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Multi-criteria assessment model on environmental ergonomics for decision-making in schoolyards based on remote-sensing and GIS resources

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A R T I C L E I N F O

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A B S T R A C T

The consequences of global warming have led to an acceleration of action strategies towards efficient and passive renovation work in the building stock. Most existing schoolyards are becoming obsolete with respect to current bioclimatic design patterns, for which a lack of methodological studies and diagnosis mechanisms in outdoor spaces has been identified. This research aims to design a multi-criteria assessment model on environmental ergonomics for the identification of feasible and passive measures that improve comfort conditions in schoolyards. The innovation of this system lies in its basis on weighting data that combines 12 qualitative, quantitative, and graphical parameters by using remote-sensing algorithms and GIS resources, leading to major insights regarding remote information acquisition capabilities for the promotion of bioclimatic actions in schools. The model is applied and tested in 6 representative pilot schools to demonstrate its operation and replicability. An innovative graphic output of results provides a significant research outcome, which contributes towards the visualisation of the diagnosis on environmental ergonomics and identifies potentials and weaknesses for decision-making. The conclusions focus on methodological insights and implications from an integral diagnosis for schoolyards, thereby serving as a decision-support system to identify optimal interventions that would ensure a more appropriate environmental performance.

1. Introduction

The viable and eco-efficient management of the built environment has gained importance within the main challenges of the urban agenda for sustainable development (United Nations, 2021). Research motivations in the 21st century strongly demand extra effort in generating new research studies that establish new protocols for inspection, diagnosis mechanisms, and decision-making models towards an integrated urban regeneration, which would ascertain the most feasible and most optimised renovation actions to tackle the continuous deterioration and ageing of the building stock (Serrano-Jiménez et al., 2022; Stanganelli et al., 2020). Furthermore, the consequences of global warming have led to an acceleration of action strategies towards bioclimatic and passive renovation work in order to improve the environmental performance in both indoor and outdoor spaces of obsolete buildings that were designed decades ago and that currently lie outside the established comfort parameters (European Commission, 2017; Franco et al., 2019).

Regarding the building stock and the built environment, schools represent approximately 20% of all public buildings in Europe (European Commission, 2020), and constitute a significant urban and architectural typology in each municipality. As for traditional building typology, many schools were built more than 50 years ago, and these schools are notoriously suffering the consequences of global warming, especially in the Mediterranean region, since they are social and educational institutions used on a daily basis and must offer the best comfort conditions to the educational community (Mokhtarmanesh & Ghomeishi, 2019; Simanic et al., 2019). Furthermore, children and adolescents spend approximately 30% of their day either outside in schoolyards or inside the classrooms, with high concentrations of occupancy and increasingly hot temperatures in warm regions, without any guarantee of established comfort conditions (Díaz-López et al., 2021; Kelly & Fussell, 2019).

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Table 1
Contributions, findings, and/or gaps in particular research subtopics related to this study.

Subtopic	Research study	Contributions, innovation, and/or limitations
Environmental assessment at schools	Droutsa et al. (2021)	· Assesses the environmental performance in 350 representative schools in Greece. Schools are mostly not insulated and there is insufficient shade in schoolyards.
	Kenawy et al. (2021)	· Determines the thermal comfort requirements of people visiting outdoor spaces. Provides recommendations for improving thermal benchmarking assessment.
	Kükrer and Eskin (2021))	· Evaluates and improves thermal comfort in a multi-purpose school building. No approach to thermal comfort is considered for outdoor spaces of the schoolyard.
	Mohamed et al. (2021)	· Assesses the impact of passive strategies on improving outdoor factors in schools. Enhances the design of outdoor areas in schools in hot climates.
	Equere et al. (2020)	· Elevation morphology as a factor to improve prediction of urban heat islands. Remote-sensing satellite images and a GIS-based approach in 20 built up areas.
	Shooshtarian and Ridley (2016)	· Studies the role of non-thermal factors on the users' perceptions by using a survey. Provides specific thermal comfort requirements in educational enclosures.
Outdoor thermal comfort / Heat mitigation strategies	Zhang et al. (2022)	· Identifies students' perception of schoolyards and their impact on performance. Enhances how green schoolyards give benefits and positive feelings to students.
	Giezen and Pellerey (2021)	· States greening of schoolyards as optimal strategy to increase urban climate resilience. Upscales framework to analyse two greening initiatives in the Netherlands.
	Bäcklin et al. (2021)	· Monitored outdoor heat stress at preschools during a hot summer in Sweden. States that preschools need more shade from trees to provide healthy schoolyards.
	Serrano-Jiménez et al. (2021)	· Assesses heat stress of 100 schoolyards using NDVI shadow percentage in Spain. Promotes new renovation guidelines to environmentally improve schoolyards.
	Shooshtarian (2019)	· Theoretical framework of current procedures to assess outdoor thermal comfort. Concludes that there are limitations in the applications of theories and models.
	Vanos et al. (2016)	· Multi-scalar analysis of surface temperatures in schoolyards and children's health. States children are more vulnerable to heat stress effects in schoolyards than adults.
	Fu et al. (2022)	

Table 1 (*continued*)

Subtopic	Research study	Contributions, innovation, and/or limitations
Remote-sensing / GIS models		· Underlines the usefulness of remote-sensing in earth analysis and shadow detection. Uses schools as pilot cases to detect multi-scale features from remote-sensing.
	Halder et al. (2021)	· Uses thermal remote-sensing to assess urban heat islands in India. Reveals potential of remote-sensing to identify critical areas on surface temperature.
	Browning and Locke (2020)	· Detects the variety of ways that greenspace is measured by using remote-sensing. Reveals that greenspace is considered a low-cost way to improve state schools.
	Zhu et al. (2019)	. Highlights remote-sensing contributions in outdoor spaces from multiple studies. Claims the need for scientists to work together on urban data and remote-sensing.
	Andersen et al. (2019)	·Assesses physical activity in renewed schoolyards with GIS, GPS, and accelerometers. ·States that shading strategies are the most promising heat mitigation techniques.
	Coutts et al. (2016)	·Introduces the use of thermal imagery to identify hotspots of urban heat. ·Suggests using remote-sensing to improve thermal comfort in urban spaces.

Regarding schoolyards, most existing schools are becoming obsolete with respect to current sustainable and bioclimatic design patterns, especially in warm regions (Díaz-López, Serrano-Jiménez, Verichev et al., 2022; Gil-Baez et al., 2017). The reasons are multiple and diverse depending on the geographical, socio-economic, and climatic context, and include financial limitations, a lack of knowledge regarding the environmental considerations to be taken into account to guarantee comfort in the schoolyards both during recreation periods and during student sports periods (Bernardo et al., 2017; Poza-Vilches et al., 2019).

Environmental ergonomics has emerged as a new concept that focuses on the physical and perceived conditions of the human environment that influence their performance in various activities, such as thermal, noise, lighting, and air-quality levels (Parsons, 2000). The schoolyards are considered micro-systems that are influenced by numerous physical characteristics, such as micro-climate, urban design, and thermal properties of building materials (Lindberg et al., 2016). In addition, environmental ergonomics in schoolyards is directly linked to guaranteeing better thermal comfort, which refers to the perceived feeling on the human body as the result of the effect of heat and cold sources in the environment (Brager & De Dear, 1998). As potential resources to be used in environmental ergonomics, the latest advances in satellite images provide enormous possibilities for the capture of environmental data through remote-sensing, as well as other related parameters through the use of algorithms (Song et al., 2020; Vali et al., 2020). These resources are increasing their usefulness in research, as are the hierarchy and geographic organisation offered by GIS (Österbring et al., 2016); together these open a new paradigm regarding the treatment and organisation of multiple data, which in turn translates into new research opportunities.

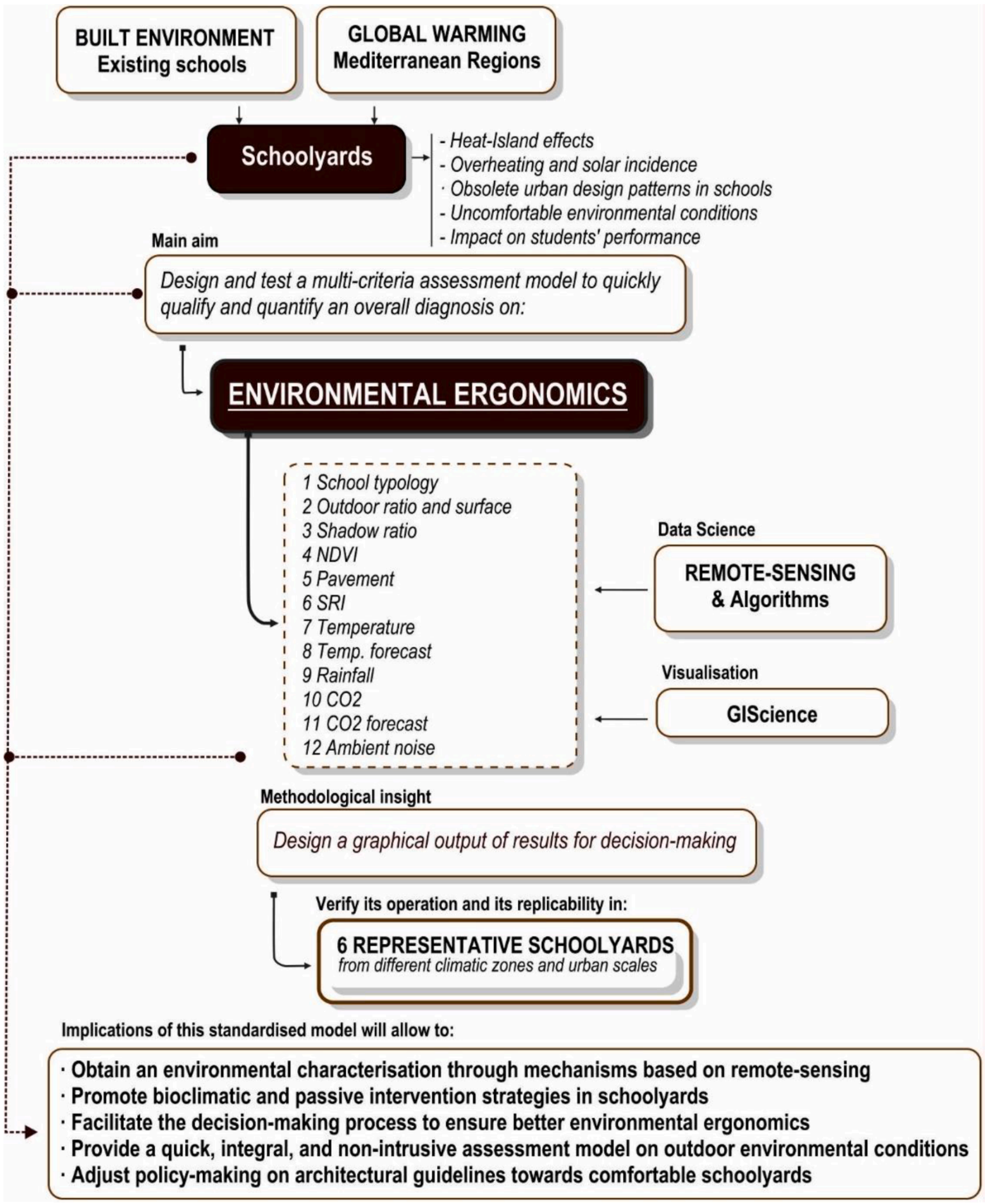

Fig. 1. General outline of the environmental ergonomics assessment procedure for schoolyards. Source: Authors.

1.1. Literature review

Table 1 presents the majority of the influential research studies subsequent to carrying out a literature review from different subtopics: Environmental assessment at schools; Schoolyards – heat mitigation strategies; and Remote-sensing/GIS models. For each study, its main contribution, innovation, and/or limitations are highlighted, and these have helped to determine key concepts in the design of the assessment model for schoolyards and the methodological approach of the manuscript.

Regarding the reference studies from the first subtopic, these all demonstrate both the research trend and the importance of identifying determining parameters and patterns in the thermal effects of outdoor conditions (Song et al., 2020). Studies developed by Kenawy et al. (2021) and Equere et al. (2020) have incorporated new data collection mechanisms through the use of remote-sensing, the application of GIS resources, and the incorporation of users' participation in the perception of outdoor environmental parameters. In this respect, the studies developed in recent years for the application of these resources in favour of identifying suitable thermal adaptive strategies in outdoor spaces remain relevant, such as the research developed by Shoosshtarian et al. (2018), which defines a model with 3 clusters based on environmental and technological modifications, behavioural adjustments, and psychological adaptation.

Furthermore, regarding the particular focus on schoolyards and heat mitigation strategies, this topic has recently expanded and a trend is beginning to be perceived as emerging, such as in Zhang et al. (2021 & 2022) wherein participatory studies with students were conducted to reveal the significant influence green schoolyards have on learning, fun, and mental health, thereby demonstrating the positive feelings that schoolyards induce in students and promoting institutional support nature-based activities therein. In fact, Vanos et al. (2016) demonstrate the significant effect of high temperature values on children's health, and demand new mechanisms for the diagnosis of the built environment that would promote bioclimatic principles and effective green spaces in schoolyards. Lastly, regarding the use of remote-sensing and GIS resources in the selected references, Nice et al. (2018) had previously introduced the development of VTUF-3D remote-sensing technology to

Table 2
Parameters, variables, and obtaining procedures for the environmental ergonomics assessment.

PARAMETER	Variables and obtaining procedure	Tools, weighting, and algorithms
A| School Typology	- Architectural analysis of the educational building location on the plot, along with the composition of the volume. · Four main typologies are classified: 1. Linear; 2. Compact with inner courtyard; 3. H-type with open courtyards; & 4. Mixed typology.	*Qualitative: Visual inspection and/or study of the planimetry and orthophoto of the plot*
B| Outdoor ratio & surface *(% - m^2)*	- The surface of the schoolyard is weighted with respect to the total of the plot in absolute value and percentage ratio. · Suggested optimal range: 70–80% of the school plot.	*Land registry & remote-sensing through kml or .dxf file* $Scyard_{ratio.} = \frac{\sum S_{scyard}}{Splot_{max}} * 100$
C| Shadow ratio *(%)*	- Quantification of the area of trees in satellite images of Sentinel 2-L2A with remote-sensing (Landsat) with respect to the total area of the schoolyard. · Suggested optimal range: 20–30% of the schoolyard	*Remote-sensing – Landsat crown tree detection* $Shadow_{ratio} = \frac{\sum S_{trees}}{S_{scyard}} * 100$
D| NDVI *(0–1 value)*	- Average calculation based on multi-spectral reflectance values of the near infrared and the red bands, combining Sentinel 2-L2A and 2-L1C satellites (Crop Monitoring). μ_nir and μ_red are multi-spectral reflectance values of the near infrared band and the red band, respectively. · Suggested optimal NDVI range for schoolyards: 0.4–0.7	*Remote-sensing – Crop Monitoring Calculation* $NDVI = \frac{\mu_{nir} - \mu_{red}}{\mu_{nir} + \mu_{red}}$
E| Pavement *(%)*	- Type of paving measurement and proportion in schoolyard by using Landsat, according to 3 material families: 1) Hard (H) (concrete, cement slab); 2) Earthen (E) (sand, soil); and 3) Green (G) (garden, grass)	*Remote-sensing – Landsat ground type and measuring.* $Pavement_{ratio} = \frac{\sum S_{H\|E\|G}}{S_{scyard}} * 100$
F| SRI *(0–1 value)*	- An average SRI value has been determined for the entire schoolyard by interpolating between different materials and using remote-sensing calculations through black and white reference values 0–1. · Suggested optimal SRI range for schoolyards: 0.5–0.7.	*Remote-sensing – Crop Monitoring Interpolating calculation* $SRI = \frac{T_b - T_s}{T_b - T_w}$
G| Temperature *(℃)*	- Temperature based on fAPAR (RF - fraction of absorbed photosynthetically active radiation) (ambient temperature collected by remote-sensing platforms through satellite images or also by NDVI algorithms). The average annual, maximum, and minimum temperatures are obtained.	*Remote-sensing – Crop Monitoring Average measured temperature or by using the algorithm:* $T^{o}(^{\circ}C) = (-11.5 \cdot NDVI + 302) - 273.15$
H| Temperature forecast *(Δ °C - year)*	- Based on an algorithm that uses fAPAR (RF) and consequently calculates the average incident radiation, since the higher the radiation, the higher the incidence according to the year. That fraction of the radiation depends linearly on the expected temperature and also the NDVI value, because vegetation does not have a positive effect on protecting the natural ecosystem.	*Interpolation according to year and average temperature of a plot* $RF = 0.564 - 0.011 * Tm(^{\circ}C)$ $r = 0.83; R^2 = 0.7\ p <= 0.001$
I| Rainfall *(mm/year)*	- Sum of the rainfall collected during the last year in the plot, which shows the evolution by months and the rainfall in the area.	*Remote-sensing – Landsat* $\sum Rainfall - year$
J| CO_2 *(Outdoor ppm)*	- Quantification of the average outdoor concentration in ppm of CO_2 for the plot by using an algorithm based on the fractal D dimension according to the images obtained in remote-sensing using the Sentinel2-L1C.	*Remote-sensing – Crop Monitoring Alg.: 149,393,642*D-143,806,27* $(r = 0.91; R^2 = 0.873; p \leq 0.001)$ *D fractal value for the plot by using fractalise tool*
K| CO_2 forecast *(Δ outdoor ppm)*	- Prediction of the increase (ppm) in the average outdoor concentration of CO_2 for the plot by using an algorithm based on the current value, the years of prediction. and the month of measurement (Cm).	*Remote-sensing – Crop Monitoring Alg.: 201.99 – 9.95·10 −2·year) ·Cm* $(r = 0.91; R^2 = 0.873; p \leq 0.001)$
L| Ambient noise *(dB)*	- Average ambient noise (dB) during the period of school use, based on real measurements and/or its corresponding interpolation algorithm depending on annual average NDVI in the school plot.	*Measuring & interpolation algorithms* $Alg.: 47.1 + 27.015 \cdot NDVI_{avge}$ $(r = 0.83; R^2 = 0.77; p \leq 0.05)$

assess the urban micro-climate and support the assessment of urban vegetation influences on human thermal comfort. Subsequently, the increasing trend and its usefulness in providing essential data and methodological support for the identification of environmental problems in outdoor spaces was addressed by Andersen et al. (2019). Selected research studies have applied both tools in the assessment variables that influence the environmental ergonomics of schools (Bäcklin et al., 2021; Zhu et al., 2019).

1.2. Aims and objectives

Based on the current literature framework in which it is required to introduce new methodological perspectives on the management of the built environment, this research arises from considering that environmental ergonomics need be introduced into schoolyards in terms the synergy between hygrothermal comfort and outdoor environmental quality experienced by the educational community (Mijorski et al., 2019). However, although most studies focus their research on the indoor environmental quality of schools, as well as on improving energy efficiency, few studies focus on diagnosing and assessing the environmental quality of schoolyards in schools (Becerra et al., 2020; Wang, 2016). By considering the research trends highlighted in the previous subsection, a research gap can be identified in those topics that propose mechanisms for diagnosing schoolyards through the multiple parameters of influence that enable a global and replicable vision for the different types and locations of existing schools. This study identifies an absence of methodological studies and standardisation procedures that contribute towards the diagnosis and evaluation of the environmental conditions of the schoolyards, in such a way that it can serve to remotely graph the diagnosis of the conditions of each school based on weighted parameters in environmental ergonomics.

This research aims to design a multi-criteria assessment model to evaluate the environmental ergonomics in schoolyards of existing schools by introducing the use of remote-sensing, interrelation

Table 3
Definition of 6 selected case studies in Primary and High schools.

Case Study Abbrev. | Name	Location, description, and context of case studies
CS-M1 | Isaac Albeniz High School	Located in Malaga, this represents a high school belonging to a temperate-maritime climatic zone and on an urban scale, inside the city itself. The school was built in 1978 and has an elongated plot where 2 main buildings are distributed. LCZ:6.
CS-M2 | Isaac Peral Primary School	Located in the municipality of Alhaurín de la Torre, in the province of Malaga, this represents a school in a temperate-maritime climatic zone and the metropolitan area, corresponding to the municipalities surrounding the city. The primary school was built in 1981 and is distributed on a square plot with 1 main building and 2 annex buildings. LCZ:7.
CS-M3 | La Axarquía Primary School	Located in the municipality of Velez-Malaga, in the province of Malaga, this represents a school in a temperate-maritime climatic zone and in a rural area, isolated from the city. The primary school was built in 1984 and has an irregular plot where 1 main building is located. LCZ:8
CS-S1 | Joaquín Turina Primary School	Located in Seville, this represents a primary school belonging to a warm interior climatic zone and on an urban scale, inside the city. The school was built in 1980 and has an elongated plot where 2 main buildings are distributed. LCZ:4.
CS-S2 | Itaca High School	Located in the municipality of Tomares, in the province of Seville, this represents a school in a warm interior climatic zone and in a metropolitan area, in a municipality on outskirts of the city. The high school was recently built in 2008 and has a rectangular plot where 1 elongated main building and two small annex buildings are located. LCZ:7.
CS-S3 | Andalucía Primary School	Located in the municipality of Guillena, in the province of Seville, this represents a school in a warm interior climatic zone and in a rural area, isolated from the city. The primary school was built in 1979 and has a rectangular plot where 1 main building and several annex buildings are located. LCZ:7.

algorithms between certain parameters and the geographic organisation of GIS models. The findings of this model are expected to be useful in obtaining an integrated diagnosis of the outdoor environmental conditions in schools of hot micro-climates, thereby allowing the main weaknesses to be visualised and the decision-making to be facilitated towards identifying feasible and efficient passive or bioclimatic strategies. The innovation of this system is based on an assessment protocol that combines qualitative, quantitative, and graphical parameters by applying an innovative approach from remote-sensing and GIS resources, which in turn leads to major insights into the optimisation of schoolyard design to combat the impact of global warming and promote eco-efficient actions. Lastly, as a subsequent objective, this paper aims to test and verify the operation of the designed multi-criteria assessment model of schoolyards for decision-making and, following the methodological steps, incorporates the selection of 6 pilot schools to enable the testing and comparison of the results.

This paper fulfils the aforementioned research gap by defining a remote mechanism for outdoor environmental data collection in schoolyards through remote-sensing, algorithms, and the use of GIS. The advantages of this procedure allow a rapid non-intrusive visualisation and a multi-disciplinary diagnosis of outdoor spaces from existing schools, thereby providing an original graphic output of results that will contribute towards supporting decision-making and the promotion of the most appropriate and viable passive and bioclimatic strategies for each geographical and architectural context (GBCe, 2020).

The following sections are structured to define the proposed environmental ergonomics assessment system, the scope of application, and the data collection procedure. Subsequently, the results obtained for each pilot school are displayed in tables and graphs, which enables the usefulness of the model to be discussed and conclusions to be drawn regarding the advantages for decision-making and the implications of the model regarding reducing the impact of global warming in schoolyards.

2. Methodology

Fig. 1 introduces a graphic methodological outline that represents both the starting background, the topics addressed, the aims, the parameters, and the tools developed within the environmental ergonomics concept, together with the main insights and implications of the study. This graphic provides an image of the research concept and a summary overview to demonstrate its innovation and usefulness; further details are laid out in the subsequent subsections.

2.1. The proposed environmental ergonomics assessment system

Following the main aim of the research on establishing a multi-criteria assessment model to remotely qualify and quantify an overall diagnosis on environmental ergonomics, this subsection delves into the definition of the parameters to be considered and explains the data collection mechanisms for each of the items, their measurement units, their weighted expression or interrelated algorithms, and certain optimal ranges within which they should lie.

As methodological principles, this research is structured into three fundamental phases that lead to the proper assessment of the outdoor environmental conditions of schoolyards:

1 **Data science**. Data collection, fundamentally remotely through the use of remote-sensing and interrelation algorithms, obtains the organisation and structure of each of the items and the weighting of their values;
2 **Visualisation**. Design and composition of the graphic output of results provide an optimal overview of the schoolyard diagnosis and the implementation through GIS in a Geographic Information System platform for each school;
3 **Analytical Hierarchy Process** (AHP) compares alternatives and ranks different quantitative and qualitative parameters that serve to facilitate decision-making of bioclimatic and passive actions to improve the environmental performance of the schoolyard, thereby adjusting policy-making on architectural guidelines towards schoolyards of a more comfortable nature.

The proposed assessment model on environmental ergonomics in schoolyards incorporates the 12 following parameters that characterise and quantify the most determining variables:

A) **School typology**: Qualitative characterisation of the building composition with respect to the plot, thereby enabling visualisation of the distribution of surfaces in the schoolyard with respect to the educational centre.
B) **Outdoor ratio** (%) **and surface** (m^2): Quantifies the whole area of the schoolyard and the ratio that it represents, as a percentage, compared to the building in the total plot. This data shows the level of representativeness that the schoolyard has in the school.
C) **Shadow ratio** (%): Represents the percentage of shaded surface, due to the presence of trees, with respect to the total area of the schoolyard through the use of remote-sensing and the data collected by Sentinel 2-L2A.
D) **NDVI** (0–1): Mean Normalised Difference Vegetation Index represents a weighted estimation of the quantity, quality, and development of vegetation based on the measurement of the intensity of the radiation of certain bands of the electromagnetic spectrum. This index provides information on the quality of vegetation and shade in their spaces, not only in an average numerical index, but also in an exported graphical heat map.

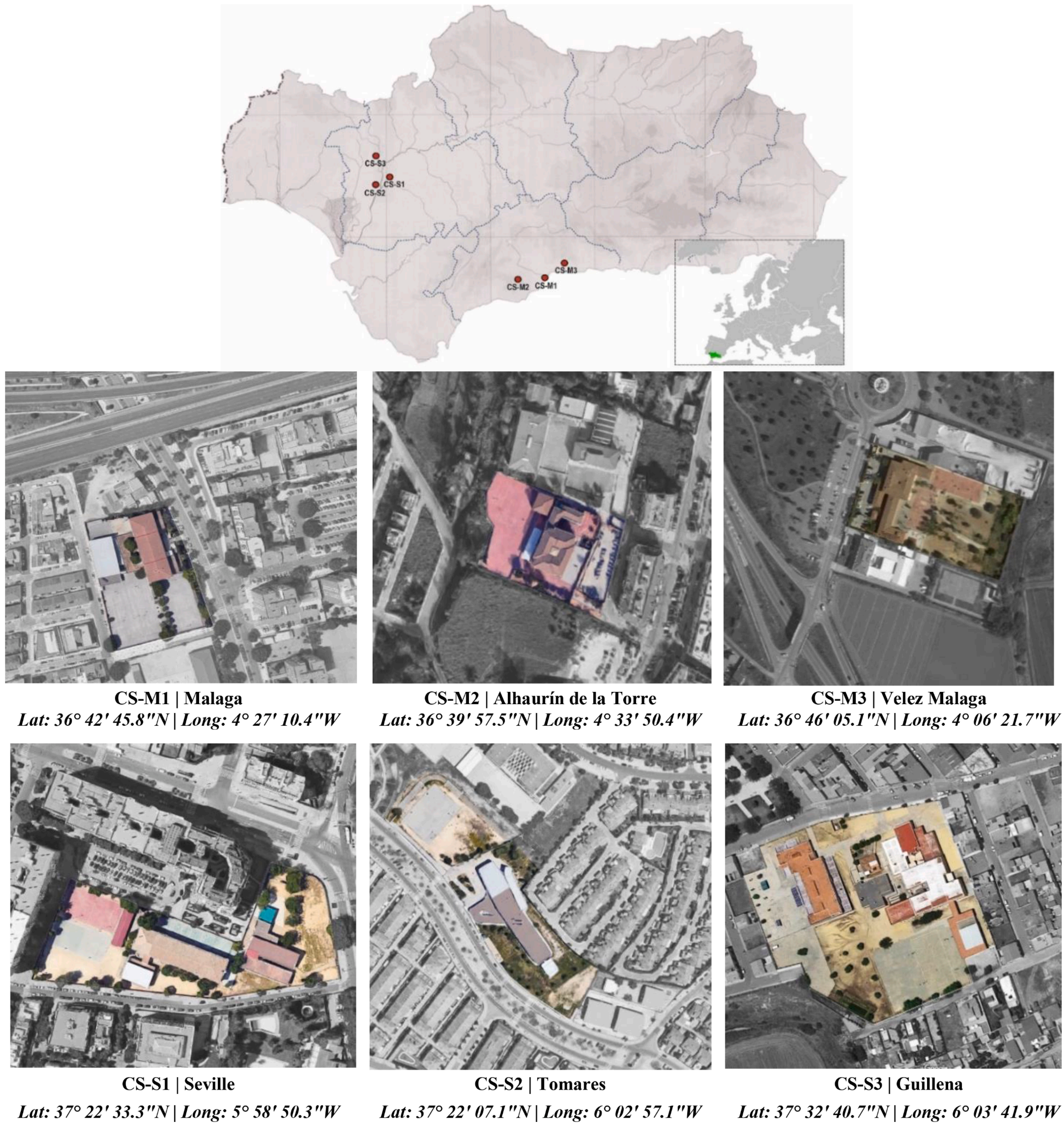

Fig. 2. Aerial view of the selected pilot schools in Andalusian regions. Source: Google Earth & Authors.

E) **Pavement** (%): Identification through remote-sensing of the proportion in the type of ground used in the schoolyard according to a fundamental classification into three types: Hard, understood as all stone paving or related to in-situ or prefabricated concrete; Earthen, as the whole family of arid or sandy soils; and Green, grouping gardens, lawns, and green areas.

F) **SRI** (0–1): Average value of the Solar Reflection Index obtained through reflection in satellite images for the schoolyard in its area as a whole. The SRI is a single indicator of the solar reflectance and emissivity of materials that represents the ability to reflect solar heat thereby mitigating the temperature increase of flat opaque material exposed to direct sunlight.

G) **Temperature** (°C): Average annual temperature obtained for the geographical coordinates of the plot, at a height of 2 metres using the sentinel 2-L2A and L1C thermal risers through remote-sensing. This mechanism for obtaining Temperature from remote sensing is proposed as an alternative to the traditional collection of meteorological data through experimental observation, for those cases in which its in situ measurement is not available for long periods of time during the year. Moreover, maximum and minimum values are obtained and the most predominant quartiles during the year are represented in a box and whisker diagram.

H) **Temperature forecast** (Δ °C): Prediction of the average annual temperature increase in a future interval of years, following the weighting established in remote-sensing algorithms (Ramírez-Juidías, 2022), directly related with fAPAR radiation values. This prediction enables the thermal evolution of the area to be viewed, based on the evolution in recent years and the geographical location, thereby offering the degree of warming that is expected in the region.

I) **Rainfall** (mm/year): Quantifies the mm of water collected during the last calendar year to indicate the rainfall in the area when characterising a schoolyard. This data is also collected using remote-sensing tools, which are often useful for irrigation, plantations, and soil moisture.

J) **CO_2** (outdoor ppm): Average level of ppm outdoors in the selected plot, obtained by using weighting algorithms included in remote-sensing tools through the reflective levels obtained in bands of the sentinel 2-L2A spectrum.

K) **CO_2 forecast** (outdoor ppm increase): Predicted increase in the average level of particular ppm of CO_2 in the outside environment for future years, following a prediction algorithm of the increase based on the evolution in recent years and the environmental conditions.

L) **Ambient noise** (dB): Environmental noise measured as an average in the plot, using weighting algorithms according to the annual average NDVI data obtained in the remote-sensing tools. This data is measured mid-morning and depends on the environmental conditions.

Further to the definition, and in a more systematic and scientific way, Table 2 provides the set of parameters and their measurement and weighting variables, and explains the resources and tools employed to obtain such parameters for data science. In certain items, a series of optimal values suggested for environmental ergonomics appear for schoolyards used by children outdoors. Nevertheless, all these parameters depend on the climatic conditions of the location, the morphology of the plot, and its architectural composition, amongst other factors, and therefore the proposed assessment tool must remain open and flexible to the various locations of the schools in order, to be able to adapt to multiple circumstances and replicate them.

The usefulness of gathering all this data lies in the possession of complete environmental information and a design diagnosis of the schoolyards, although this same procedure could well be applied to unbuilt plots, in the architectural analysis prior to a new construction. Nevertheless, this set of parameters has the capacity to gather the items related to hygrothermal and acoustic comfort, to architectural and formal parameters, along with outdoor environmental quality, with the final aim of promoting an assessment model to optimise schoolyard design under the context of global warming.

Further to these qualitative and quantitative values from the aforementioned items, the methodology incorporates graphic maps on NDVI and SRI. Regarding vegetation and shaded spaces, the wooded area and the corresponding ratio in the outdoor space of each school can be measured by using aerial images along with remote-sensing tools, mainly using the Crop Monitoring tool based on data provided by the Landsat and Sentinel 2-L2A satellites, especially the second one, whose spatial resolution is much more exhaustive with a 1 × 1 m wide mesh as resolution according to European Space Agency (ESA, 2022). Additionally, vegetation maps and mean values have been provided through the NDVI, after having introduced the perimeter of the plot and having obtained the average value and the detailed map (Guo et al., 2020). The SRI is a single indicator of the solar reflectance and emissivity of materials which represents the ability to reflect solar heat thereby mitigating the temperature increase of flat opaque material exposed to direct sunlight. Crop monitoring simulation of this SRI parameter is obtained by introducing the plot, the characterisation of the soil, and the reflected spectrum of the materials in the remote-sensing tool through the Sentinel-2 satellite (Marceau & VanGeem, 2015).

Moreover, another thermal isopleth graph is displayed and calculated in accordance with environmental equations for the plot of each school, relating the average temperature values during the season and days of the year, thereby offering thermal information on the area. The most representative and hottest average temperature values are normally recorded in May and June at 11:00 a.m., when schoolyards are in full use by students during their morning break. The environmental conditions and the geographical location influence the quantification of this isopleth map, which enables more information to be provided regarding environmental ergonomics.

Certain parameters originate largely from data from Sentinel-2-L2A and 2-L1C satellites, while other data is obtained by triangulation of real satellite data and the climatic stations closest to the determined point. In fact, for the calculation of algorithms such as the CO_2 level, it is necessary to obtain specific magnitudes such as the d dimension of an aerial image through the application of Fractalise. Furthermore, use is also made of the fraction of the mean incident radiation, whose fraction depends linearly on the temperature.

2.2. Scope of application. Case studies

This subsection establishes all schoolyards that suffer the consequences of imminent global warming as the scope of application of this model. These include both isolated plots and those located in the compact city that were mostly designed in the second half of the 20th century or in recent years. The 6 selected pilot schools include common school architecture patterns in southern Spain, which one of the warmest regions of Europe that belong to Mediterranean climate. Both primary and high schools are covered in order to ensure the representativeness and receptiveness of the case study context. In fact, certain pilot schools are located in a very hot area corresponding to the valley of the main river that crosses this region, where the average temperature values in May, June, July, August, and September frequently exceed 30 °C or even 35 °C before midday, and where the solar radiation is the highest in Spain, exceeding 18 MJ/m^2 per day (AEMET, 2020; CIEMAT, 2020).

Two variables are taken as criteria for the selection and testing of the designed model in the pilot schools, in an effort to demonstrate its replicability under different representativeness conditions:

- **Climatic zone**: 2 provinces, Malaga and Seville, belonging to two climatic zones: 1) Temperate-maritime; and 2) Warm-interior.
- **Urban scale**: 3 different location scales: a) Inside the city; b) Municipalities in the surroundings of the city; and c) Rural areas.

Furthermore, given that the NDVI and GIS parameters are going to be used in the study, it has been considered appropriate to incorporate the LCZ classification based on the World Urban Database model WUDAPT to complement the climatic and morphological information in the urban context where it is located (Ching et al., 2018; *World Urban Database*, 2022). The tabulated definition of the case studies is presented in Table 3 together with their graphical location and aerial views in Fig. 2.

The representativeness of the pilot schoolyards enables significant results and conclusions based on the operation of the model and on the diagnosis graphical report between typologies, by adjusting the bioclimatic and passive action strategies based on their results.

3. Results

In accordance with the established multi-criteria assessment system for schoolyards, Table 4 breaks down the measured and weighted quantitative and qualitative results obtained for each pilot school, and

Table 4
Parameters, variables, and obtaining procedure for the environmental ergonomics assessment.

PARAMETER / CASE STUDY	CS-M1 *Málaga*	CS-M2 *Alhaurín*	CS-M3 *Velez*	CS-S1 *Seville*	CS-S2 *Tomares*	CS-S3 *Guillena*
A| School typology	1| Linear	2| Compact with inner courtyard	2| Compact with inner courtyard	3| H-type with open courtyards	4| Mixed typology	4| Mixed typology
B| Outdoor ratio (%) & **surface** (m^2)	72.7 6085	79.6 7042	86.8 8880	79.4 9566	82.9 13,937	77.0 14,436
C| Shadow ratio (%)	4.1	5.4	3.4	6.1	4.8	1.5
D| NDVI *(Avg)*	0.17	0.21	0.22	0.22	0.16	0.14
E| Pavement (%) (H)ard|(E)arthen|(G)reen	H:100	H:100	H:40|E:40|G:20	H:20|E:70|G:10	H:20|E:50|G:30	H:30|E:70
F| SRI *(Avg)*	0.45	0.50	0.39	0.52	0.36	0.56
G| Temp. (°C)	19.5 Max:44.5|Min: 0.3	17.7 Max:42.4|Min: −0.9	19.5 Max:44.2|Min: 0	19.0 Max:44.2|Min: −2.0	18.7 Max:43.6|Min: −2.2	18.9 Max:45.0|Min: −2.3
H| Temp. Forecast (Avg Δ °C – 10 years)	0.8	0.5	0.6	0.9	1.0	1.0
I| Rainfall (mm/year)	318.0	327.1	461.9	447.7	454.2	340.9
J| CO_2 (Outdoor ppm)	393	447	465	463	506	420
K| CO_2 Forecast (Avg Δ ppm – 10 years)	16 (4.0%)	12 (2.7%)	13 (2.8%)	18 (3.9%)	13 (2.5%)	16 (3.8%)
L| Ambient noise (db)	56	49	46	49	51	45

organises the results into columns associated with the 12 parameters defined from multiple disciplines together with their corresponding units. These are given as absolute values, percentages, dimensionless parameters, or established ranges in keeping with the tools, the weighting procedure, and the corresponding algorithms defined in Table 2.

The purpose of this results table is to demonstrate the application of the model to 6 case studies and identify the main potentials or weaknesses in the design and environmental conditions of the schoolyards in order to facilitate the comparison and identification of particular values across the various cases. This table provides significant insights into the organisation of all the parameters and variables, by implementing this numerical and descriptive output of results, with information on an overall diagnosis of the outdoor environmental conditions of the schoolyard, obtained in a swift, integral, and remote way, which fully encompasses the concept of environmental ergonomics along with fulfilling the established research gap.

The presentation of the results was supported by a background of the system's qualitative and quantitative information that was mostly obtained remotely through remote-sensing. As detailed in Table 3,

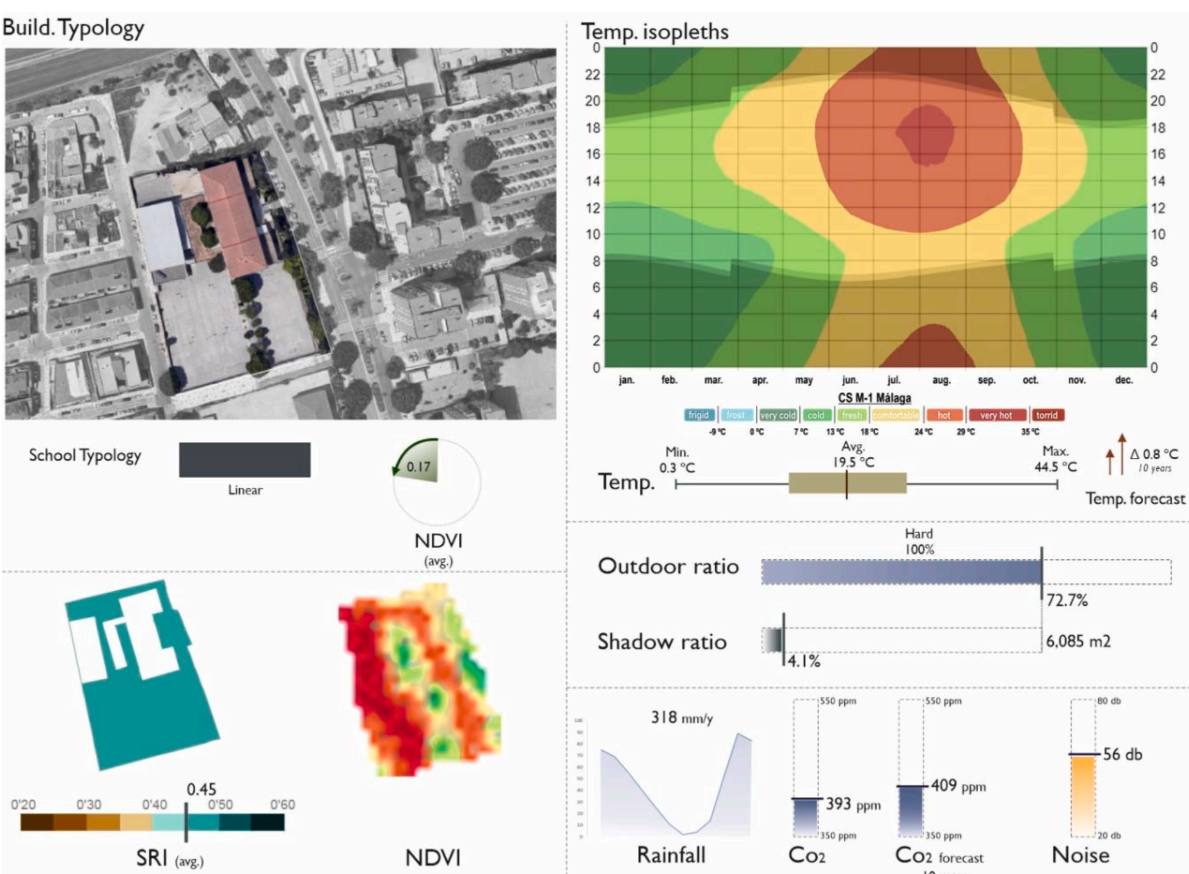

Fig. 3. Graphic output of results on environmental ergonomics parameters for CS-M1. Source: Authors.

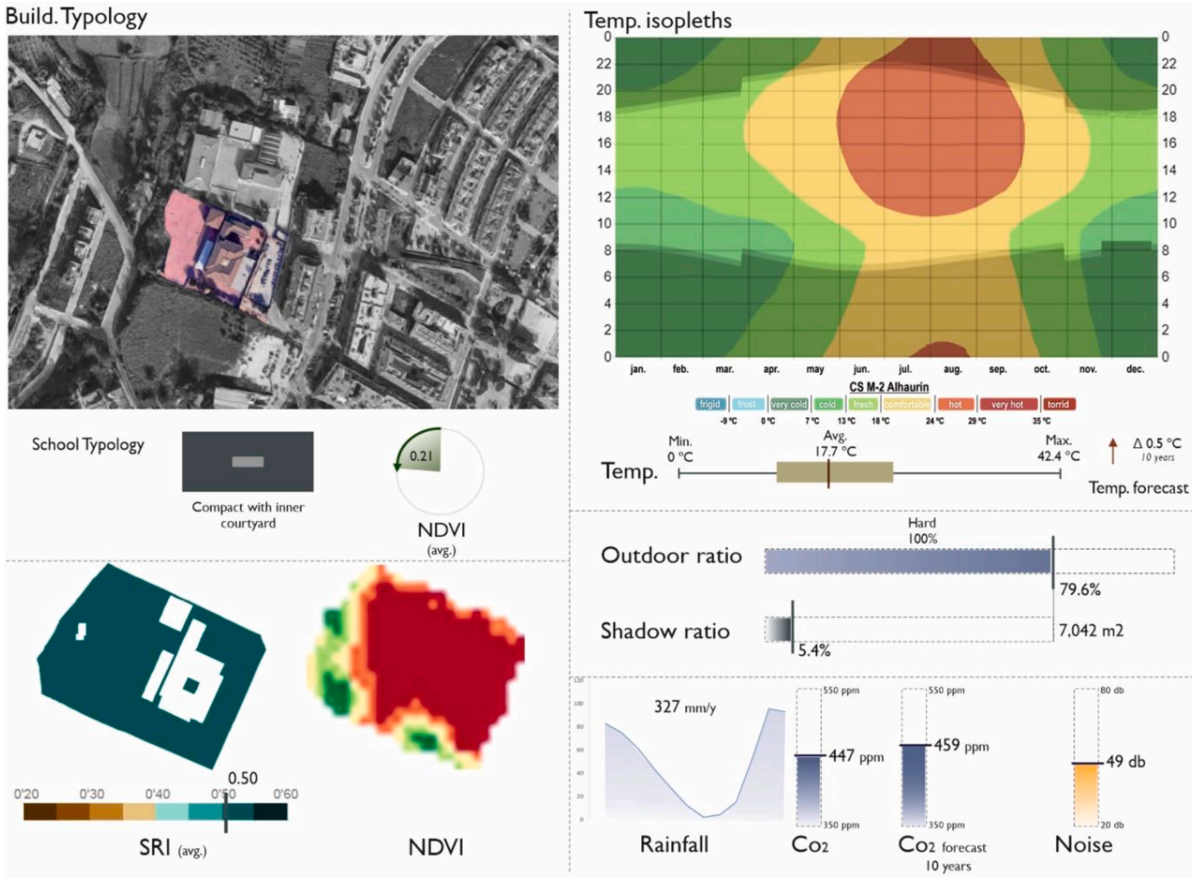

Fig. 4. Graphic output of results on environmental ergonomics parameters for CS-M2. Source: Authors.

information related to the design patterns of the schoolyard was gathered (school typology, outdoor ratio and surface, shadow ratio, and pavement) together with numerical parameters based on the consequences of its design and maintenance (NDVI, SRI, and ambient noise), and other outdoor environmental parameters linked to the conditions of the location, the climatic zone, and the location of the plot (e.g., average temperature and its forecast, rainfall, and outdoor CO_2 and its forecast). During the design process of the multi-criteria assessment system for schoolyards, the need to create a graphic composition for the output results was addressed, which would serve as an original contribution within the topic of study in schools, and would allow designers, promoters and the educational community to illustrate the schoolyard diagnosis.

Figs. 3-8 present the graphic display of the results of the selected pilot schools. Each diagram, based on providing information on environmental ergonomics, comprises: an aerial image of the building typology; a colour diagram on the temperature isopleths for the hours and months of the year; a box-and-whisker graph of the average annual temperature, its maximum and minimum values, and the temperature increase forecast calculated for the next10 years; values of the NDVI parameter and its corresponding heat map in the plot, together with information on the outdoor and the shadow ratio on the absolute values; a schema of the mean value of the SRI and the classification of the materials that make up the pavement; and finally, environmental information on annual rainfall and its monthly distribution, the average external value of CO_2 and its growth forecast, and a value of environmental noise at midday.

4. Discussion

The results obtained in the 6 schoolyards belonging to the region of Andalusia show the existence of multiple coincidences and variations between their results that deserve discussion. Regarding the size of the plot and the proportion of schoolyard, the surfaces and percentages vary widely (ranging from 6085 $m^2$and 72.7% in CS-M1 to 14,436 m^2 in CS-S3 and 86.8% outdoor ratio in CS-S1), as do the types of building, which, for the pilot cases, include linear, compact, H-type, and mixed buildings, as representative selection of schoolyards in the Mediterranean Region, following the design patterns concluded by Díaz-López et al. (2022).

Regarding the parameters linked to the design and management of each schoolyard, the assessment system incorporates quality and quantity vegetation indices by introducing the shadow ratio, as a percentage, which enables the proportion of the schoolyard protected by trees to be observed. These are almost null values (1.5% in CS-S3) and close intermediate values (6.1% in CS-S1), although they all remain far from the range established as ideal in manuals and tree guides: between 15 and 20% of a schoolyard. Additionally, the quality of the vegetation in its tree crown is determined by the average NDVI, whereby values between 0.14 (CS-S3) and 0.22 (CS-M3 and CS-S1) are attained, equally far from values of suitable leafiness. However, since these are average values in the plot, it can be observed in the NDVI maps that there are specific areas in certain centres where green is highlighted, as is the case of CS-M1, CS-M2, and CS-S1. This enables the identification of which areas of the schoolyard are stocked with trees and which areas present tree-planting potential, following the research demand stated by Bäcklin et al. (2021)and thereby introducing the benefits established by Yang et al. (2019). Regarding the type of paved area, the graphic results offer a range of average values and colours relative to the Solar Reflection Index factor, whereby darker and more absorbent values are obtained, at 0.36 (CS-S2), while 0.56 (CS-S3) represents greater reflective quality, and the graph showing the proportion of paved area in accordance with the established classifications of hard, earthen, and green.

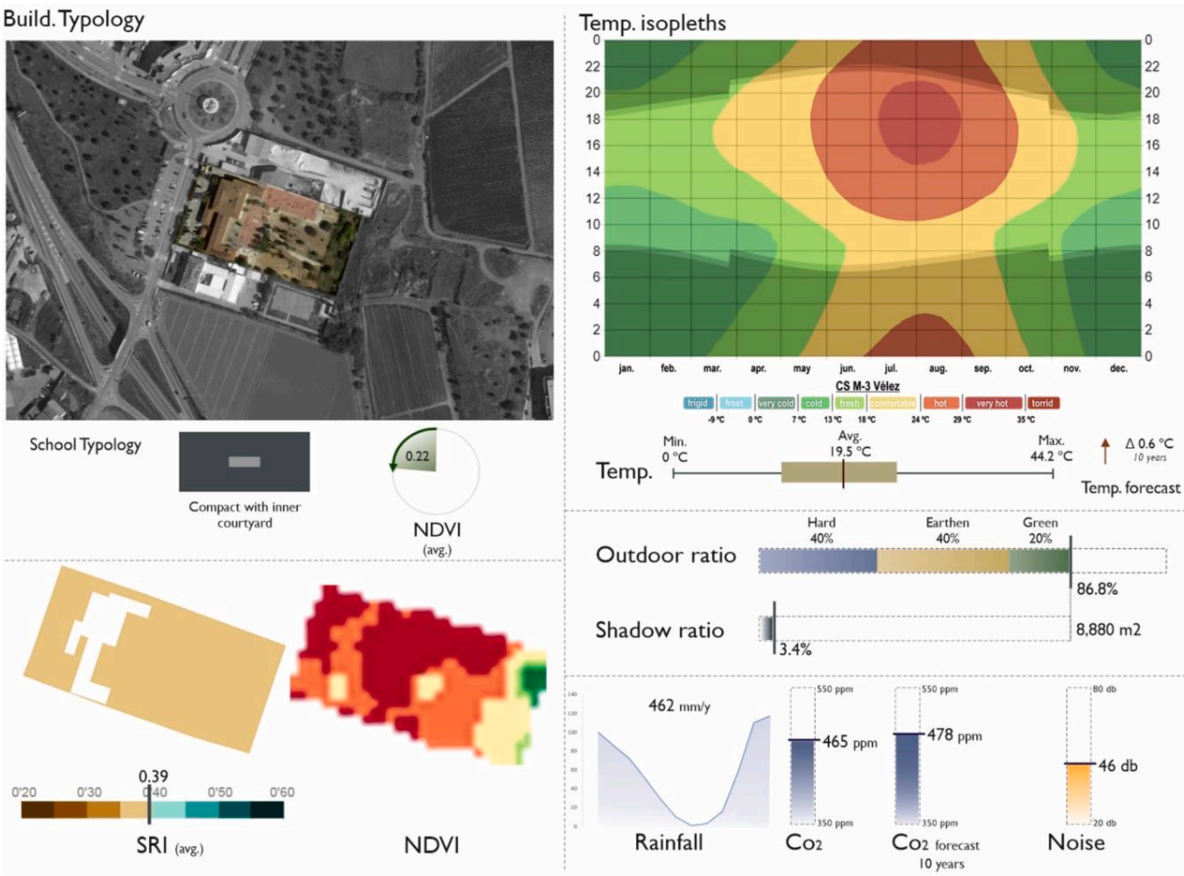

Fig. 5. Graphic output of results on environmental ergonomics parameters for CS-M3. Source: Authors.

With respect to the outdoor environmental conditions, variations between climatic zones are observed depending on the location and on the perspective of an increase in the average temperature according to the urban scale. In the province of Seville, there is a higher temperature and an increase of approximately one degree centigrade in the coming years, which is higher than in the coastal micro-climate. Similarly, the location of the schoolyards in the urban environment exerts a major influence on the presence of CO_2, measured in ppm, in the outdoor environment, and ranges from 393 ppm obtained for CS-M1 to 506 ppm obtained for CS-S2, largely due to its proximity to the city of Seville and its higher altitude, which means that the concentration of particles and the air quality is lower, in accordance with the conclusions stated by Droutsa et al. (2021). Finally, the environmental noise parameter also determines the external environmental quality in a given area, depending on its location with respect to major traffic routes and industrial areas. In this respect, there is a variation between cases ranging from 46 dB obtained for CS-M3 up to 56 dB obtained in CS-M1 due to the proximity of the schoolyard to a highway.

As key outcomes of the proposed system, it is observed that the various numerical and graphic results change under differing circumstances. The graphic results show the variety of parameters that outline the diagnosis of an outdoor space, based on which lines of action can be defined, and allow the public administration to clearly observe and compare the level of urgency as an aid towards deciding which retrofitting interventions are the most appropriate and feasible for selected schools in a region. Similarly, as a significant implication, this device also allows patterns and trends to be detected in the environmental performance of schoolyards and hence specific actions can be appropriately adjusted and renovation patterns can be introduced into policy-making for future guidelines that lead to outdoor environments for the educational community of a more comfortable and liveable nature, as stated and demanded in their research studies Andersen et al. (2019) and Browning and Locke (2020).

Lastly, these particular results in the 6 pilot schools demonstrate a growing problem in recent years in schoolyards: the design of the built environment of schools in densely built-up cities or municipalities is mainly based on structural materials and surfaces characterised by high thermal capacity, such as asphalt and concrete (Habibi et al., 2020), and, over the last 12 months, a controversial trend of reducing green spaces and trees has been applied in schools in southern European countries in an effort to reduce maintenance costs, as stated Abdallah et al. (2020) and Guo et al. (2020).

4.1. GIS and decision-making implications

Decision-making is becoming increasingly popular as a topic in research in architecture and in the management of the built environment since it is a mechanism that facilitates success and efficiency in urban regeneration and stock renewal processes of existing buildings (Gandini et al., 2021). The possession of broad, multi-disciplinary and exhaustive knowledge of the research field, in which the urban environment, building, and indoor environmental performance are characterised, implies successful and determined decision-making thanks to the contributions of recent papers on this subject, such as the one developed by Cruz et al. (2021) or Serrano-Jiménez et al. (2022). One of the main contributions of this methodological mechanism and of the design of the results shown involves facilitating decision-making in the choice of bioclimatic and passive improvement actions to be implemented in schoolyards. Different construction agents, educational administration, and parent associations in the school community will gain advantages from ascertaining the environmental ergonomics of the schoolyard when determining which solutions to approach by using the benefits

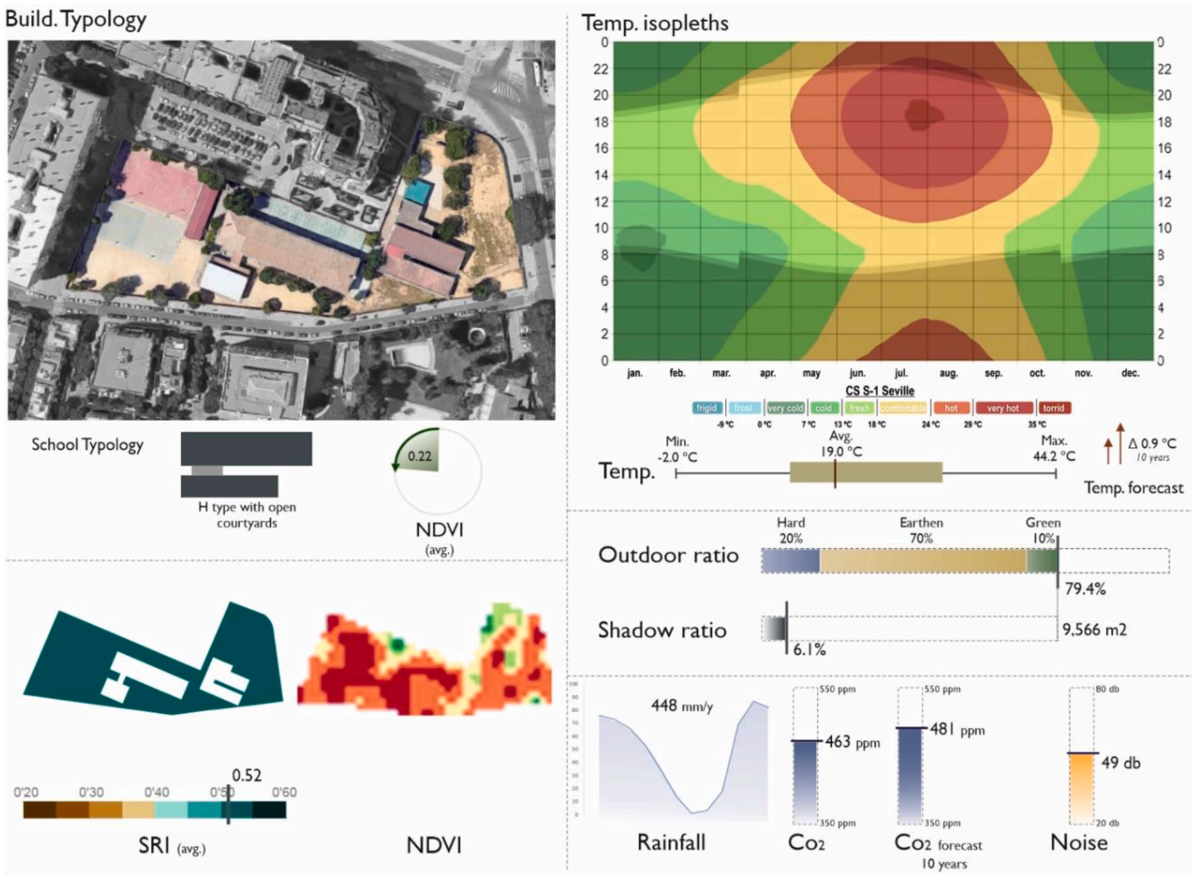

Fig. 6. Graphic output of results on environmental ergonomics parameters for CS-S1. Source: Authors.

from GIS, as concluded Österbring et al. (2016).

This manuscript introduces a new insight that enhances the possibilities of visualising the diagnosis of schoolyards and geolocating the schools in their locations. This study also incorporates the use and application of Geographic Information Systems where it is possible to insert the diagnosis of the schools, depending on different filters, attributes, and particular parameters of the 12 established. This study has gone beyond the 6 selected pilot cases and has applied this multi-criteria assessment system in more than 100 schools in the Andalusian region. Authors have included information by using GIS in each school within the region of Andalusia, in the south of Spain, with numerous points corresponding to the diagnosis of schoolyards, whereby each school has a graphic visualisation incorporated through the use of said application. Thus, the combination of the use of remote-sensing, the design in the visualisation of the diagnosis of schoolyards, and the use of GIS together represents a major advance and contribution towards promoting knowledge of environmental ergonomics in schoolyards, by identifying vulnerabilities and their corresponding areas of action since linked priorities exist when it comes to solving the detected drawbacks in line with what Shooshtarian and Ridley (2016) set out to provide specific thermal comfort requirements in school enclosures. Lastly, the usefulness of this model is also applicable to plots where a school is scheduled to be built in the coming years, in such a way that it provides information on the criteria to be taken into account in the design of the schoolyard. Thus, this procedure of data collection, weighting, and illustration of outdoor diagnosis demonstrates that the model could be replicated and tested in schoolyards located in other warm-climate countries affected by global warming, fulfilling the research gap identified by Fu et al. (2022) and Zhang et al. (2022).

5. Conclusions

This research fulfils the research absence of methodological studies and standardised processes for the diagnosis of outdoor conditions in urban spaces, by following the emerging concept of environmental ergonomics, and specifically adapting the models to schoolyards. Starting from previous research in existing schools on the state, design patterns, and conditions of outdoor spaces in schoolyards (Díaz-López, Serrano-Jiménez, Verichev et al., 2022; Serrano-Jiménez et al., 2021), the main contribution of this research is the design and develop of a diagnostic tool to facilitate management and decision-making for the selection of renovation strategies in schoolyards of existing educational centres, and for their conversion into CO_2-reducing spaces that favour not only the resilience of communities but also their adaptation to the effects of climate change. The originality of this remote evaluation methodology lies in the attainment of a systematic assessment procedure to obtain an integral diagnosis along with an evaluation of their environmental quality parameters, by assuming an incentive to carry out effective passive measures that improve the outdoor comfort in the face of a future scenario of global warming.

This novelty of the study is based on a methodological mechanism to obtain a generalised diagnosis on environmental ergonomics from schoolyards, thereby providing major insights to remotely map the graphic output of results and to assign geographic information through remote-sensing and GIS resources. Moreover, this work represents an important scientific insight by introducing new tools and resources for the assessment and improvement of schoolyards, through established identified parameters in environmental ergonomics: distribution space, shadow proportion, NDVI, SRI, pavement, and outdoor environmental parameters. Lastly, an additional implication of this paper involves the proposed design of the graphic output of results, as a visual resource to

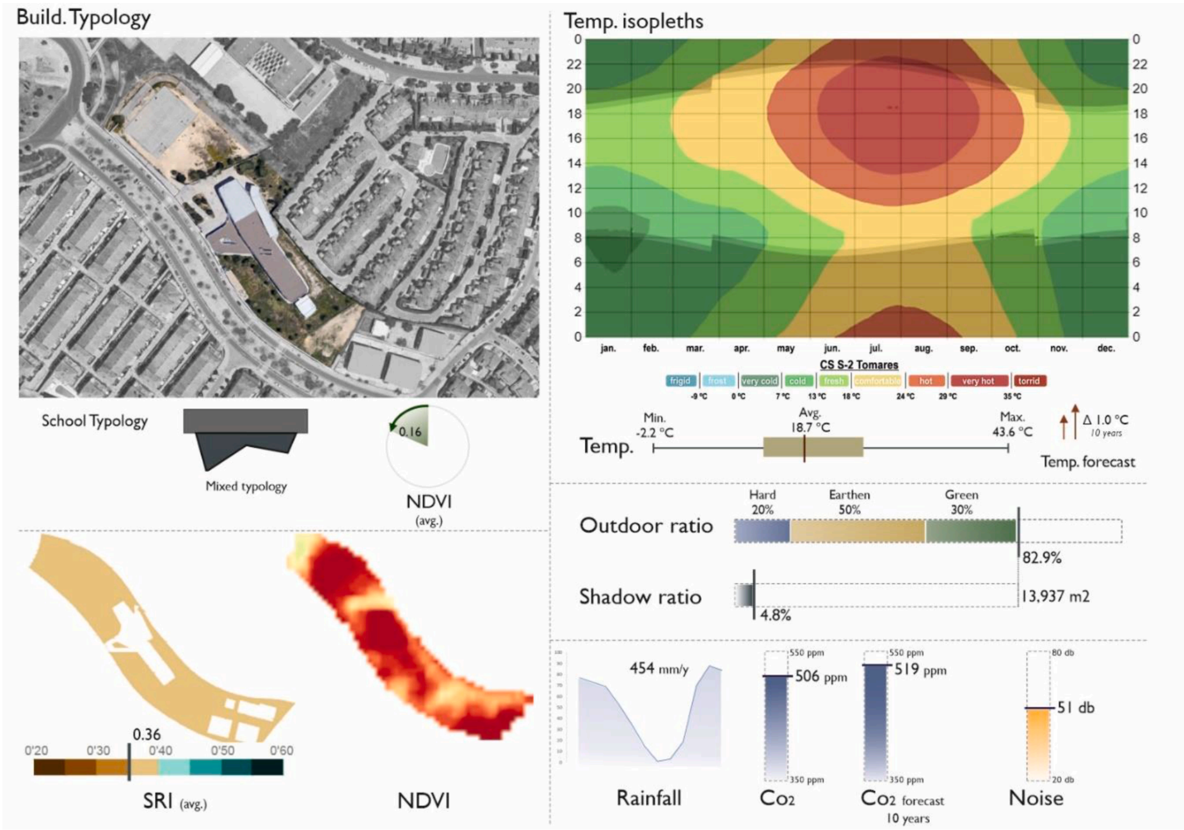

Fig. 7. Graphic output of results on environmental ergonomics parameters for CS-S2. Source: Authors.

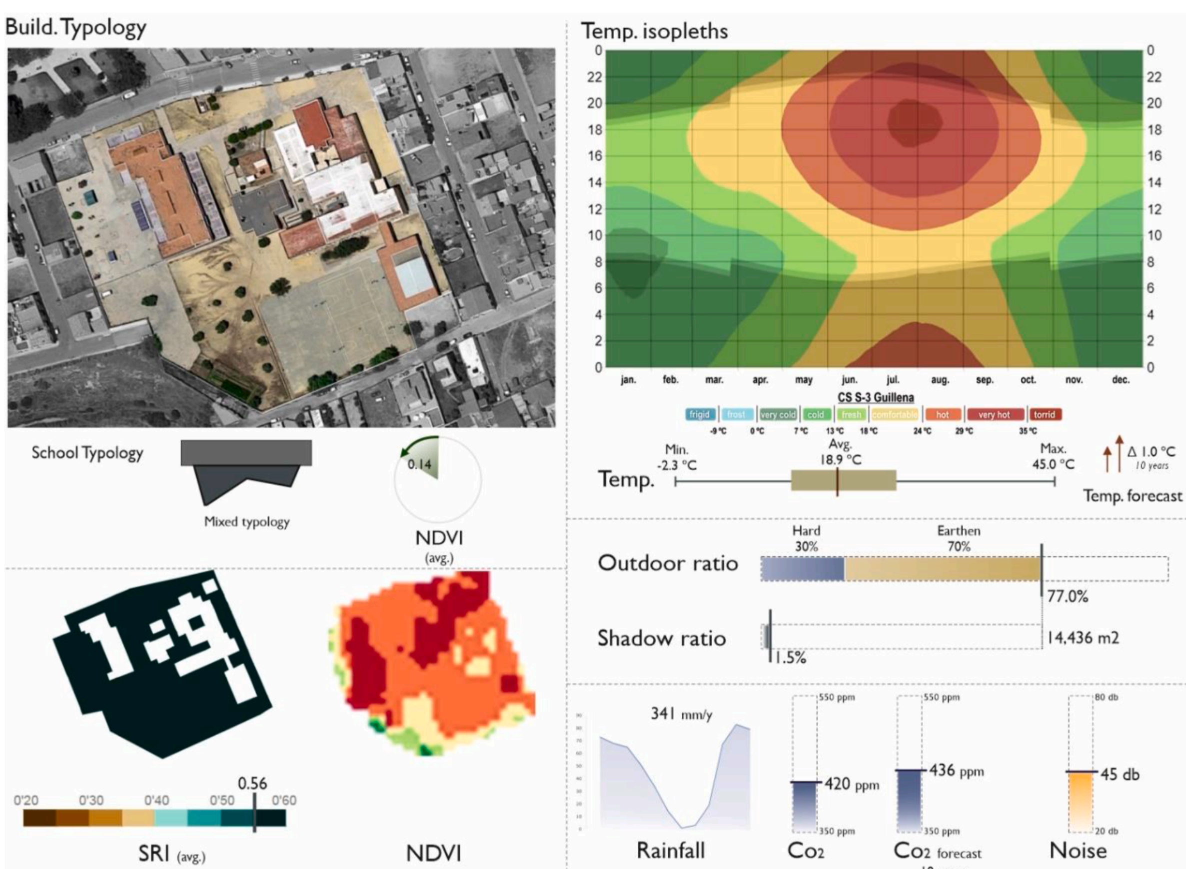

Fig. 8. Graphic output of results on environmental ergonomics parameters for CS-S3. Source: Authors.

help identify the diagnosis and ascertain its corresponding design patterns and outdoor environmental ergonomics for decision-making.

The key outcome on the significance of results is focused on standardising and systematising indicators that together yield results on environmental ergonomics in schoolyards, by combining remote-sensing and geographic information systems, thereby providing the administration with a decision-making tool to identify passive interventions in schools that guarantee the optimisation of their outdoor environmental performance through the incorporation of eco-efficient criteria. Although the proposed assessment system can be replicated for a wide variety of locations and typologies, this study has provided its application and testing in 6 representative pilot schools in southern Spain that belong to two climatic zones at different urban scales, in order to demonstrate its replicability under differing placement conditions. The highlighted recommendation of the study, the multiple parameters that influence outdoor environmental quality, must be considered and weighted in order to assess not only the perception of urban overheating and the consequences of global warming effects, but also the impact on student performance, in order to subsequently establish an action protocol with the administration that enables appropriate actions to be carried out under multi-criteria decision-making. Practical perspectives of this research are focused on a tool that allows the administration to locate those schoolyards of strategic educational centres in order to carry out passive interventions that guarantee the suitability and the incorporation of eco-efficient criteria when mitigating global-warming effects, and can be replicated in across various school typologies.

Finally, given the limitations of this study, mainly based on the exclusive application to schoolyards and dependency on remote-sensing technology for obtaining a prior diagnosis before quantifying the impact that renaturation and passive actions would have, two lines of future research direction are proposed from this study: 1. Carrying out an in situ study to improve the conditions of the schoolyard, through revegetation actions and other bioclimatic patterns, in these selected pilot schools and compare the remote-sensing diagnosis and quantify the action performance; and 2. Extend the scope of this methodology to urban areas and housing neighbourhoods, adapting the database of parameters and carrying out an in-depth study of the impact of other private and public buildings on the urban heat island.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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