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Assessing urban sustainability: a proposal for indicators, metrics and scoring—a case study in Colombia

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Abstract
Although there are different methodologies for evaluating the sustainability of urban areas in Latin America, they usually apply to a specific city as a whole and cannot be generalized to other cities; besides, they do not address smaller urban units, such as the district, and rarely approach all sustainability dimensions. This study aims to propose a methodology for the evaluation of urban sustainability in the context of a country, whose approach can be adapted to evaluate the urban sustainability of any country or territory, taking into account environmental, social, economic and institutional aspects. The methodology is structured as an ordered protocol in five stages: (I) revision of PROGRAMMES on urban sustainability, (II) revision and cluster of indicators, (III) definition of indicators and metrics, (IV) definition of the scoring method of indicators, and (V) graphical representation of indicators. Accordingly, the methodology was applied in the context of Colombia, particularly to the medium-sized city of Mosquera, as a case study, and both as a whole and by socio-economic strata. As a result, a set of indicators with their corresponding metrics and score in sustainability levels was obtained, as well as a graphical representation that facilitates the interpretation of results and enables the comparison of different urban areas within the city. The results made it possible to identify vulnerable or degraded urban areas, and on a lower level, to detect specific critical aspects that require the implementation of improvements geared towards a more sustainable urban environment. The overall conclusion is that there is room for improvement in the municipality, since its level of sustainability ranges, generally, from 1 to 2 on a scale of 3.

Keywords Urban sustainability · Built environment · Sustainability assessment tool · Urban indicator

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1 Introduction

The Latin American (LA) region is the second most highly urbanized area in the world and most of its population live in medium-sized and large cities in poor conditions (Jaitman & Brakarz, 2013). This trend is increasing progressively and leads to a rapid and uncontrolled growth, while many inhabitants are still poorly housed, without safe drinking water, sewage systems, adequate building materials, sufficient living space, formal tenure and a secure location (Boullon, 2012). Additionally, considering that urban improvement plans are scarcely applied and, when they are, the initiative is performed in a disjointed and limited manner (Montoya et al., 2020), LA regions are liable to fail to meet the sustainable development goals (SDG) set by the United Nations (2015). Colombia is one of the countries included in the LA region, and its population has concentrated increasingly in cities over the last few decades, this urban population reaching a figure of 81.5% in 2020 (CEPAL, 2020).

In the field of sustainability assessment in the international context, great efforts have been made by the scientific community to measure the level of sustainability of urban areas through indicators grouped in the three classical dimensions: social, economic and environmental. More recently, the institutional dimension has also aroused interest and is being approached in order to increase administrations support, but only tentatively. Sharifi and Murayama (2014) exhaustively reviewed a number of urban sustainability assessment tools and found that many regions have developed their own, such as LEED (US GBC, 2009) in USA, BREEAM (BRE Global, 2011) in UK, CASBEE (IBEC, 2007) in Japan, HQE2R (Blum, 2007) or Ecocity (Gaffron et al., 2008) in Europe, or Green Star (GCBA, 2003) in Australia. As seen, most of these tools apply to Europe, North America and Asia, where robust and proven methodologies for developing sustainability indicators exist and have been widely implemented yet.

However, these kinds of methodologies or tools have been very little developed in LA (Peralta Arias, 2020). Even though several studies that focused in some LA countries were found in the literature. In Peru, Martínez Vitor (2019) analysed the influence of a set of existing urban indicators in the sustainable development of the metropolitan area of Huancayo using three different methodologies (census and cartographic data, urban plans implemented by the city hall along time, and the biogram made by the Inter-American Institute for Cooperation on Agriculture). His work focused on the three dimensions of sustainability, included the monitoring of indicators in different time periods and represented the results through spider graphs in a clear and visual manner. In Chile, Moreno and Inostroza (2019) evaluated the performance and the sustainability level of 4 neighbourhoods of the city of Temuco, through 11 indicators, and established three levels of performance (low, medium and high). Nonetheless, these indicators were only focused on physical (morphological) and environmental aspects, not in socio-economic ones, and did not define the method for granting the score. In Costa Rica, Romero Vargas et al. (2020) explored environmental, social and economic indicators through an expert's panel and identified a total of 327 indicators that finally simplified in 19 and grouped in 9 criteria (water, energy, fauna, green areas, etc.). They also defined a scale from 1 to 5 to score them, but the method used seemed fuzzy. Pinedo and Pimentel (2021) proposed a global index (in a scale of 0–1) to assess the sustainability of the municipality of Sao Joao da Ponta in Brasil, which was decomposed in the social, the economic and the environmental dimensions. They also defined a scale for evaluating four levels of sustainability, according to the value of the index obtained after the evaluation. In the context of Colombia, also some advances in the definition of sustainability indicators can be identified in the recent literature. Carrillo-Rodríguez and Toca (2013) designed a sustainable performance index for the city of Bogota. Gaviria (2013) proposed a set of indicators grouped into five dimensions (institutional, technology and innovation, economic, environmental and social) to assist construction sector companies in their decision-making. Montoya et al. (2020) defined a set of thirteen sustainability indicators for the specific case of Bogota's informal settlements, which were validated by applying them to two case studies. Also in relation to the informal settlements, López Borbón (2016) identified a number of variables, parameters and indicators to evaluate their functioning and prospects. More recently, Mesa García (2021) proposed a methodology for the measurement and assessment of six urban sustainability criteria (scale, accessibility, connectivity, density, diversity and nodal), specifically for the municipality of Bucaramanga; but these approached only morphological aspects (urban form) and the methodology cannot be generalized to other cities or similar regions in the country.

As depicted from the literature, one characteristic of Latin America is that although there is some work done within the development of sustainability indicators, the countries are working at the national level, not offering a global vision of specific regions. Urban sustainability indicators require a holistic approach, the definition of scales, the selection of parameters and levels of characterization and also have to be flexible tools capable of adapting to the urban fabric and features of the city or region where are to be applied, since urban ecosystems are dynamic and changing.

The studies carried out to date in LA focused on the evaluation of a certain city of the country, and then, the method used cannot be applied to other cities. Besides, sometimes the method or procedure used for identifying exiting indicators for their direct application or, otherwise, the development of new ones, seemed a little bit fuzzy. It was also observed that much emphasis was placed on the environmental aspect and less on the socio-economic one. Also, it was seen that the evaluation of the cities included in these studies is mainly addressed to the city as a whole system, but not cover the evaluation of smaller urban units, such as the neighbourhood or the district, in order to identify different sustainability performance within the same city, what is foreseeable to occur due to the marked physical and socio-economic differences that usually occur within the same urban area.

Specifically, in Colombia, the opportunity to measure intermediate Colombian cities through sustainability indicators is strategic, in the search to determine particularized environmental and socio-economic problems, possibly different from other areas at the national or LA level, with a focus on sustainability. The most recent legal framework has been adopted some legislation and tools approaching sustainable building and urban practices, which have been taken into consideration in this study. This is the CONPES 3919 policy (Política Nacional De Edificaciones Sostenibles, 2018), whose objective is to promote the inclusion of sustainability criteria within the life cycle of buildings, through instruments for transition, monitoring and control, and financial incentives that allow the implementation of sustainable construction initiatives. This policy was born from different initiatives for the strengthening the sustainability of cities, such as the previous CONPES 3819 policy (2014) and National Development Plan 2014–2018 (2015), whose main objectives are the consolidation of the city system for economic, social and environmental development, and the mitigation of climate change with the focus on social mobility. As a result of these policies, some Colombian cities have formulated their own policies. This is the case of Bogotá and Valle de Aburrá, as an example of good practices. The policy of ecourbanism and sustainable construction of Bogotá (Alcaldía Mayor de Bogotá, 2014) was designed to address the problem of climate change generated by construction and urban environment, and was based on different sustainability advances in the city and on international standards and regulations, such as the urban sustainability assessment tools above-mentioned (LEED, BREEAM or CASBEE). As for the sustainable construction policy of the Metropolitan Area of Valle de Aburrá (AMVA-UPB, 2015), it works as a tool to implement sustainable construction in the region, at different phases of the life cycle of buildings, and under conditions of economic viability and resilience, eco-efficiency in the consumption of natural resources and low impact in relation to the landscape, biodiversity and ecological connectivity. This policy transcends the scale of the building, also influencing the proper development of public space, offering knowledge for sustainable urban planning.

Nevertheless, despite some efforts have been done in Colombia, no urban sustainability assessment general methodology for establishing of a set of comprehensive, clear and objective indicators capable of assessing the sustainability of urban areas that were adapted to the context and specificities of the region under study and that covered the four dimensions of sustainability, namely environmental, social, economic and institutional, has been developed in LA and Colombia. Nor that it can evaluate smaller urban scales than the whole city, such as the district or neighbourhood or even degraded informal settlements in the periphery of the city.

This paper aims to cover this research gap by presenting a methodology for proposing a set of indicators, their metrics and the method for scoring them in sustainability levels, which allows to assessing and comparing different urban areas, even in the same municipality. The proposed methodology is a contribution for the evaluation of urban sustainability in the context of a country, whose approach can be adapted to evaluate the urban sustainability of any country or territory. For the validation of the methodology, it is applied to Colombia, as a case study, and particularly to the medium-sized city of Mosquera (Cundinamarca, Colombia).

2 Methodology

To define the set of indicators capable of evaluating the sustainability of urban areas, a general methodology is proposed, which can be adapted to the context-specific characteristics of the region where the sustainability assessment is to be conducted. The methodology (Fig. 1) is divided into five stages, as described below. Additionally, in order to establish an ordered protocol to apply the stages, a method to approach the analysis of evidence

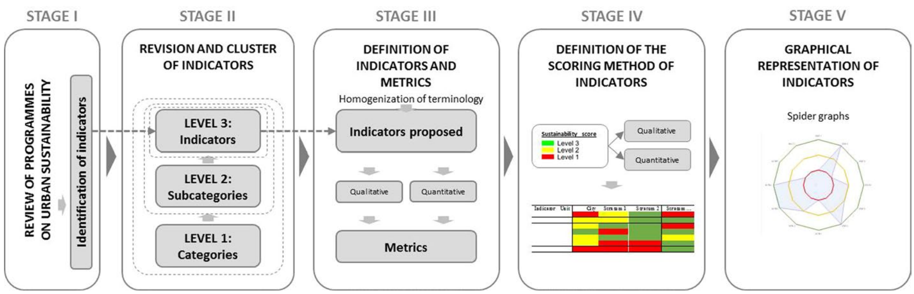

Fig. 1 Methodology

and representation of results is proposed along the methodology (McGregor & Murnane, 2010).

- *Stage I. Selection of programmes about urban sustainability* The methodology starts with the search and selection of programmes of urban indicators in the context of the region under study and the identification of the indicators included.
- *Stage II. Revision and cluster of indicators* After identifying the indicators, these are classified and grouped according to a common and hierarchical structure, as done in similar work by Arrieta et al. (2016) and Córdoba et al. (2020). The hierarchical structure is composed of thematic categories (level 1) and subcategories (level 2), as proposed by Braulio-Gonzalo et al. (2015) previously, which finally include the indicators (level 3).
- *Stage III. Definition of indicators and metrics* The indicators (level 3) are analysed in detail, and thus, the terminology can be homogenized for proposing a final set of indicators adapted to the context-specific characteristics of the region under study. Afterwards, the indicators are classified in quantitative or qualitative, what would determine the kind of metric to be used. Then, the metric is defined for each indicator. It should be noted that the set of indicators proposed can be applied to large scale urban areas (such as an entire country), or instead to smaller scale urban areas (such as municipalities or even, districts or neighbourhoods).
- *Stage IV. Definition of the scoring method of indicators* In order to classify each of the indicators on a rated scale, so that they are easily comparable, a method for scoring for both quantitative and qualitative indicators was defined.

For those quantitative that can be calculated for different districts/neighbourhoods in the same municipality, a grading of the results of each indicator was established according to the method proposed by Sturges (1926). The optimal class interval (C) can be estimated from the formula:

$$C = \frac{R}{1 + 3.322 \log N}$$

where R is the range and N is the number of items involved in the computation. This formula gives the class interval for the computation of the averages, measures of dispersion and skewness of frequency distributions. It is based on the principle that the proper distribution into classes is given for all numbers which are powers of 2, by a series of binominal coefficients. A numerical value, a sustainability score and a colour, 1 (low, red), 2 (medium, yellow) or 3 (high, green) were assigned to the scale that was finally obtained in order to represent the indicators' results both graphically and in a table with numerical values.

When the indicator is only calculated once (in general for the municipality under study), this value cannot be graded and should be compared to reference values that can be obtained from a country scale, or a smaller scale, if appropriate.

For those qualitative indicators, the procedure for measuring is based on checking if some specific criteria or standard are accomplished or not, then, the score results in level 1 (not accomplished: low, red) or level 3 (accomplished: high, green).

- *Stage V. Graphical representation of indicators* The methodology finally generates a graphic result that allows to differentiate the level of sustainability (1, 2 or 3) of the

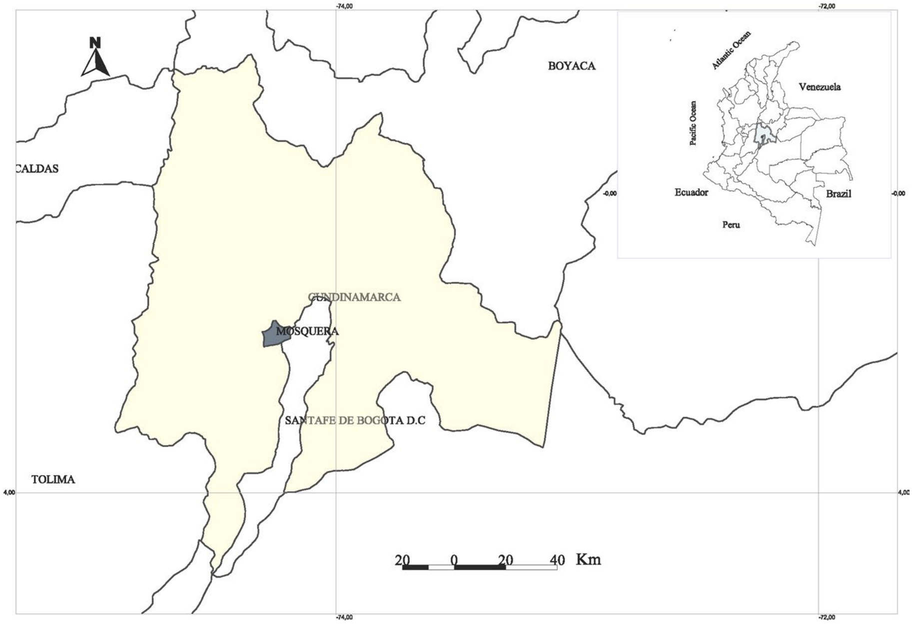

Fig. 2 Localization of the case study (Mosquera, Cundinamarca, Colombia)

Table 1 Climatic data of Mosquera

Parameter	Maximum value	Average value	Minimum value
Temperature	18 °C	12 °C	10.9 °C
Annual precipitation	787 mm/year	640 mm/year	410 mm/year
Wind	3.2 m/s	1.88 m/s	0.2 m/s
Relative humidity	90%	82%	74%
Cloudiness	7/8 oktas	6/8 oktas	4/8 oktas

urban environment analysed, as done in similar studies conducted by Martínez et al. (2019) and Arrieta et al. (2016). The spider graph type was chosen to show the indicators scores in the urban area, for a clear and reliable visual representation.

3 Description of the case study: city of Mosquera

The municipality of Mosquera is located in Colombia in the western side of the department of Cundinamarca, 23 km from Bogota D.C, as presented in the map in Fig. 2. The city has a territorial extension of 107 km^2, of which 12.8 km^2 correspond to the urban area and 94.2 km^2 to the rural area, and it is located in a cold climate, with the conditions reported in Table 1. It has a population of 150,665 inhabitants, of which 98.8% live in urban areas and 1.2% in rural areas (Alcaldía de Mosquera, 2020). According to the cadastral census, Mosquera has a built area of 831.33 Ha with 35,064 parcels of land distributed according to the socio-economic strata established in the country.

The Colombian System for the Selection of Beneficiaries for Social Programmes (SISBEN) classifies households into six strata, according to their socio-economic conditions: 1-low-low, 2-low, 3-medium–low, 4- medium, 5-medium–high, and 6-high. In Mosquera, stratum 1 is made up of the neighbourhoods located near the peripheral limits, close to the wastewater discharge points. It is characterized by the presence of traditional self-built dwellings in informal settlements with difficult access. Strata 2 and 3 are made up of VIS located near the centre of the municipality and with leisure areas and paved roads. Strata 4 and 5 consist of dwellings, mostly single-family houses, built with private funds. Stratum 6 comprises semi-detached houses where the population with the highest purchasing power resides.

4 Results from the application to the case study

4.1 Stage I. Selection of programmes about urban sustainability in the context of Colombia

The legal framework in Colombia related to building and urban sustainability adopted the international protocols of Kyoto (Corte Constitucional de Colombia, 2000) and Paris COP21 (Congreso de la República de Colombia, 2017) in order to mitigate climate change and to reduce greenhouse gas (GHG) emissions in the country. Taking into account the agreements reached in these protocols, Colombia defined a series of urban planning strategies to fight against climate change (DNP, 2011). To do so, Law 1753 (Congreso de la República de Colombia, 2015) incorporated cross-cutting and regional strategies related to infrastructure, social mobility, transformation of rural areas, security and justice, good governance and ecological growth. This legal framework was accompanied by CONPES 3819 (DNP, 2014), which is focused on the consolidation of cities by creating metropolitan areas with homogeneous aspects by grouping different municipalities and by CONPES 3870 (DNP, 2016), which concentrates on achieving an orderly and sustainable growth by integrating rural and populated areas in agreement with SDG11 (Sustainable cities and communities). In addition, Decree 1077 (Presidencia de la República, 2015) and CONPES 3919 (DNP, 2018) promoted the incorporation of a set of sustainable criteria during the life cycle of buildings and their urban environment. However, what are intended to be criteria are in fact just general guidelines that are difficult to apply and quantify (Córdoba et al., 2020).

Also derived from Decree 1077, Resolution 0549 (Ministerio de Vivienda Ciudad y Territorio, 2015) and Colombian Technical Standard 6112 (NTC6112, 2016) defined several sustainable development initiatives for buildings. They were mainly focused on strategies for water and energy savings in specific new buildings (shopping centres, offices, hotels, educational centres, hospitals and non-social interest housing (VIS)). However, these initiatives are only voluntary for VIS and priority interest housing (VIP). These mechanisms therefore do not adopt a global urban approach, but apply only to the specific area of buildings, leaving aside the urban perspective.

From the literature review of the regulatory framework and the programmes applicable to the context of Colombia, the following were selected and analysed in depth:

- CONPES 3919 (Política Nacional De Edificaciones Sostenibles, 2018). It includes 38 indicators grouped into 3 criteria (social, environment for the territory and environment for the building) and, in turn, into 9 subcategories (citizen participation, equity and accessibility, location, mobility, adaptation to climate change, efficiency in water, energy efficiency, material and resource management, and indoor environment quality). The indicators are qualitative and are coded in the study as CP01 … CP38 (Table S1). It provides general guidelines but does not use a rating system to calculate the level of sustainability.
- BOGOTA (Alcaldía Mayor de Bogotá, 2014). It includes 35 qualitative and quantitative indicators grouped into 6 categories: social, public services, hydrological cycle, pollution, urban context, and buildings, which are coded in this study as BG01 … BG35 (Table S2). The document does not constitute a rating system, but rather a guide to sustainability guidelines to be applied in urban and building environments.
- VALLE DE ABURRA (AMVA-UPB, 2015). It is structured into 5 guides, 3 of them applicable to the urban environment (characterization of the place, urban planning and open spaces). These comprise a total of 64 indicators, which address 9 topics: climate and atmosphere, water resources, geology and soil, biotic component, energy resource, materiality, built environment, habitability and viability. The indicators, both qualitative and quantitative, are presented as technical criteria that contribute to the sustainability of the region. However, it does not constitute a rating system either. These are coded in this study according to VA01 … VA62 (Table S3).
- CALI (DAGMA, 2019). It includes 31 indicators (qualitative) belonging to 5 topics: knowledge of the territory, water and energy, construction and demolition waste, climate adaptation, and protection of biota. It provides illustrative and non-quantifiable guidelines for each indicator. They are coded in this study as CA01 … CA31 (Table S4).
- LEED (US GBC, 2009) was also selected, since it is the international urban sustainability assessment tool promoted by the CCCS. It includes 56 indicators grouped into 5 topics: smart location and linkage, neighbourhood pattern and design, green infrastructure and buildings, innovation and design process and regional priority. The indicators in the study are coded as LEED01 … LEED56 (Table S5). It is a rating system that allows the sustainability of the urban environment to be classified on four levels: certified, silver, gold and platinum.

It should be noticed that the cities of Bogotá, Valle de Aburrá (Medellin) and Santiago de Cali recently joined the international partnership Building Efficiency Accelerator (BEA), which is focused on actions to mitigate climate change and to provide support for cities that are transforming the energy use of their buildings. The programmes developed and described are evidence of the increasing efforts being made in these regions to improve urban sustainability.

4.2 Stage II. Revision and cluster of indicators

Prior to comparing the programmes selected in Stage I, it is necessary to define a common structure as each of them uses different classification topics and a distinct nomenclature. To address this, the structure proposed by Braulio-Gonzalo et al. (2015) was applied, based on a hierarchical structure composed of three levels. Level 1 was made up of 14 categories (site and soil (SS), urban morphology (UM), mobility and transport (MT), nature and biodiversity (NB), building and housing (BH), energy (E), water (Wr), materials (M), waste (Ws), pollution (P), social aspects (SA), economic aspects (EA), management and institution (MI), innovation (I)) and Level 2 of 69 subcategories, as reported in Table 2. The indicators found in the selected programmes were reviewed, and those related to the urban context were extracted. Table 2 shows the indicators belonging to each programme with a direct relationship with each category and subcategory. The full description of each indicator (CPXX, LEEDXX, BGXX, VAXX and CAXX) is detailed in the Supplementary Information. As observed in Table 2, some of the subcategories are not covered by any of the indicators included in the programmes analysed. These are: transport management in the MOB category; diversity of housing and maintenance of buildings in BUD; civil association and energy poverty in SOC; tourism and new business and investment in ECO; administrative transparency, knowledge and information management, information and communications technology (ICT), investment in activities for society, environmental education, and regulations to improve sustainability in MI.

These results were represented graphically in order to identify which aspects are the most and least discussed, and to be able to compare them. Figure 3 presents, as percentages, the number of indicators that each programme contributes to the 14 categories.

4.3 Stage III. Definition of indicators and metrics

After analysing the programmes currently available in Colombia and classifying their 222 indicators into 14 categories and 69 subcategories, Stage III proposes a set of 105 indicators capable of assessing the sustainability of the current urban context in Colombia.

The selection of indicators was done throughout the following criteria. The distribution of the 222 total indicators found in the policies in Table 2 showed that for some indicators there is more than one way to measure them, for which the indicator that fitted better to the problems of any municipality in Colombia was selected, leaving a total of 115 indicators. Therefore, for each subcategory at least one indicator has been suggested, which is intended to be intelligible and easy to apply. It was also considered that the indicators presented in the study would cover all aspects of sustainability on an urban scale, either in the entire municipality or at the district level. Besides, for the formulation of the set of indicators, the building and housing (BUI) category has been excluded, as it is related to the building scale, which falls outside the scope of this study. Excluding these 10 indicators that make up this category, the proposed system of indicators was finally made up of 105 indicators.

The proposed indicators are based on some of the those belonging to the programmes reviewed, while others are indicators belonging to other international verified programmes (Agencia de Ecología Urbana de Barcelona, 2007; Ministerio de Medio Ambiente y Medio Rural y Marino, 2010) or our own proposal developed ad hoc in this study. The indicators are reported in Tables 3, 4, 5, 6, 7 and 8 and are grouped into 7 topics: site & biodiversity, infrastructure, urban metabolism (inputs), urban metabolism (outputs), social, economic, and institutional and innovation. These tables are structured in six columns, described as follows: the code of the indicators is indicated in the first column; secondly, the type indicates if whether the indicator is qualitative (QL) or quantitative (QT); in the third column, the description provides the title of the indicator and a comprehensive explanation; fourthly, unit defines the units for measuring each indicator; in the fifth column, the metric provides the formula for evaluating each indicator, when quantitative, and the criteria, when qualitative; finally, the reference provide the bibliographic detail from which

Table 2 Cluster of the indicators of the programmes into a common hierarchical structure of categories and subcategories

Level 1 categories	Level 2 subcategories	Level 3 indicators
Site and soil (SS)	Weather and site conditions	LEED5, LEED6, LEED11, CA02, CA03, CA04, CA14, CA15, CA16, CA17, CA05, CA26, VA01, VA02, VA03, VA04, VA05, VA06, VA07, VA08, VA11, VA12, VA13, VA14, VA15, VA16, VA38, VA44, VA58, VA59, VA60, VA61
	Land occupation	LEED1, CA01
	Soil and heritage reuse and conservation	LEED7, LEED41, LEED42, LEED43
	Compactness	LEED16, LEED19, BOG25, BOG26, VA30
Nature and biodiversity (BIO)	Green areas	CP11, BOG27, BOG28, BOG29, VA18, VA19, VA20, VA21, CA25
	Urban farming and food	LEED4
	Natural resources	LEED12, LEED13, LEED14, CA31
	Species biodiversity	CP07, CA29, LEED2, VA22, VA24, VA25, VA57, CA29, CA30
	Architectural elements and infrastructure with vegetation	VA23, VA45, VA46
Urban morphology (URB)	Design and quality of public spaces	LEED15, LEED18, LEED22, LEED23, BOG35, VA26, VA27, VA28, VA29, VA31, VA47
	Mixed-use development	CP08, LEED20
	Equipment	LEED26, LEED27, LEED28
	Universal design and architectural barriers	CP05, LEED28, VA50
	Safety, health and hygiene	VA49, VA51
Mobility and transport (MOB)	Distance reduction and private vehicle use	CP13, BOG30, VA32, LEED8, LEED10, LEED24
	Public transport and other sustainable alternatives	CP09, CP10, CP12, LEED9, LEED17, BOG31
	Efficiency of public transport	LEED25
	Transport management	–

Table 2 (continued)

Level 1 categories	Level 2 subcategories	Level 3 indicators
Building and housing (BUD)	Fulfilment of standards and regulations	LEED33, CA20, LEED37
	Building renovation and adaptation of use	BOG34, BOG32, BOG33
	Building resource efficiency	LEED34, LEED35, LEED38, LEED39
	Energy in buildings	CP20
	Bioclimatic building design	CP35, CP37, CP38, CP27
	Diversity of housing	–
	Maintenance of buildings	–
Energy (ENG)	Bioclimatic urban design	LEED31, LEED46, VA10
	Urban heat island	CP16, CA27, LEED45
	Energy efficiency of facilities and monitoring	CP21, CP23, LEED48, LEED49, VA52, CA19
	Renewable energy	CP24, LEED47
	Energy supply	BOG10, BOG11, CA10, CA11
	Energy consumption	VA39
Water (WTR)	Water consumption	CP17, LEED40, BOG7, BOG8, BOG13, VA40, CA09, CP18
	Rainwater and wastewater management	CP15, CP19, CP25, LEED44, LEED50, BOG21, BOG24, VA53
	Water quality	LEED3, BOG12, VA09
Materials (MAT)	Low-impact materials	CP34, CP36, CP26
	Certified reference materials	CP33, VA54
	Reused and recycled materials	CP31, LEED51
	Local materials	CP30
Waste (WST)	Minimizing waste production	VA41, CA21
	Waste treatment	CP28, LEED52, BOG20, BOG9, VA42, VA55, CA22, CP29, CP32

Table 2 (continued)

Level 1 categories	Level 2 subcategories	Level 3 indicators
Pollution (POL)	Soil	CA28
	Air	BOG22, VA16, CA13
	Water	BOG14, BOG15, BOG16, BOG17, BOG18, BOG19, CA24
	Noise	BOG23, VA17, CA18
	Light	CP22, LEED53
	Resources and others (environmental footprint)	CP14, LEED36, VA43, VA56
Social aspects (SOC)	Social cohesion and mixed neighbourhoods	LEED21, BOG1, BOG4, VA34, VA35, VA36, CA08, CA12
	Citizen participation	CP01, CP03, LEED29
	Civil association	–
	Affordable housing	BOG2, CA06
	Energy poverty	–
	Education	CP02, VA33
Economic aspects (ECO)	Local, social and green jobs	CP06, LEED30
	Employment rates	BOG3
	New business and investment	–
	Quality of employment	BOG5, BOG6, VA37, CA07, BOG6
	Tourism	–
	Return on investment and affordable costs	CP04, VA48

Table 2 (continued)

Level 1 categories	Level 2 subcategories	Level 3 indicators
Management and institution (MI)	Process management	LEED56
	Administrative transparency	LEED55
	Knowledge information and management	–
	Information and Communications Technology (ICT)	–
	Investment in activities for society	–
	Environmental education	–
	Regulations to improve sustainability	–
	Innovation	–
Innovation (IN)	Process management	LEED54

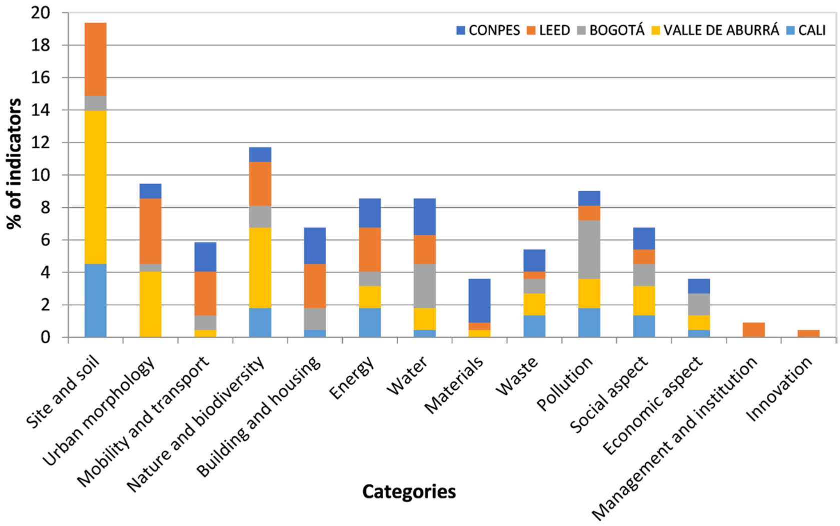

Fig. 3 Contribution of each programme to the 14 categories analysed

the indicator was retrieved or, otherwise, indicates "proposed" when the indicator was proposed in the framework of this study.

The indicators are qualitative or quantitative and can be applied both at the global level of the municipality and at the neighbourhood or district level, depending on the information available to quantify them. In the case of quantitative indicators, their metric is provided through a mathematical expression used to calculate them. Qualitative indicators are advisory in nature and offer sustainability guidelines to carry out good practices.

4.4 Stage IV. Definition of the scoring method of indicators

The information needed to apply the metrics proposed for each of the indicators was collected from the sources of data available in Mosquera. Depending on the data source, some indicators can be calculated by strata and others for Mosquera as a whole. Despite the efforts made to collect all the data, some of it is missing for the calculation of indicators ENG4, MAT1, POL1 and POL7, so that these metrics cannot be obtained. Results are reported in Table 9, according to the colour scale described in Stage IV, which represents the sustainability score in three levels: 1 (low, red), 2 (medium, yellow) and 3 (high, green). The reference values to rate each indicator, which resulted from the Sturges (1926) formula or Colombian standards, are presented in "Appendix 1" in Tables 10, 11 and 12.

4.5 Stage V. Graphical representation of indicators

Results are reported graphically in Figs. 4 and 5, using spider graphs. Figure 4 shows the results for the overall municipality of Mosquera, in such a way that it provides a general vision and diagnosis, while Fig. 5 shows the comparison by socio-economic strata (for those indicators calculated by strata). Finally, Fig. 6 presents the results on a map of

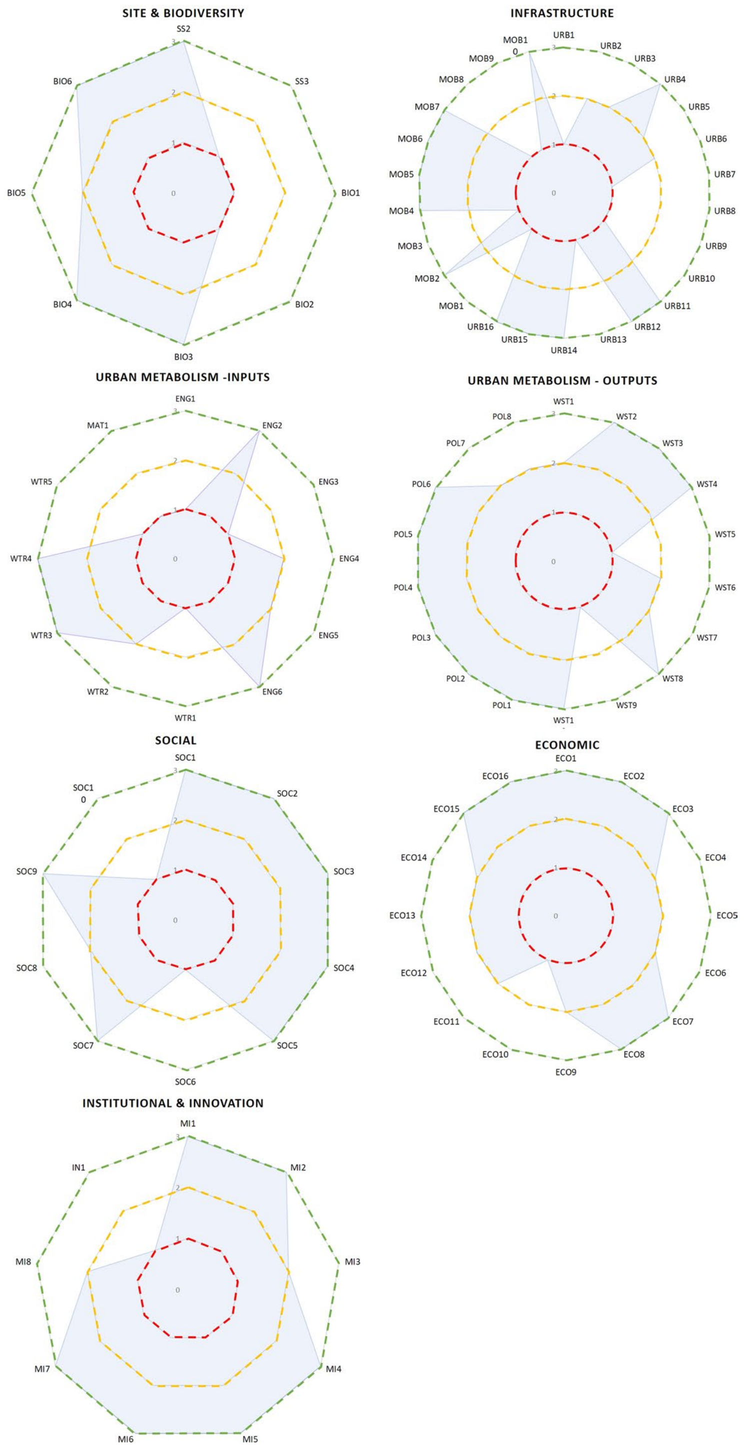

Fig. 4 Metrics and graphical representation of indicators at the Mosquera level

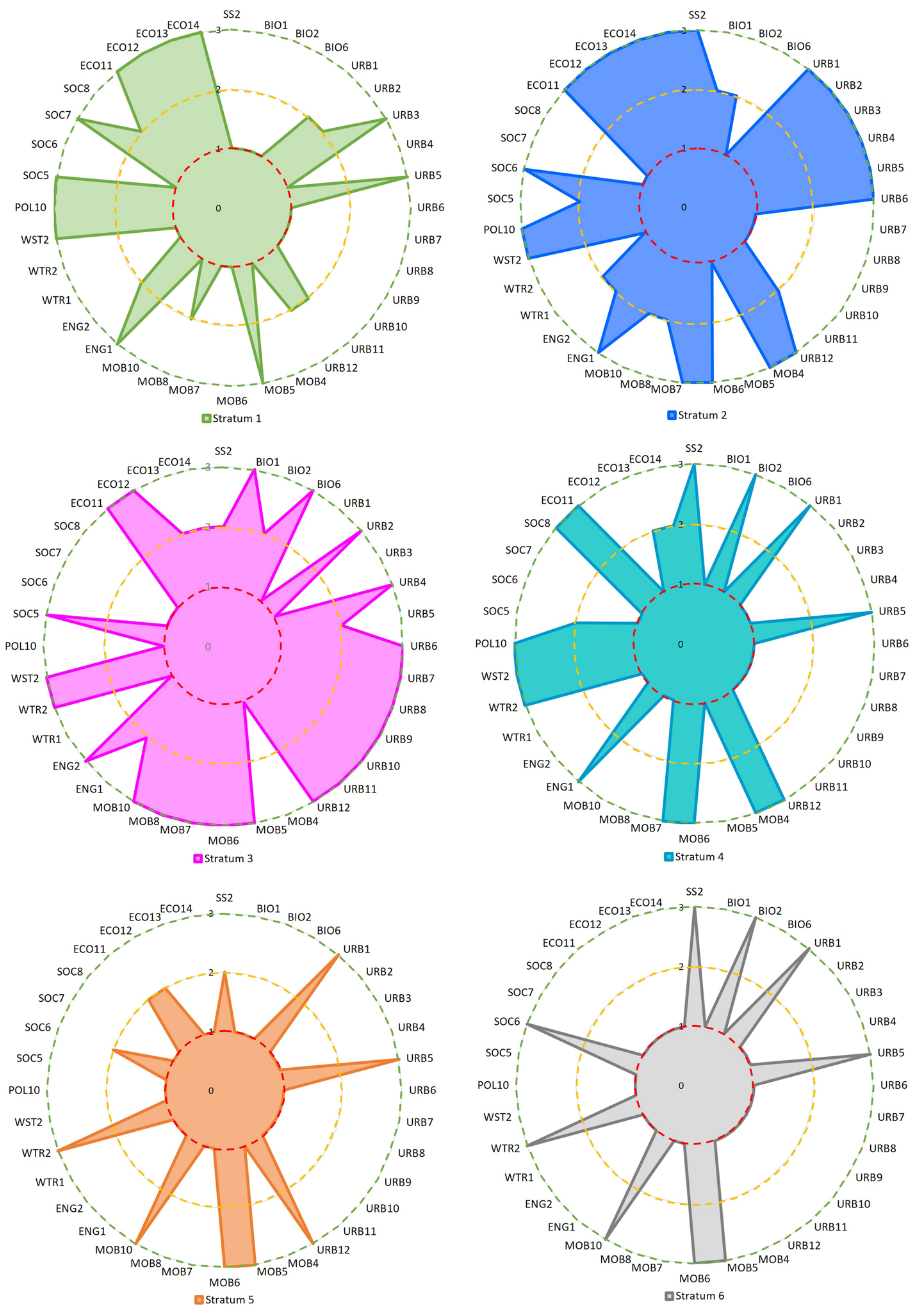

Fig. 5 Metrics and graphical representation of indicators at the socio-economic strata level

Mosquera, where the six socio-economic strata are delimited by a contour and coloured according to their average level of sustainability: low (1), medium (2) or high (3).

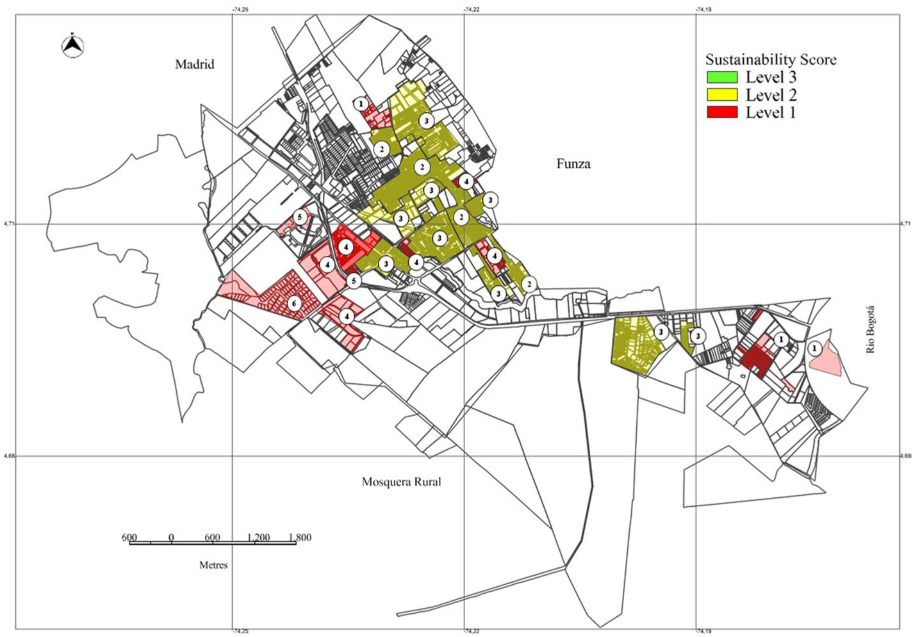

Fig. 6 Urban sustainability map of Mosquera per socio-economic stratum (the numbers in circles represent the strata from 1 to 6)

5 Discussion

The results showed that none of the socio-economic strata reached the highest level of sustainability (3, green), as depicted in Fig. 6. Strata 2 and 3 achieved the medium level (2, yellow), while strata 1, 4, 5 and 6 presented the lowest levels (1, red). As shown in the spider graphs in Fig. 5, strata 2 and 3 successfully covered a large number of the indicators, especially those related to URB and MOB. The fact that they are located near the city centre leads to better sustainability performance, due to higher building compactness, and the presence of mixed-use buildings (both housing and equipment) brings people closer to services and helps to reduce distances and the use of private vehicles. Stratum 1, located in informal peripheral settlements and characterized by self-constructed dwellings, houses the families with the lowest incomes and embraces the lowest sustainability level regarding infrastructure, due to the low quality of water and energy services, the proximity to wastewater discharge points, the lack of green areas and the difficulties in having direct access to everyday services. Strata 4, 5 and 6, despite accommodating people with higher levels of income and being made up of residential buildings with good quality construction features, are usually also located in peripheral districts outside the city centre. This implies lower compactness and dispersed residential areas with poor direct access both to services (high distances) and also to public transport. This, together with their inhabitants' high levels of income, gives rise to the intensive use of private vehicles, thereby compromising the sustainability of transport. In general, mobility is one of the most critical aspects in the city, also because of the low frequencies and long times spent travelling.

Table 3 Proposal of urban sustainability indicators for Colombia

Code	Type	Description	Unit	Metric	Reference
SS1	QL	Local climatic conditions (temperature, precipitation, wind, humidity, cloudiness)	°C , mm/year, m/s, %, oktas	–	Proposed
SS2	QT	Relationship between built area and total area	%	$\frac{\text{Built area (Ha)}}{\text{Total area (Ha)}}$	Proposed
SS3	QT	Existing Building Reuse (% buildings reused as dwellings)	%	$\frac{\text{\#reused buildings}}{\text{\#total buildings}}$	Based on LEED.41 US GBC (2009)
BIO1	QT	Green area: proportion of green area in relation to total area	%	$\frac{\text{Green area (Ha)}}{\text{Total area (Ha)}}$	Ministerio de Medio Ambiente y Medio Rural y Marino (2010)
BIO2	QT	Green area: green area per inhabitant	m^2/p	$\frac{\text{Green area } (m^2)}{\text{\# inhabitant (p)}}$	Ministerio de Medio Ambiente y Medio Rural y Marino (2010)
BIO3	QL	Urban farming: proportion of urban farming area per inhabitant (on public roads or buildings)	m^2/dw	$\frac{\text{Urban farming area } (m^2)}{\text{\#dwellings}}$	Based on LEED.30 US GBC (2009)
BIO4	QT	Protected green area: proportion of protected green area in relation to the total	%	$\frac{\text{Protected green area (Ha)}}{\text{Total green area (Ha)}}$	Ministerio de Medio Ambiente y Medio Rural y Marino (2010)
BIO5	QT	Ecosystem services: maintained area of strategic ecosystem services	Ha	–	Ministerio de Medio Ambiente y Medio Rural y Marino (2010)
BIO6	QL	Green infrastructure: presence of green corridors and/or integration of greenery in buildings (roofs and façades)	–	–	Proposed

Topic: Site & Biodiversity

QT quantitative, *QL* qualitative; #, number; °C, degree Celsius; %, percentage; *m* metre, *Ha* hectare, *p* person/inhabitant, *dw* dwelling

Table 4 Proposal for urban sustainability indicators for Colombia

Code	Type	Description	Unit	Metric	Reference
URB1	QT	Population density (relationship between the number of registered inhabitants in census and the total area)	p/Ha	$\frac{\#\text{inhabitants (p)}}{\#\text{total urban area (Ha)}}$	SINCHI Instituto Amazónico de Investigaciones cientificas (2003)
URB2	QT	Building density (number of dwellings in relation to the urban area)	dw/Ha	$\frac{\#\text{dwellings}}{\text{Total urban area (Ha)}}$	Based on Ministerio de Medio Ambiente y Medio Rural y Marino (2010)
URB3	QT	Net residential urban area (proportion of land area for permanent housing of people)	%	$\frac{\text{Net residential urban area (Ha)}}{\text{Total urban area (Ha)}}$	Proposed
URB4	QT	Mixed integrated urban area (proportion of urban land and/or expansion for urban projects that combine commercial and service areas)	%	$\frac{\text{Mixed integrated urban area (Ha)}}{\text{Total urban area (Ha)}}$	Proposed
URB5	QT	Residential urban area delimited by commerce and services (proportion of residential land complemented by commercial activities)	%	$\frac{\text{Residential−commercial area (Ha)}}{\text{Total urban area (Ha)}}$	Proposed
URB6	QT	Non-residential area for educational use (relationship between area and number of inhabitants)	%	$\frac{\text{Educational area } (m^2)}{\#\text{inhabitants (p)}}$	Proposed
URB7	QT	Non-residential area for healthcare use (relationship between area and number of inhabitants)	%	$\frac{\text{Healthcare area } (m^2)}{\#\text{inhabitants (p)}}$	Proposed
URB8	QT	Non-residential area for sports use (relationship between area and number of inhabitants)	%	$\frac{\text{Sports area } (m^2)}{\#\text{inhabitants (p)}}$	Proposed
URB9	QT	Non-residential area for leisure use: religious, cultural, commercial, etc. (relationship between area and number of inhabitants)	%	$\frac{\text{Leisure area } (m^2)}{\#\text{inhabitants (p)}}$	Proposed
URB10	QT	Proportion of area for non-residential use (relationship between non-residential area and urban area)	%	$\frac{\text{Non−residential area (Ha)}}{\text{Total urban area (Ha)}}$	Based on Ministerio de Medio Ambiente y Medio Rural y Marino (2010)
URB11	QT	Accessibility of pedestrian walkways (average width)	m	–	Based on LEED.15 US GBC (2009)
URB12	QL	Universal accessibility: existence of traffic lights with sound signals for people with hearing impairment	–	Yes/no	Proposed
URB13	QT	Universal accessibility: proportion of parking spaces for disabled people	%	$\frac{\#\text{parking spaces for disabled}}{\#\text{total parking spaces}}$	Proposed

Table 4 (continued)

Code	Type	Description	Unit	Metric	Reference
URB14	QL	Universal accessibility: existence of ramps on pavements	–	Yes/no	Proposed
URB15	QT	Universal accessibility: proportion of pedestrian bridges with ramps	%	$\frac{\#\text{pedestrian bridges with ramps}}{\#\text{total bridges}}$	Proposed
URB16	QL	Road safety: existence of a road safety plan in the municipality	–	Yes/no	Proposed
MOB1	QT	Private vehicle use: number of vehicles per inhabitant	veh/p	$\frac{\#\text{vehicles}}{\#\text{inhabitants (p)}}$	Proposed
MOB2	QT	Private vehicle use: proportion of dwellings with private vehicles	%	$\frac{\#\text{dwellings with vehicle}}{\#\text{total dwellings}}$	Proposed
MOB3	QT	Daily reduction in time and distances from home to work and services: average daily time per trip on public transport	min/p day	–	Alcaldía de Mosquera (2016)
MOB4	QL	Bicycle use: existence of cycle lanes	–	Yes/no	Based on LEED.9 US GBC (2009)
MOB5	QT	Public transport use: inhabitants who use the public transport system daily	p/day	$\frac{\text{Distance travelled (km)}\cdot\text{passenger(p)}}{\text{day}\cdot\text{km}}$	Proposed
MOB6	QT	Walkable streets: proportion of public roads intended for pedestrians	%	$\frac{\text{Pedestrian area }(m^2)}{\text{Total road area }(m^2)}$	Agencia de Ecología Urbana de Barcelona (2007)
MOB7	QL	Visual status of walkways and roads	–	Tarmacked, gravel or chippings, dirt	Proposed
MOB8	QT	Parking in public spaces: guaranteed parking space (car parks) on public roads	#	$\frac{\text{Total parking area (Ha)}}{\text{Standard area per parking space (Ha)}}$	Proposed
MOB9	QT	Parking on public space: car parks on public roads per private vehicle	#	$\frac{\#\text{car parks}}{\#\text{vehicles}}$	Proposed
MOB10	QT	Private parking: private car parks in closed condominium	#	–	Proposed

Topic: Infrastructure

QT quantitative, *QL* qualitative, #, number; %, percentage; *m* metre, *h* hour, *min* minute, *p* person/inhabitant, *Ha* hectare, *dw* dwelling, *veh* vehicle

Table 5 Proposal of urban sustainability indicators for Colombia

Code	Type	Description	Unit	Metric	Reference
ENG1	QL	Solar gains: optimal orientation of the urban pattern to promote north-oriented building façades	–	Yes/no	Proposed, based on VA.10 AMVA-UPB (2015)
ENG2	QL	Heat island reduction: existence of vegetation in public spaces and green construction solutions in buildings	–	Yes/no	Proposed, based on CP.16 Política Nacional de Edificaciones Sostenibles (2018) and LEED.45 US GBC (2009)
ENG3	QT	Energy efficiency of facilities and monitoring: existence of energy consumption monitoring equipment at urban level	–	Yes/no	VA.52 AMVA-UPB (2015)
ENG4	QT	Renewable energy: intermediate energy acquired and consumed from renewable energy (RE)	MJ	RE = EiAC-NRE	Gaviria (2013)
ENG5	QT	Electric energy supply: proportion of subscribers in relation to the number of dwellings	%	$\frac{\#subscribers}{\#dwellings}$	Proposed
ENG6	QT	Energy consumption: electricity consumption in the municipality	KWh/mth	–	Proposed
WTR1	QT	Water consumption: water supply coverage (relationship between the number of subscribers and the number of dwellings)	%	$\frac{\#subscribers}{\#dwellings}$	Proposed
WTR2	QT	Drinking water consumption	m^3	$\frac{\text{Water consumption}\ (m^3) \cdot \#subscribers}{\text{month} \cdot \text{subscriber}}$	Proposed
WTR3	QT	Rainwater and Wastewater management: sewage discharge points	#	–	Proposed
WTR4	QL	Rainwater and Wastewater management: wastewater treatment system	–	–	Proposed
WTR5	QT	Water quality: IRCA index	%	–	Alcaldía de Mosquera (2013)
MAT1	QT	Low-impact materials: percentage of material from excavation reused on site	%	$\frac{\text{Material from excavation reused}\ (m^3)}{\text{Material from excavation}\ (m^3)}$	Proposed
MAT2	QL	Certified reference materials: materials with SAC, EPD or other label	–	Yes/no	Proposed
MAT3	QT	Reused and recycled materials: reuse of CDW	%	$\frac{\text{CDW reused (T)}}{\text{CDW generated (T)}}$	Proposed
MAT4	QL	Local materials: promote the purchase of local products	–	Yes/no	Proposed

Table 5 (continued)

Code	Type	Description	Unit	Metric	Reference
WST1	QT	Minimizing waste production: relation between recovered waste and generated waste	%	$\frac{\text{Waste recovered (T/month)}}{\text{Waste generated (T/month)}}$	Proposed
WST2	QT	Waste treatment: proportion of users with supply from waste collection system	%	$\frac{\text{\#subscribers}}{\text{\#dwellings}}$	Proposed
WST3	QT	Solid waste generation: fraction of solid urban waste	%	$\frac{\text{Solid urban waste (T/month)}}{\text{Total waste generated (T/month)}}$	Proposed
WST4	QT	Solid waste generation: fraction from street sweeping and cleaning activities	%	$\frac{\text{Cleaning waste (T/month)}}{\text{Total waste generated (T/month)}}$	Proposed
WST5	QT	Solid waste generation: fraction from pruning	%	$\frac{\text{Pruning waste (T/month)}}{\text{Total waste generated (T/month)}}$	Proposed
WST6	QT	Solid waste generation: fraction of CDW	%	$\frac{\text{CDW waste (T/month)}}{\text{Total waste generated (T/month)}}$	Proposed
WST7	QT	Solid waste generation: fraction of special waste	%	$\frac{\text{Special waste (T/month)}}{\text{Total waste generated (T/month)}}$	Proposed
WST8	QT	Solid waste generation: fraction from rural activities	%	$\frac{\text{Rural waste (T/month)}}{\text{Total waste generated (T/month)}}$	Proposed
WST9	QT	Solid waste generation: solid waste generated per capita	kg/p day	$\frac{\text{Total waste(kg/day)}}{\text{\#inhabitants (p)}}$	Proposed
WST10	QT	Solid waste generation: weekly collection frequency	Times/wk	$\frac{\text{\#Times of collection}}{\text{week}}$	Proposed
POL1	QL	Soil pollution: observation of changes in soil aridity	–	Yes/no	Based on CA.28 DAGMA (2019)
POL2	QT	Air pollution: concentration of atmospheric emissions (PM_{10})	µg/m^3	–	Proposed
POL3	QT	Air pollution: concentration of atmospheric emissions (PST)	µg/m^3	–	Proposed
POL4	QT	Air pollution: concentration of atmospheric emissions (SO_2)	µg/m^3	–	Proposed
POL5	QT	Air pollution: concentration of atmospheric emissions (NO_2)	µg/m^3	–	Proposed
POL6	QT	Air pollution: proportion of users who perceive problems in the air quality of their home	%	$\frac{\text{\#Air−polluted dwellings}}{\text{\#Total dwellings}}$	Proposed
POL7	QT	Water pollution: concentration of polluting metals in discharges	mg/l	–	Proposed
POL8	QT	Noise: user's perception of the presence of noise in the home	%	$\frac{\text{\#Noise−polluted dwellings}}{\text{\#Total dwellings}}$	Proposed

Table 5 (continued)

Code	Type	Description	Unit	Metric	Reference
POL9	QT	Light pollution: light pollution caused by public lighting (points replaced by LED luminaires)	#	–	Proposed
POL10	QT	Distance from residential areas to industrial zones	m	–	Proposed

Urban metabolism

QT quantitative, *QL* qualitative, #, number; %, percentage, *kg* kilogram, *mg* milligram, *μg* microgram, *l* litre, *m* metre, *mth* month, *wk* week, *h* hour, *p* person/inhabitant, *MJ* megajoules, *kWh* kilowatt-hours, *EiAC* amount of intermediate energy acquired and consumed from external sources, *NRE* non-renewable energy, *IRCA* index for risk of water quality for human consumption, *SAC Sello Ambiental Colombiano* (Colombia Environmental Label), *EPD* environmental product declaration, *CDW* construction and demolition waste, PM_{10}, inhalable particulate matter; *PST* total suspended particles

Table 6 Proposal of urban sustainability indicators for Colombia

Code	Type	Description	Unit	Metric	Reference
SOC1	QT	Social subsidies: inhabitants with SISBEN level I: 0–44,79	%	$\frac{\#\text{Inhabitants SISBEN I(p)}}{\#\text{ Total inhabitants (p)}}$	Proposed
SOC2	QT	Social subsidies inhabitants with SISBEN level II: 44,79–54,58	%	$\frac{\#\text{Inhabitants SISBEN II (p)}}{\#\text{Total inhabitants (p)}}$	Proposed
SOC3	QT	Social subsidies: inhabitants with SISBEN level III: > 51,58	%	$\frac{\#\text{Inhabitants SISBEN III (p)}}{\#\text{Total inhabitants (p)}}$	Proposed
SOC4	QL	Citizen participation: existence of a citizen participation plan	–	Yes/no	Proposed
SOC5	QT	Civil association: percentage of attendees at the roundtables	%	$\frac{\#\text{attendants (p)}}{\#\text{Total inhabitants (p)}}$	Proposed
SOC6	QT	Civil association: proportion of Community Action Board (Junta de Acción Comunal, JAC) in relation to number of dwellings	%	$\frac{\#\text{ JAC}}{\#\text{ Total dwellings}}$	Proposed
SOC7	QT	Affordable housing: housing rental price	$COP	–	Proposed
SOC8	QT	Affordable housing: housing sale price referred to built area	$\$COP/m^2$	–	Proposed
SOC9	QT	Energy poverty: energy poverty index IPREM	%	–	Aguado and Duque (2013)
SOC10	QT	Education: truancy rate	%	–	Secretaría Distrital de Planeación (2017)

Topic: Social

QT quantitative, *QL* qualitative, #, number; %, percentage; *m* metre, *p* person/inhabitant, *SISBEN* sistema de selección de beneficiarios para programas sociales, *$COP* Colombian peso, *kWh* kilowatt-hours

Table 7 Proposal of urban sustainability indicators for Colombia

Code	Type	Description	Unit	Metric	Reference
ECO1	QT	Employment rate: employment rate of salaried employees	%	–	Secretaría Distrital de Planeación (2017)
ECO2	QT	Employment rate: rate of informal employment (self-employed)	%	–	Secretaría Distrital de Planeación, 2017)
ECO3	QT	Employment rate: general employment rate	%	–	Secretaría Distrital de Planeación (2017)
ECO4	QT	Employment rate: unemployment rate (men)	%	–	Secretaría Distrital de Planeación (2017)
ECO5	QT	Employment rate: unemployment rate (women)	%	–	Secretaría Distrital de Planeación (2017)
ECO6	QT	Tourism: rate of population benefitted by tourism	%	$\frac{\#\text{Inhabitants benefitted (p)}}{\#\text{inhabitants (p)}}$	Secretaría Distrital de Planeación (2017)
ECO7	QT	Quality of employment: proportion of households with primary education	%	$\frac{\#\text{Households primary}}{\#\text{ Total dwellings)}}$	Secretaría Distrital de Planeación (2017)
ECO8	QT	Quality of employment: proportion of households with secondary education	%	$\frac{\#\text{Households secondary}}{\#\text{Total dwellings}}$	Secretaría Distrital de Planeación (2017)
ECO9	QT	Quality of employment: proportion of households with university education	%	$\frac{\#\text{Households university}}{\#\text{Total dwellings}}$	Secretaría Distrital de Planeación (2017)
ECO10	QT	Quality of employment: proportion of households with postgraduate education	%	$\frac{\#\text{Households postgraduate}}{\#\text{Total dwellings}}$	Secretaría Distrital de Planeación (2017)
ECO11	QT	Services costs: cost of electricity consumption	$COP/kWh	–	Secretaría Distrital de Planeación (2017)
ECO12	QT	Services costs: cost of natural gas consumption	$\$COP/m^3$	–	Secretaría Distrital de Planeación (2017)
ECO13	QT	Services costs: cost of water consumption	$\$COP/m^3$	–	(Secretaría Distrital de Planeación, 2017)
ECO14	QT	Services costs: cost of sewage service	$\$COP/m^3$	–	Secretaría Distrital de Planeación, (2017)
ECO15	QT	Average hourly pay for self-employed workers	$COP/h	–	(Secretaría Distrital de Planeación, 2017)
ECO16	QT	Average hourly remuneration received by salaried employees	$COP/h	–	Secretaría Distrital de Planeación, (2017)

Topic: Economic

QT quantitative, *QL* qualitative, #, number; %, percentage; *m* metre, *p* person/inhabitant, *kWh* kilowatt-hours, *h* hour, *$COP* Colombian peso

Table 8 Proposal of urban sustainability indicators for Colombia

Code	Type	Description	Unit	Metric	Reference
MI1	QT	Institutional management: fulfilment of the political objectives	%	–	Alcaldía de Mosquera (2020)
MI2	QT	Process management: fulfilment of the political schedule	%	–	Alcaldía de Mosquera (2020)
MI3	QT	Administrative transparency: municipal administrative transparency index	%	–	Corporación Transparencia por Colombia (2014)
MI4	QL	Knowledge and information management: public participation allowed in tender procedures	–	Yes/no	Proposed
MI5	QL	ICT management: promotion of the use of ICT tools, social networks and web pages according to the needs of the population	–	Yes/no	Proposed
MI6	QL	Investment in activities for society: definition of a programme of activities that integrates the population	–	Yes/no	Proposed
MI7	QL	Environmental education: promotion of environmental education at the institutional and social level	–	Yes/no	Proposed
MI8	QT	Regulations to improve sustainability: schedule activities to mitigate climate change	#	Yes/no	Proposed
IN1	QT	Innovation: promotion of the certification of institutional, commercial and residential buildings with an environmental label (i.e. LEED)	–	Yes/no	Based on LEED.54 US GBC (2009)

Topic: Institutional and innovation

QT quantitative, *QL* qualitative, #, number; %, percentage

Table 9 Results of the metrics of the indicators

Code	M/S	Unit	Mosquera	Stratum 1	Stratum 2	Stratum 3	Stratum 4	Stratum 5	Stratum 6
SS1	S	-	See Table 1						
SS2	S	%	84.40	37.07	94.72	72.89	96.35	71.64	85.33
SS3	M	%	0.00						
BIO1	S	%	4.84	3.25	6.64	9.12	7.81	2.84	7.41
BIO2	S	m^2/p	5.14	2.95	1.39	11.62	(1)	(1)	(1)
BIO3	M	m^2/dw	537.27						
BIO4	S	%	49.64	44.13	0.00	0.00	0.00	0.00	0.00
BIO5	M	Ha	17.23						
BIO6	S	-	yes	no	yes	yes	yes	yes	yes
URB1	S	p/Ha	94.21	297.44	504.84	107.62	1.92	0.7	0.15
URB2	S	dw/Ha	28.93	25.69	65.76	58.83	17.55	2.89	2.46
URB3	S	%	40.53	0.00	0.00	66.66	100.00	100.00	100.00
URB4	S	%	2.23	13.34	0.00	0.00	0.00	0.00	0.00
URB5	S	%	39.14	86.66	100.00	33.40	0.00	0.00	0.00
URB6	S	%	0.250	0.084	0.114	0.772	0	0	0
URB7	S	%	0.056	0.046	0	0.227	0	0	0
URB8	S	%	0.028	0.017	0.015	0.075	0	0	0
URB9	S	%	0.391	0.036	0.258	1.048	0	0	0
URB10	S	%	1.00	0.19	1.57	3.03	0	0	0
URB11	S	m	4.5	3.5	4.7	6.83	4.5	4.5	0
URB12	S	-	yes	no	yes	yes	yes	(1)	(1)
URB13	S	%	0	0	0	0	0	0	0
URB14	S	-	yes	yes	yes	yes	yes	yes	
URB15	M	%	100						
URB16	M	-	yes						
MOB1	M	veh/p	1.22						
MOB2	M	%	5.99						
MOB3	M	min/p·day	45						
MOB4	S	-	yes	no	yes	yes	yes	yes	yes
MOB5	S	p/day	322,099	40,262	60,394	100,656	46,973	33,552	40,262
MOB6	S	%	36.00	31.32	25.70	50.00	15.79	15.79	0.00
MOB7	S	-	3	1	3	3	3	3	3
MOB8	S	#	846	4,894	1,713	1,725	0	0	0
MOB9	M	#	0.073						
MOB10	S	#	4,749	596	1,313	2,492	323	9	16
ENG1	S	-	no	no	no	no	no	no	no
ENG2	S	-	yes	no	yes	yes	yes	yes	yes
ENG3	M	-	no						
ENG5	M	%	85.93						
ENG6	M	KWh/mes	6,555,202.25						
WTR1	S	%	106.27	90.22	96.05	117.07	102.27	(1)	(1)
WTR2	S	m^3	324,936.59	34,625.71	81,204.64	187,817.92	21,288.32	(1)	(1)
WTR3	M	#	4						
WTR4	M	-	(2)						
WTR5	M	%	1.25						
MAT2	M	-	no						
MAT3	M	%	50.00						
MAT4	M	-	no						
WST1	M	%	9.11						
WST2	S	%	100.00	92.37	99.61	112.59	111.34	5.77	25.00
WST3	M	%	84.06						
WST4	M	%	3.32						
WST5	M	%	2.16						
WST6	M	%	4.98						
WST7	M	%	5.18						
WST8	M	%	0.34						
WST9	M	kg/p·day	0.775						
WST10	M	times/wk	3						
POL2	M	$\mu g/m^3$	44						
POL3	M	$\mu g/m^3$	68						
POL4	M	$\mu g/m^3$	59						
POL5	M	$\mu g/m^3$	44						
POL6	M	%	26.60						
POL8	M	%	34.03						
POL9	M	#	2172						
POL10	S	m	340	205	310	277	348	348	549
SOC1	M	%	2.20						
SOC2	M	%	11.24						
SOC3	M	%	9.74						
SOC4	M	-	yes						
SOC5	S	%	3.97	2.95	0.77	3.06	0.00	(1)	(1)
SOC6	S	%	0.19%	0.25	0.33	0.10	0.10	0.00	0.00
SOC7	S	$COP	1,173,000	550,000	580,000	750,000	1,108,000	1,750,000	2,300,000

Table 9 (continued)

Code	M/S	Unit	Mosquera	Stratum 1	Stratum 2	Stratum 3	Stratum 4	Stratum 5	Stratum 6
SOC8	S	$COP	2,840,724	1,080,000	2,000,000	2,062,500	2,620,000	3,170,731	6,111,111
SOC9	M	%	9.13						
SOC10	M	%	5.85						
ECO1	M	%	56.23						
ECO2	M	%	42.86						
ECO3	M	%	11.40						
ECO4	M	%	4.09						
ECO5	M	%	5.69						
ECO6	M	%	74.68						
ECO7	M	%	27.72						
ECO8	M	%	49.55						
ECO9	M	%	5.11						
ECO10	M	%	0.52						
ECO11	S	$COP/kWh	443.32	211.48	264.36	436.80	513.90	616.70	616.70
ECO12	S	$COP/m³	1,189.84	893.17	1,120.50	1,167.00	1,167.00	1,395.70	1,395.70
ECO13	S	$COP/m³	2,708.80	806.80	2,017.00	2,393.50	2,698.40	4,034.10	4,303.00
ECO14	S	$COP/m³	1,799.32	547.10	1,185.30	1,586.60	1,823.60	2,735.50	2,917.80
ECO15	M	$COP/h	4,731						
ECO16	M	$COP/h	4,557						
MI1	M	%	92.70						
MI2	M	%	97.50						
MI3	M	%	77.40						
MI4	M	-	yes						
MI5	M	-	yes						
MI6	M	-	yes						
MI7	M	-	yes						
MI8	M	#	960						
IN1	M	-	no						

M: municipal data; S: data by strata; (1) No data available; (2) Oxidation ponds

Social and economic issues are, however, more developed in strata 1, 2 and 3, where the cost of services and housing are more affordable and citizen association and participation is more active thanks to the Community Action Boards (Juntas de Acción Comunal, JAC), which support neighbourhood development and interaction with the local government. At the institutional level of the city as a whole, it was identified that many sustainability initiatives are being launched, such as the promotion of local employment, the improvement of educational programmes for inhabitants to reduce illiteracy rates and also carrying out environmental awareness campaigns.

Overall, it can be concluded that there is room for improvement in Mosquera, since its level of sustainability ranges from levels 1–2 on a scale of 3. Greater efforts should therefore be made to improve the weaknesses found herein. To do so, the involvement and support of the local government is essential to ensure collaboration between stakeholders and to make a serious commitment towards urban sustainability. However, as concluded from the evaluation of programmes that have previously been implemented and tested, for instance BEA, some limitations during the real implementation of the indicators proposed may be expected, such as the lack of third-party inspection and validation, insufficient support through monetary resources, and the non-mandatory and regular character of the measurement of the indicators (Evans et al., 2018). In order to ensure a successful implementation of indicators, these aspects should be revised, focused and strengthened.

The results of the application of the indicators to the case study of Mosquera are aligned with the results obtained in the studies analysed in the literature review. Mesa García (2021), in the context of Colombia, obtained similar conclusions. She rated the indicators in a scale of three levels (not accomplished, little accomplished, accomplished), and most of indicators were scored as not accomplished or little accomplished. Martínez Vitor (2019) in Peru, who also represented the indicators through spider graphs, obtained low values in a qualitative scale comprised between the levels of collapse, critical and unstable, not being any of them in stable or optimum levels. Moreno García and Inostroza

Seguel (2019) evaluated four different neighbourhoods in Chile and the results denoted that although some aspects such as public transport, proximity to green areas and to recycling points presented high performances, most of the other aspects evaluated showed low or medium performances. In Brazil, Pinedo and Pimentel (2021) developed a numerical global index for evaluating the environmental, social and economic aspects; however, all these indices adopted values lower than 0.50 in a scale from 0 to 1.

6 Conclusions

This paper proposed a methodology for the evaluation of urban sustainability in the context of a country, considering environmental, social, economic and institutional aspects. It was applied to the context of Colombia, and a set of 105 indicators were developed, implemented and tested in Mosquera, a medium-sized city in Cundinamarca which forms part of the metropolitan area of Bogota together with other municipalities. The scale of implementation was the stratum, which allowed to compare different urban areas even in the same municipality. For those quantitative indicators, a metric for calculating them is proposed, along with a three-level scale for both quantitative and qualitative indicators. This would allow all the proposed indicators to be measured objectively and then different urban areas can be compared.

Many of the indicators included in the study could only be measured at the whole city level, limiting the quality of the results. To improve the quality of measurement and to be able go deeper into the comparison of smaller urban areas, there is a need for more publicly available data and information that is disaggregated at a lower level, i.e. the stratum or even neighbourhood level. For instance, the cadastral office can systematically collect socio-economic georeferenced information in order to be mapped easily by means of a geographical information system (GIS).

The methodology proposed in this paper can be applied in any city in Colombia or any other territory and allows the set of indicators to be adapted to the environmental and socio-economic specificities of the region, by modifying some of the indicators included (i.e. adapted to the climatic zone) or including new ones, but maintaining the original hierarchical structure of the topics, categories and subcategories as a reference. The scheme proposed is thus intended to be dynamic and adaptable to the context of the region where the indicators are applied. Additionally, the implementation of the indicators would enable the progress of the city to be analysed and would serve local governments as a tool for measuring and demonstrating to citizens the implementation of urban improvements towards enhanced sustainability, with administrative transparency.

Appendix 1

Tables 10, 11 and 12

Table 10 Results of the scoring method for quantitative indicators implemented by strata in Mosquera, according to Sturges (1926) formula

		Sustainability score		
Code	**Unit**	**Level 1**	**Level 2**	**Level 3**
SS2	**%**	36.95-56.95	56.95-76.95	76.95-97.07
URB1	**p/Ha**	0.265-168.265	168.265-336.265	336.265-504.15
URB2	**dw/Ha**	2.51-23.51	23.51-44.51	44.51-65.46
URB3	**%**	0.17-33.17	33.17-66.17	66.17-99
URB4	**%**	0.22-4.22	4.22-8.22	8.22-12
URB5	**%**	0.17-33.17	33.17-66.17	66.17-99
URB6	**%**	0.13-0.39	0.39-0.64	0.64-0.77
URB7	**%**	0.04-0.11	0.11-0.18	0.18-0.22
URB8	**%**	0.01-0.04	0.04-0.06	0.06-0.08
URB9	**%**	0.2-0.54	0.54-0.87	0.87-1.04
URB10	**%**	0.0033-1.0033	1.0033-2.0033	2.0033-3
URB11	**m**	0.14-2.14	2.14-4.14	4.14-6
MOB5	**p/day**	33552-55920	55920-78288	78288-100656
MOB6	**%**	0-16.83	16.83-33.83	33.83-51
MOB8	**#**	0-1631	1631-3262	3262-4893
MOB10	**#**	9-837	837-1665	1665-2493
BIO1	**%**	2.89-4.89	4.89-6.89	6.89-8.84
BIO2	**m2/p**	1.49-1927.49	1927.49-3853.49	3853.49-5779.39
WTR1	**%**	0-39.02	39.02-78.02	78.02-117
WTR2	**m3**	0-62606	62606-125212	125212-187818
WST2	**%**	5.6-41.6	41.6-77.6	77.6-113.77
POL10	**m**	205.12-320.12	320.12-435.12	435.12-550.3
SOC5	**%**	0.01-1.01	1.01-2.01	2.01-3
SOC6	**%**	0.0005-0.0016	0.0016-0.0027	0.0027-0.0032
SOC7	**$COP**	1716666-2299999	1133333-1716666	550000.2-1133333
SOC8	**$COP/m2**	4434074-6111111	2757037-4434074	1080000-2757037
ECO11	**$COP/kWh**	481.5167-616.48	346.5167-481.5167	211.5167-346.5167
ECO12	**$COP/m3**	1228.92-1397.17	1060.92-1228.92	892.92-1060.92
ECO13	**$COP/m3**	3137-4301.8	1972-3137	807-1972
ECO14	**$COP/m3**	2127.22-2917.2	1337.22-2127.22	547.22-1337.22

Table 11 Reference values of Colombia for quantitative indicators implemented in the whole city of Mosquera

			Sustainability score		
Code	**Unit**	**Reference Value Colombia**	**Level 1**	**Level 2**	**Level 3**
SS3	**%**	0,05	-		+
URB15	**%**	90%	-		+
URB16	**-**	Yes	No		Yes
MOB1	**veh/p**	5,9	-		+
MOB2	**%**	14%	-		+
MOB3	**min/p·day**	46	+		-
MOB9	**#**	0,02	-		+
BIO4	**%**	47%	-		+
BIO5	**Ha**	60	-		+
ENG5	**%**	0,9972	-0,5	>50%	<100%
WTR5	**%**	1%	-		+
MAT3	**%**	0,15	-		+
MAT4	**-**	No	No		Yes
WST1	**%**	17%	-		+
WST3	**%**	0,98	-		+
WST4	**%**	0,045	+		-
WST5	**%**	1%	-		+
WST6	**%**	0,1	-		+
WST7	**%**	0,0769	-		+
WST8	**%**	2%	+		-
WST9	**kg/p·day**	0,63	+		-
WST10	**times/wk**	3	-		+
POL2	**µg/m³**	5000%	+		-
POL3	**µg/m³**	100	+		-
POL4	**µg/m³**	80	+		-
POL5	**µg/m³**	10000%	+		-
POL6	**%**	0,382	+		-
POL8	**%**	0,42	+		-
SOC1	**%**	22%	+		-
SOC2	**%**	0,362	+		-
SOC3	**%**	0,268	+		-
SOC4	**-**	Si	No		Si
SOC9	**%**	0,233	+		-
SOC10	**%**	0,0308	-		+
ECO1	**%**	43%	-		+
ECO2	**%**	0,485	+		-
ECO3	**%**	0,214	+		-
ECO4	**%**	9%	+		-
ECO5	**%**	0,164	+		-
ECO6	**%**	0,66	-		+
ECO7	**%**	15%	-		+
ECO8	**%**	0,232	-		+
ECO9	**%**	0,08	0	<8%	>8%
ECO10	**%**	3%	-		+
ECO15	**$COP/h**	3657,51	-		+
ECO16	**$COP/h**	3785,52	-		+
MI1	**%**	100%	-		+
MI2	**%**	1	-		+
MI3	**%**	0,745	-0,5	>50%	<100%
MI4		Yes	No		Yes
MI5		Yes	No		Yes
MI6	**-**	Yes	No		Yes
MI7	**-**	Yes	No		Yes
IN1	**-**	Yes	No		Yes

Table 12 Scoring method for qualitative indicators implemented in Mosquera

		Sustainability score		
Code	**Unit**	**Level 1**	**Level 2**	**Level 3**
URB12	-	No		Yes
URB14	-	No		Yes
MOB4	-	No		Yes
MOB7	-	Dirt	Gravel or chippings	tarmacked
BIO6	-	No		Yes
ENG1	-	No		Yes
ENG2	-	No		Yes

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