface (ha) | Max LST July – playgrounds | Max LST July – neighborhood | Mean NDVI – playgrounds | Mean NDVI – neighborhood | Average noise level | Air quality (AQI) | Average playgrounds vulnerability |
|---|---|---|---|---|---|---|---|---|---|---|
| Tătăraşi Nord | 23 | 21,862 | 365 | 36.0 | 36.8 | 0.39 | 0.30 | 59.5 | 58.6 | 47.8 |
| Alexandru | 22 | 41,812 | 236 | 36.2 | 39.5 | 0.29 | 0.29 | 59.0 | 66.4 | 59.6 |
| Păcurari | 15 | 13,457 | 378 | 36.5 | 40.5 | 0.24 | 0.28 | 68.0 | 63.8 | 66.0 |
| Dacia | 15 | 25,918 | 235 | 36.7 | 41.0 | 0.24 | 0.23 | 58.3 | 66.4 | 76.0 |
| Canta | 13 | 12,334 | 69 | 36.1 | 38.9 | 0.26 | 0.24 | 60.0 | 64.0 | 66.0 |
| Nicolina I | 12 | 17,700 | 150 | 35.9 | 38.3 | 0.37 | 0.25 | 58.0 | 66.0 | 50.4 |
| Nicolina II | 11 | 15,751 | 239 | 37.2 | 41.1 | 0.34 | 0.30 | 61.8 | 64.3 | 61.2 |
| Podu Roş | 10 | 15,063 | 108 | 36.0 | 37.7 | 0.40 | 0.28 | 59.5 | 67.1 | 50.3 |
| CUG II | 10 | 8,784 | 706 | 35.8 | 44.4 | 0.34 | 0.32 | 59.0 | 67.4 | 53.5 |
| Tătăraşi Sud (Ciurchi) | 10 | 12,888 | 75 | 34.4 | 35.2 | 0.48 | 0.37 | 55.0 | 57.7 | 27.1 |
| Frumoasa | 9 | 6,403 | 128 | 35.8 | 43.1 | 0.30 | 0.27 | 56.1 | 65.1 | 52.9 |
| Ţesătura | 9 | 5,339 | 72 | 36.1 | 39.1 | 0.43 | 0.27 | 60.0 | 66.7 | 49.3 |
| Gară | 8 | 8,882 | 94 | 37.1 | 40.3 | 0.32 | 0.19 | 67.5 | 63.9 | 73.3 |
| CUG I | 6 | 8,367 | 74 | 35.6 | 38.1 | 0.26 | 0.24 | 56.6 | 67.0 | 60.9 |
| Grădinari | 6 | 2,805 | 112 | 35.7 | 39.4 | 0.35 | 0.25 | 55.8 | 58.5 | 52.1 |
| Bularga | 5 | 4,881 | 128 | 37.4 | 43.7 | 0.24 | 0.23 | 58.0 | 61.9 | 70.3 |
| Mircea cel Bătrân | 5 | 15,705 | 61 | 35.6 | 36.7 | 0.26 | 0.29 | 55.0 | 68.7 | 59.7 |
| Centru | 5 | 10,247 | 338 | 37.6 | 39.0 | 0.50 | 0.22 | 63.0 | 64.4 | 55.0 |
| Copou | 5 | 4,304 | 896 | 32.9 | 38.2 | 0.41 | 0.43 | 57.0 | 56.2 | 23.2 |
| Tătăraşi Sud | 4 | 10,963 | 120 | 33.5 | 36.3 | 0.27 | 0.32 | 63.8 | 54.6 | 51.9 |
| Cantemir | 4 | 8,063 | 93 | 35.1 | 37.1 | 0.43 | 0.29 | 60.0 | 65.1 | 44.8 |
| Tudor (Studenţesc) | 2 | 9,028 | 156 | 36.0 | 39.9 | 0.25 | 0.25 | 60.0 | 62.1 | 67.6 |
| Podul de Piatră | 2 | 1,206 | 100 | 33.5 | 38.9 | 0.32 | 0.23 | 60.0 | 61.3 | 48.0 |
| Manta Roşie | 1 | 1,145 | 84 | 35.6 | 38.9 | 0.13 | 0.23 | 60.0 | 64.3 | 75.2 |
| Uzinei | 1 | 2,383 | 69 | 33.4 | 40.3 | 0.55 | 0.21 | 55.0 | 66.1 | 28.9 |
| Bucium | 1 | 3,384 | 68 | 31.0 | 39.2 | 0.54 | 0.48 | 65.0 | 55.6 | 22.5 |
| | | | AVERAGE | 35.5 | 39.3 | 0.30 | 0.30 | 59.7 | 63.0 | 53.6 |

*Tab. 3: Neighborhood-level statistics of the analyzed variables*
*Source: Authors' calculations*

season LST values in areas adjacent to playgrounds consistently exceed 33–35 °C. These localized patterns are consistent with the LCZ-scale analysis of Creţu et al. (2025), who documented the long-term spatial distribution of LST across Iaşi Municipality and identified comparable configurations of persistent thermal hot and cold spots. Previous research in this study area found that summer daytime SUHI reaches its peak extent, delineated by the 35 °C isotherm. LST increases sharply when imperviousness exceeds 10%, with maximum values occurring above 80% imperviousness (Creţu et al., 2022). In contrast, playgrounds that are placed in neighborhoods such as Copou, Bucium or Tătăraşi have visibly lower surface temperatures (29–31 °C), attributable to the presence of a continuous, almost uninterrupted tree canopy layer, more favorable building spacing, and because of the natural ventilation associated with higher altitudes. These differences are accentuated by the city's geomorphology: playgrounds in the lower-lying Bahlui floodplain exhibit higher and more persistent LST values, while higher-elevated areas benefit from improved air circulation and evapotranspiration-driven cooling. The Iaşi UHI generally corresponds to densely built-up areas where artificial surfaces exceed 70% coverage. This includes the lower city areas with industrial and residential zones in the Bahlui floodplain, as well as the historic center situated on lower river terraces (Sfică et al., 2018).

Overall, LST distribution highlights that approximately a third of the 214 analyzed playgrounds are exposed to high thermal risk, especially those placed in post-socialist neighborhoods that are high-density and those that are in close proximity to intensely-circulated thoroughfares. Prolonged exposure to such conditions contributes to a reduction in time spent outdoors, also affecting the safety of the playground equipment (due to material overheating and burn risk, respectively) and limiting access of children to recreative activities during warm days.

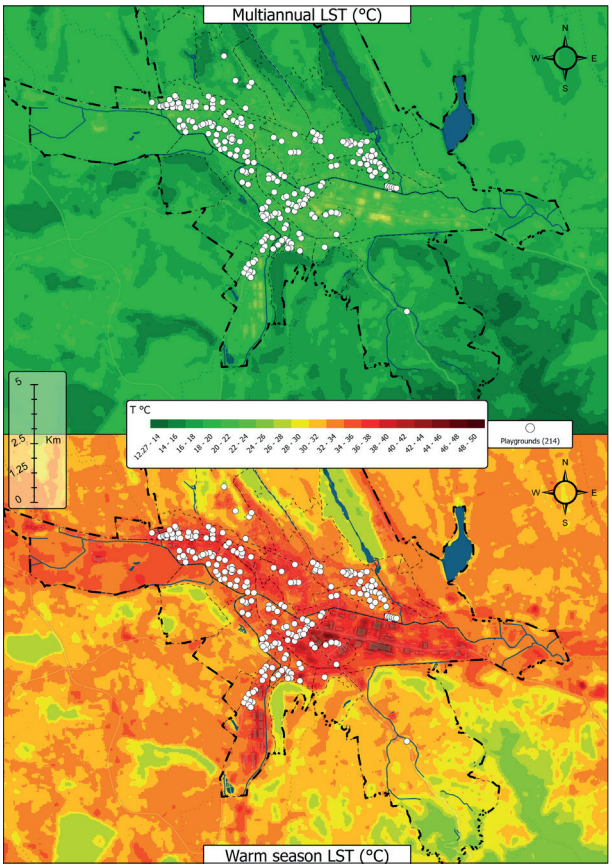



*Fig. 3: Multiannual (top) and warm-season (bottom) LST distribution in Iaşi Municipality, with the spatial distribution of urban playgrounds. Source: Authors' elaboration based on Landsat LST data courtesy of the U.S. Geological Survey (USGS, 2026)*

Therefore, UHI becomes one of the most determinant factors of environmental vulnerability, having a direct impact over the usability of playgrounds, especially during the warm season, a fact which can raise serious concerns and attract more research attention and local administration concentration efforts.

#### *5.1.2 Tree canopy and NDVI analysis*

The statistical analysis of satellite-derived NDVI values confirms individual field observations. Across the 26 neighborhoods that have at least one playground, the mean NDVI for playgrounds ranged between 0.13 and 0.55, with an overall municipal mean of 0.30. The highest NDVI values were recorded in Uzinei (0.55), Bucium (0.54), and Centru (0.50), all characterized by larger patches of vegetation and lower building densities. These neighborhoods are also distinguished by a denser, more continuous tree canopy, which provides efficient shading and evapotranspiration-based cooling, crucial in improving microclimatic comfort. Intermediate values (0.40–0.50) were observed in neighborhoods such as Tătăraşi Sud – Ciurchi (0.48), Cantemir, Ţesătura (0.43), Copou (0.41) and Podu Roş (0.40) where vegetation persists in fragmented but functionally significant forms. In these neighborhoods, partial tree canopy continuity mitigates radiant heat fluxes, but gaps between individual tree crowns reduce the overall efficiency of shading and pollutant filtration. Low NDVI values (< 0.25) were documented in highly urbanized or industrial districts such as Manta Roşie (0.13), Canta (0.26), Dacia, Bularga and Păcurari (0.24), where impervious surfaces dominate across the land cover spectrum. Here, sparse or even immature trees rarely form a closed canopy, resulting in higher surface temperatures and diminished ecosystem services.

When averaged at neighborhood level, NDVI values remain modest (0.3 overall), revealing limited vegetative resilience in the surroundings of most playgrounds. Tree canopy continuity follows a clear spatial gradient, from fragmented structures in the urban core to cohesive canopies in peripheral districts, directly influencing shading potential and summer heat buffering. This gradient, from 0.19 in Gară to 0.48 in Bucium reflects a high environmental contrast between the compact, heat-accumulating urban core and the greener periphery.

#### *5.1.3 Noise exposure*

Statistical results reveal an overall municipal mean noise level of 59.7 decibels (dB), placing Iaşi city's playgrounds within a moderate noise exposure range, according to World Health Organization Environmental Noise Guidelines (WHO, 2018). Spatially, however, noise intensity varies considerably, especially among neighborhoods. The highest average noise levels captured within playgrounds during the day were recorded in Păcurari (68 dB), Gară (67.5 dB), Bucium (65 dB), Tătăraşi Sud (63.8 dB), and Centru (63 dB), mainly due to the playgrounds' close proximity or adjacency (50–100 meters) to high-capacity roads such as Boulevards Păcurari, Nicolina, Poitiers and Anastasie Panu. These values exceed the recommended limit of 55–60 dB for urban recreational environments, indicating a persistent acoustic burden on playground users.

Based on guideline thresholds, city-scale wise, noise levels across the 214 analyzed playgrounds range from 55 to 85 dB. More than half of all playgrounds (113 – 52.8%) register values below 60 dB, suggesting relatively acceptable conditions under urban environmental standards. When the threshold is raised to 65 dB, a total of 187 playgrounds (87.3%) remain within the moderate exposure range (55–65 dB), while 27 playgrounds (12.6%) exceed this value, marking zones of high acoustic stress. Among these, 12 play spaces surpass 70 dB, six exceed 75 dB, and five reach or exceed 80 dB levels considered harmful for prolonged outdoor exposure, according to the WHO Environmental Noise Guidelines (WHO, 2018).

Also, as demonstrated by the PCA conducted in this study's methodology, noise pollution functions independently from the other evaluated hazards. Unlike thermal exposure and air pollution, which closely resemble the city's topography and building density, severe noise exposure is strictly dictated by immediate proximity to high-traffic arterial routes. Thus, high noise levels frequently compromise playgrounds that otherwise benefit from dense tree canopy and lower temperatures, highlighting a critical gap in playground safety that requires localized sound-buffering solutions.

#### *5.1.4 Air pollution and topography*

A critical dimension of environmental vulnerability in Iaşi city's playgrounds network is air pollution, as the topographic configuration and the local atmospheric conditions directly influence pollutants dispersion and accumulation. The city's 'bowl-like' geomorphology, structured around the Bahlui river valley and encircled by low hills causes frequent temperature inversions – especially during the cold season – that trap pollutants near ground level. Such conditions are particularly harmful for children using outdoor play facilities, whose respiratory systems are more sensitive to fine particulate matter.

Recent studies (Buculei et al., 2020; Burghelea et al., 2024; Cazacu & Breabăn, 2025) identify Iaşi as one of Romania's most polluted urban centers, with mean annual PM10 concentrations between 38–44 $\mu g/m^3$ and PM2.5 levels reaching 22–25 $\mu g/m^3$, periodically exceeding EU limit values (Iorga, 2021). The interpolated AQI values extracted for this study empirically confirm these exposure patterns across the municipal playground network. Across the 214 analyzed playgrounds, the AQI values range from a minimum of 50.3 to a maximum of 72.3, with the municipal mean being 63.7. Spatially, pollution hotspots align closely with high-traffic corridors, including major boulevards and arterial roads, as well as the industrial zone in the eastern sector of the city. Consequently, playgrounds placed in these exposure areas register the highest direct pollution exposure. The highest neighborhood-level AQI averages were recorded in Mircea cel Bătrân (68.7), CUG II (67.4), Podu Roş (67.1) and CUG I (67.0).

This spatial vulnerability is compounded by the absence of effective policy measures to divert heavy vehicle traffic from residential areas. The continued presence of freight and transit vehicles along these corridors – combined with proximity to both heavily trafficked roads and rail lines – creates cumulative exposure conditions that disproportionately affect children's environments in these neighborhoods, raising critical concerns about environmental justice and the equitable distribution of safe play spaces across the urban fabric.

Topography is the leading factor amplifying these spatial disparities; lower-lying neighborhoods positioned below 100 meters, such as Podu Roş, Nicolina I and Gară experience reduced air circulation and more persistent pollutant accumulation. In stark contrast, elevated neighborhoods like Copou (56.2), Bucium (55.6) and Tătăraşi Sud (54.6) register the lowest AQI values, benefitting from enhanced ventilation and vegetation-mediated filtration. This vertical gradient is consistent with previous meteorological findings, showing a ~15–20% reduction in PM10 concentrations at higher altitudes (> 150 m) compared with valley bottoms (Galon-Negru et al., 2019).

Based on the spatial characteristics of the study area and established atmospheric dispersion patterns documented in the literature (Burghelea et al., 2024; Cazacu & Breabăn, 2025; Drăgoi et al., 2025; Galon-Negru et al., 2019, Năstase et al., 2018), playgrounds situated within the Bahlui floodplain and central valley corridor are exposed to compounded environmental stressors – including elevated particulate matter concentrations,

restricted wind circulation, and increased susceptibility to thermal inversions – whereas playgrounds at higher elevations experience comparatively improved air quality conditions and reduced exposure vulnerability due to enhanced atmospheric mixing and dispersion.

### 5.2 Relationships between the environmental factors

Collectively, these environmental stressors – noise pollution, elevated temperatures, inadequate shade provision, and poor air quality – do not operate in isolation but interact to shape the environmental conditions and usability of playground spaces. The following section examines how these factors, in combination with spatial and socio-demographic variables, influence playground accessibility, safety, and utilization patterns across the urban landscape.

The correlation matrix (Fig. 4) highlights the statistical interrelationships among the four primary environmental indicators integrated into the composite vulnerability index: LST, NDVI, noise level, and AQI. These bivariate correlations were created using Pearson's coefficient based on normalized values extracted from the 214 playground buffers.

The results show an extremely strong positive correlation between Multiannual LST and July LST (r 0.96), which indicates that thermal hotspots are not ephemeral seasonal events, but persistent characteristics of the urban fabric. Another moderate positive correlation reflected in the matrix is between AQI and LST (r = 0.38 for July and r = 0.32 for Multiannual) – this relationship demonstrates how thermally stressed playgrounds in Iaşi often coincide with areas of degraded air quality – mainly due to the simultaneous influence of low-elevation pollutant trapping and heat accumulation. A moderately negative correlation between NDVI and LST (r = – 0.31 for NDVI–Multiannual LST and r = – 0.37 for NDVI–July LST) is present, indicating that areas with higher vegetation density are consistently associated with lower surface temperatures. This relationship confirms the well-documented biophysical cooling effect of vegetation, which reduces radiant heat through shading and evapotranspiration (Bowler et al., 2010; Marando et al., 2022). However, NDVI shows

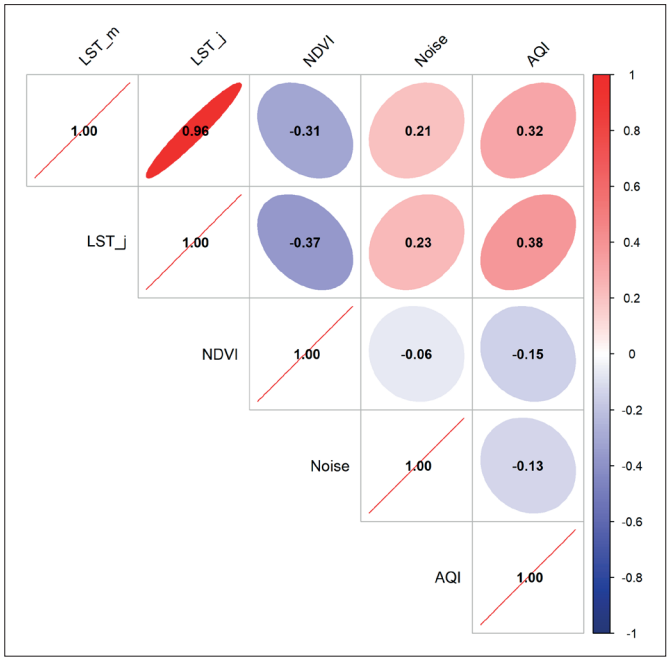



*Fig. 4: Correlation matrix between environmental indicators used in the vulnerability assessment of urban playgrounds (ellipses indicate the strength and direction of Pearson's r correlation coefficients)*
*Source: Authors' calculations; data analysis and visualization performed in Rstudio*

only a weak negative relationship with AQI (r = – 0.15), which suggests that although vegetation is efficient in thermal regulation, its role in localized air purification across the city's playgrounds is present, but less pronounced than its cooling capability.

Noise levels continue to exhibit spatial independence from other factors. While noise shows a weak positive correlation with thermal stress (r = 0.21 for noise-Multiannual LST and r = 0.23 for noise-July LST), which is suggesting some overlapping with traffic-intensive environments, its correlations with NDVI (r = – 0.06) and AQI (r = – 0.13) are negligible or statistically insignificant. This lack of linear association reinforces the PCA results, confirming that acoustic stress is a distinct hazard dictated by immediate road proximity rather than the broader topographic or vegetative patterns that govern heat and air pollution. These correlations may vary spatially, reflecting the heterogeneous structure of the urban environment and the local influence of vegetation, elevation, and built density across Iaşi city.

### 5.3 Patterns of vulnerability index

The analysis revealed significant variation in the environmental vulnerability of playgrounds across Iaşi Municipality, with scores ranging from 6 to 87 on a normalized scale from 0 to 100. This variation shows the heterogeneous environmental conditions present within the city's public play infrastructure. Approximately 18.2% (39) of playgrounds fell into the category of very low vulnerability (top-left quadrant of Fig. 5), 16.4% (35) exhibited low vulnerability (top-right quadrant), while nearly half (46.7% or 100 playgrounds) were classified as moderately vulnerable (bottom-left quadrant). High and very high vulnerability classes (bottom-right quadrant) accounted for 15.0% (32) and 3.7% (8) of the analyzed playgrounds, respectively.

On the one hand, playgrounds situated in older, compact neighborhoods – such as Păcurari, Nicolina, Alexandru cel Bun, and Dacia – recorded the highest vulnerability values, appearing in the bottom-right quadrant of Figure 5. This is a direct result of high building density, minimal vegetation, and extended exposure to road-related noise. These environmental stressors are tightly linked to the intensification of surface temperatures, a phenomenon widely attributed to land use patterns and the dominance of impervious surfaces (Tran et al., 2017). On the other hand, lower vulnerability scores (top-left and top-right quadrants) were found in newer and peripheral districts like Bucium, Tătăraşi, and Copou. These areas benefit from a more open urban form, larger distances between buildings (often exceeding 35–60 meters), and access to ecological buffers such as forests and lakes. These vegetated and aquatic features exert a measurable cooling influence on adjacent urban surfaces, helping reduce localized heat and airborne pollutants (Ichim et al., 2024). Additionally, topographic positioning significantly influenced environmental comfort, with playgrounds located at higher altitudes generally exhibiting lower vulnerability scores. This pattern suggests that air stagnation and pollutant accumulation (captured by the AQI) are more likely to occur in lower-lying zones, particularly under inversion conditions and in areas with weak ventilation (Rendón et al., 2014). Playgrounds with moderate vulnerability (bottom-left quadrant) were prevalent in mid-density residential zones, including Podu Roş, Cantemir, and CUG. These locations showed a mix of favorable and unfavorable factors – moderate vegetation, variable exposure to traffic noise, and intermediate levels of built-up surface. On the other hand, maximum vulnerability scores were highly concentrated in neighborhoods like Păcurari, Canta, Dacia, Bularga, and Tudor Vladimirescu. In these areas, NDVI values were among the lowest, while land surface temperature and noise exposure reached high values. This confirms the role of surface structure, spacing between buildings, and construction materials as key drivers in amplifying local vulnerability (Marando et al., 2022).

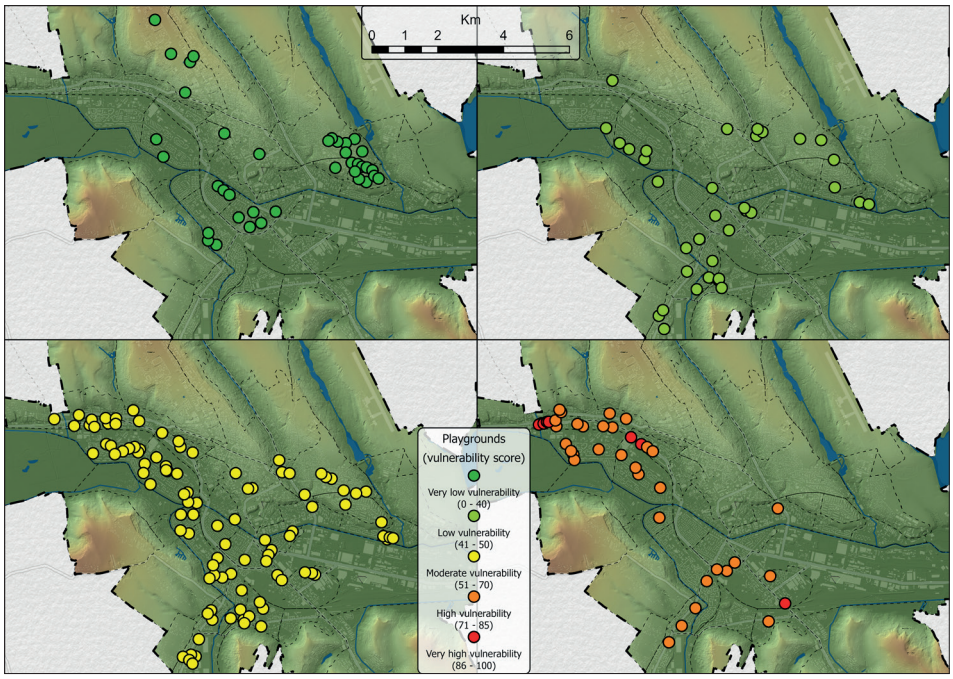



*Fig. 5: Spatial patterns of environmental vulnerability among urban playgrounds in Iaşi Municipality*
*Source: Authors' elaboration using spatial datasets from OSM and ANCPI*

Finally, the analysis reinforces that vulnerability is spatially uneven and structurally determined. Environmental stressors disproportionately affect playgrounds located in densely built zones, many of which are remnants of earlier urban planning models. These findings reflect broader concerns over ecological inequality, where children's exposure to urban stressors is shaped by spatial and socio-economic factors (Anbazu & Antwi, 2023).

## 6. Discussions and conclusions

Environmental quality of children's playgrounds remains an underexamined dimension of urban sustainability research, particularly within small and medium-sized cities of Eastern Europe. While scholarly attention has predominantly concentrated on large metropolitan areas, about three-quarters of Europe's urban population actually resides in small and medium-sized municipalities (European Environmental Agency [EEA], n.d.). These cities face distinctive socio-environmental challenges shaped by constrained municipal resources, inherited planning structures and post-socialist urban transformations, with vulnerabilities emerging at the intersection of socialist-era morphologies, market-driven developments and weakened institutional capacity for integrated environmental planning (Badiu et al., 2019; Sandu, 2024).

### *6.1 Socio-spatial inequalities and the legacy of urban planning trajectories*

Our findings show that playgrounds and green play areas are unevenly distributed across Iaşi, underlining socio-spatial inequalities documented in other post-socialist cities. Older, lower-income housing estates – many built under socialist urban models – tend to lack high-quality public play spaces, while newer suburban developments emphasize private gardens and gated amenities with limited communal facilities (Csomós et al., 2020; Kronenberg et al., 2020). This 'uneven greening' pattern corresponds with broader European trends of environmental injustice identified by the EEA (n.d.) and suggests that child-centered amenities follow the same exclusionary trajectories as green infrastructure more broadly. By focusing on playground distribution, this study contributes to urban green equity research by demonstrating that the formal spatial distribution of playgrounds across the city does not guarantee equivalent environmental quality – and that children in dense, post-socialist neighborhoods face systematically worse outdoor play conditions than those in peripheral or greener areas, raising critical concerns about the substantive equity of urban public play infrastructure.

### *6.2 Microclimatic vulnerability*

In line with our hypothesis, playground vulnerability is associated with surrounding temperatures (LST) and vegetation cover (NDVI), which reflect urban morphology shaped by past and present planning policies (Capello & Cerisola, 2023). In Iaşi, lower vulnerability generally occurs near major green infrastructure (parks, the Botanical Garden, and well-maintained green cover), where vegetation buffers improve microclimatic conditions and reduce UHI effects. Notably, some high-density neighborhoods on the upper terraces of the Bahlui river – developed during the Soviet era – also exhibit lower vulnerability despite urban compactness, linked to comprehensive planning that integrated public amenities and inter-block vegetation corridors, enabling micro-scale environmental resilience. Still, the most vulnerable playgrounds cluster in post-1960s systematization districts and near abandoned industrial and neglected urban spaces, where inadequate vegetation management and limited green space per capita coincide with intense UHI effects and compromised environmental quality (Xiong et al., 2019).

The patterns are consistent with the contrast between socialist and post-socialist urban planning trajectories in Eastern Europe. Socialist-era planning was characterized by centralized systematization policies that reshaped urban form (Sapunova et al., 2025); Romania's systematization programme (Law 58/1974) produced standardized residential complexes with high-rise prefabricated housing. Even though vegetation buffers were incorporated, heavy concrete construction contributed to elevated LST and UHI effects due to heat-absorbing materials and limited thermal protection, while green spaces also served ideological functions related to social interaction and perceived health benefits (Engel, 2022). After 1989, the transition to market-driven neoliberal policies weakened public planning capacity (Sandu, 2024), and

privatization combined with unregulated development intensified sprawl and infill, progressively reducing green space (Badiu et al., 2019). In Iaşi, periurbanization increased environmental vulnerability: SUHI intensity reached 1–4 °C and summer LST peaked at 35 °C, while vegetation loss accelerated through densification on former green plots (Cheval et al., 2022; Sfică & Ţopa, 2023). These processes are linked to suburban expansion, fragmented growth, and infrastructure deficits documented for Iaşi and its periurban areas (Chiriţă et al., 2020; Dinter & Roşu, 2021), alongside increased noise due to automobile dependency in peripheral developments. Environmental vulnerability across playgrounds strongly correlates with microclimatic conditions and vegetation cover, captured through UHI and NDVI, and hyperlocal studies emphasize that thermal exposure in playgrounds is sensitive to surface materials, shading, and immediate urban context (Tarpani et al., 2023). Playgrounds adjacent to major green infrastructure and surrounded by higher NDVI values exhibit lower thermal vulnerability due to shading and evapotranspiration (Lehnert et al., 2024; Walters & Pfautsch, 2025). Concomitantly, high-density built environments with limited vegetation intensify heat exposure, a pattern observed in post-industrial districts across East-European cities (Xiong et al., 2019). Some compact neighborhoods in Iaşi (e.g. Tătăraşi) retain relatively low vulnerability due to inter-block vegetation and connected micro-green corridors, reflecting integrated socialist-era design (Badiu et al., 2019) and supporting the argument that morphological diversity shapes environmental resilience at neighborhood scale (Capello & Cerisola, 2023).

### *6.3 Playgrounds as critical infrastructure: Policy implications and future directions*

The clustering of the most vulnerable playgrounds in systematized districts and near degraded industrial areas underscores the cumulative nature of urban environmental injustice. Disadvantaged areas experience higher exposure to heat and noise (WHO, 2018), elevated particulate matter concentrations in playground environments (Özdemir & Kuleli, 2012) limited tree canopy coverage (Locke et al., 2023), and poor green space maintenance, restricting restorative and social functions and exacerbating inequalities in wellbeing and outdoor activity (Loebach & Cox, 2022; Vanos et al., 2017). Addressing these disparities requires targeted interventions, including vegetation management and climate-adaptive playground design; evidence indicates that nature-based play environments enhance physical activity, social interaction, and wellbeing, particularly in disadvantaged contexts (Raney et al., 2023; Sabri & Abbaspourasadolah, 2014; UNICEF, 2019). The findings have implications for both research and policy in post-socialist cities confronting climate change and environmental degradation. Future work should examine temporal dynamics of playground vulnerability, evaluate the effectiveness of nature-based solutions for mitigating thermal and air quality exposures, and link environmental conditions with children's play behavior across socio-economic contexts. From a policy perspective, municipal planning should integrate climate-responsive design, vegetation management, and spatial equity into playground standards, recognizing playgrounds as green infrastructure rather than supplementary amenities.

This study advances understanding of urban environmental equity by linking playground configuration and environmental performance to planning legacies and contemporary sustainability challenges in small and medium-sized post-socialist cities. By integrating NDVI, UHI, and urban morphological analysis, it provides a transferable framework for assessing micro-scale environmental vulnerability and shows that playground quality reflects deeper socio-spatial inequalities. The most vulnerable playgrounds are concentrated in systematized districts, near high-traffic corridors and industrial zones, and in areas shaped by post-socialist densification without adequate green infrastructure compensation. Addressing these inequalities requires recognizing playgrounds as critical environmental infrastructure capable of delivering social and ecological benefits when embedded in multifunctional green networks (Miguez et al., 2025).

This study's main strength lies in its integrated assessment of multiple environmental stressors within a single spatial framework, enabling cumulative vulnerability to be evaluated at the playground scale. Long-term remote sensing data, high-resolution spatial inputs, and data-driven weighting improve robustness and reproducibility, and the fine spatial focus captures patterns not visible in neighborhood-level assessments. Key limitations include the reliance on spatially interpolated AQI data rather than continuous, in-situ playground-level monitoring, temporal inconsistencies among datasets, and the absence of behavioral and socio-demographic data linking vulnerability to actual use and social exposure. Despite these limitations, the framework remains transferable and policy-relevant for identifying priority intervention areas and guiding future longitudinal research.

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