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The development of a grey relational analysis-based composite index for environmental sustainability assessment: Towards a net-zero emissions strategy in Saudi Arabia

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A B S T R A C T

Climate change and environmental sustainability assessment are essential in city planning, design, and smart city advancement. Despite Saudi Arabia's high global greenhouse gas (GHG) emissions ranking, a comprehensive review of extant studies revealed insufficient tools enhancing the policymaking and comprehension of climate change and environmental performance. This paper developed a hybrid green city index (GCI) and grey relational analysis (GRA) composite index for appraising national environmental sustainability via a robust, efficient, effective, and replicable grading process. The index is designed based on two primary considerations. The first is the selection of quality underlying indicators/categories, while the second is the adoption of GRA for conducting the normalization, weighting and aggregation process. These two considerations influenced the proposed composite index, which was later applied to Saudi Arabia as a study area. The results revealed that the environmental sustainability of Saudi Arabia is not significant, with the most outstanding of 0.3127 for 2010. At the category level, the favourable environmental sustainability ranking is between the 2010 and 2012 assessment period, with a gradual decline till 2018. This study's findings are unique as no studies within the context of Saudi Arabia and the Gulf region have utilized this study's research approach. Although not all indicators of the proposed index were used in the study area, this study's methodology and outcomes have the beneficial impact of assisting Saudi Arabia's decision-makers across the cities in monitoring the status and progress of implementing its net zero carbon emissions by 2060.

1. Introduction

Sustainable development assessment is a buzzword that has recently captured the attention of scholars, technocrats, government officials, private institutions, nonprofit organizations, and politicians across the globe. However, while there are a plethora of studies covering the impacts of economic and social dimensions of sustainable development, there is a need for more studies focusing on environmental sustainability and climate change mitigation strategies.

Climate change has a catastrophic impact on the earth [1,2]. An extant study argues that climate change expressed in increasing temperature and humidity can be linked to the intensity and frequency of natural effects, which directly and indirectly impact human

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health and well-being [3]. Also, a correlation exists between climate change and physical activities [4]. As such, hot-humid weather will likely reduce human performance in outdoor activity, thus putting humans at risk of diseases and health issues [4]. The trouble is expected to be higher for those in the desert and semi-arid climatic regions such as Saudi Arabia. In ensuring smart, sustainable cities with carbon neutrality, recent studies revealed the importance of innovative solutions and technologies in the energy, transport, water, and food sectors without neglecting social inclusiveness and citizens' participation in achieving the 11th goal and targets of the sustainable development goals (SDGs) [5].

Within the past two decades, studies within the field of the built environment have concentrated on sustainable cities with policies prioritizing climate change actions. However, analyses of environmental-dimension indicators sustainability appraisal of nations within the Middle East and North Africa (MENA) and the Gulf region have declined. Also, SDGs and the fight against climate change are not always aligned, and in some cases, the requirements contradict each other [6]. Recently there have been a lot of lobbies and advocates promoting the fight against climate change and its consequences to the globe. Quebec City in Canada adopted two GHG reduction plans to (i) reduce 60 kilotons (kt) CO_2 equivalent from 2004 to 2010 and (ii) achieve 23 kt CO_2 equivalent from 2011 to 2020 [7]. Singapore's Green Plan, on the other hand, aims to halve its GHG emission by 2050, where the plan involves serious measures to transform the transportation sector, reduce waste, and increases accessibility to green spaces across the country [8].

Countries worldwide have been addressing climate change and adopting measures to mitigate and reduce its effects for decades. Countries like Germany have been adopting energy-saving measures to improve power use and efficiency while protecting the environment through policies and regulations [9]. However, maximizing the efforts through an integrated approach among countries is essential. The Kyoto Protocol was embraced in December 1997 as a tool to commit countries and economies to reduce GHG emissions based on predefined targets [10]. The Paris Agreement on climate change resulted from the UN Climate Change Conference in Paris in December 2015. As a result, 192 parties have agreed on three goals to tackle climate change which are (i) limit temperature rise to 2° Celsius, (ii) revise commitments of countries to reduce emissions every five years, and (iii) support developing countries in mitigating climate change financially [11].

In actualizing these goals, Saudi Arabia has officially joined the fight against climate change by joining the Paris Agreement [12]. The Saudi aspiration is to gradually reduce emissions until reaching net-zero emissions by 2060 [13]. The net-zero carbon emission target is scheduled through the carbon circular economy approach, which follows the reduce, reuse, recycle, and remove strategy [13, 14]. The 2020 National Transformation Program and Vision 2030 set a course for the country to achieve sustainable development. This course is evident in an extant study that revealed evidence of a sustainable approach to Saudi Arabia's visions and programs [15]. Since 2016, Saudi Arabia has pursued initiatives to increase awareness and promote green development (covering several initiatives, programs, strategies, and summits) across the country [16]. While measurements of those initiatives are unclear or have not been achieved yet, the inclusion of sustainable and green development can be noticed at all levels of the public and private sectors.

Despite the country's efforts to curb carbon emissions to net zero by 2060 and adopt environmental controls in its pursuit of a green development pattern, a comprehensive review of extant literature via Scopus and Google Scholar revealed the absence of a comprehensive appraisal framework or existing measures that addressed or identified the status and progress of sustainability/green development across Saudi Arabia. As the Kingdom of Saudi Arabia is galvanizing actions toward long-term carbon neutrality by 2060, the research question (RQ) of this paper is:

RQ: What is the status and progress of the environmental dimension of sustainability across Saudi cities?

Besides, the country has recently announced an ambitious plan to transform its capital into one of the world's most sustainable cities [17]. Such ambition requires a considerable investment in resource utilization and infrastructure, in addition, to reshaping the policies and regulations toward achieving more sustainable development within the city and the entire country. While it is too early to judge the success of the capital city's sustainability strategy, it is crucial to understand and gauge the country's sustainability level across many of the available sustainability rating tools and programs. Therefore, the objectives of this paper are to.

i. Comprehensively review an extant index and its corresponding indicators for environmental sustainability assessment indicators
ii. Propose a hybrid GCI and GRA composite index
iii. Assess the Kingdom of Saudi Arabia based on available data via the proposed composite index

To achieve the purpose of this paper while addressing the identified knowledge gaps, a composite index based on combined GRA and GCI was proposed. After that, the proposed composite index was tested for its efficient implementation in Saudi Arabia for nine years (2010–2018). The test running of the proposed index based on an assessment period of nine years constitutes one of the study's limitations because the variations of indicators during 2010–2018 may be influenced by inter-annual to inter-decadal variabilities. Nonetheless, the impact of this limitation is minimal due to the strength of GRA in generating a good outcome with a limited dataset without undermining normal distribution. Recent studies on carbon neutrality in Saudi Arabia also utilized data that ended in 2018 [18] and 2019 [19]. However, there is a need for future research to extend the assessment period longer to adapt to the climate change assessment.

Several extant studies have been conducted in different parts of the world with diverse outcomes and strategies towards net-zero emissions. However, recent studies [18,19] revealed a continuous increase in CO_2 and GHG emissions in Saudi Arabia's atmosphere. Therefore, to provide a pragmatic resolution to the identified knowledge gaps, a novel research approach was developed and test run to advance that of the European GCI that utilizes the normalization technique. The current research's importance, relevance, and contributions to state of the art are as follows: (i) formulation of sustainable and smart policies and regulations based on the findings/outcomes to shape Saudi's future to achieve its aspiration of becoming one of the most sustainable countries in the world, (ii) a template/solution for monitoring sustainability status and mitigating climate change in the MENA and Gulf region. This study proposed and tested a composite indicator index due to the challenges and inaccuracies of assessing an individual indicator.

The structure of this paper is as follows. A literature review of the existing studies highlighting the identified gaps is contained in **Section 2**. **Section 3** illustrated the research approach and the novel composite index development discussion. This methodology/framework development illustration is followed by the results/case study application and the discussion in **Sections 4** and **5,** respectively. The conclusion is highlighted in **Section 6**.

2. Literature review

2.1. The green city index

Different frameworks for assessing urban, national, or regional sustainability ranking exists. This study adopted the GCI (developed as a research project between the Economist Intelligent Unit and Siemens). The GCI adoption is due to its alignment with this study's aim to assess environmental sustainability issues using a tool that would enable compiling indicators into a single index, ranking indicators and sharing best practices [20]. However, the index has been criticized by a scholar in extant literature [21]. The scholar criticized the approach of pushing standardized information to the end users, where the selection and weighting of indicators may differ from one reader to another. Thus they should vary across readers. Other researchers highlighted a potential problem with the GCI ranking system [22]. They noted that depending on the methodology used and weights of indicators, a city might score high in the European GCI while ranking low in another ranking or rating system [22]. The current study advanced the GCI technique and methodology to address these criticism and knowledge gaps. The following sub-section presents a comprehensive literature review of existing studies conducted based on GCI.

2.2. Extant studies that utilized the green city index

In September 2022, the authors conducted a comprehensive desktop systematic literature review via the Scopus database to identify and study extant studies that utilized GCI. The selection of the Scopus database was because of its extensive publication coverage. While a document written in Chinese is excluded, the summary of the identified studies is contained in Table 1. The review's outcome revealed this study's need/value/originality. Regarding the country/territory of the extant studies, none originate nor utilize GCI for environmental sustainability assessment within Saudi Arabia or the Gulf region. Three studies are affiliated with Egypt, which is geographically close to Saudi Arabia. However, upon critically evaluating these publications, the following information was extracted.

In an attempt to develop a comprehensive green city assessment framework, scholars from Port Said University and Suez Canal University review selected appraisal tools that entail the GCI [25]. On the other hand, a Cairo University professor conducted a study examining some GCI-based rated cities while focusing on selected concepts [36]. This examination was followed by applying the appraisal outcome in a chosen city in Greater Cairo to compare urbanism concepts and selected indicators. Likewise, three scholars from Mansoura University, Cairo University, and Mansoura Higher Institute for Engineering and Technology utilized the African version of the GCI in three selected Egyptian cities to assess their environmental performance toward mitigating adverse environmental impacts [30]. However, none of these extant studies utilized a technique that considered the correlation among the selected environmental sustainability indicators for establishing a composite index. In ensuring novelty and advancement within

Table 1
A summary of GCI-based Extant studies. Prepared by the Authors.

Document Type	References	Year	Action
Book Chapter	[23]	2022	Sustainability appraisal and comparison between six selected cities via GCI.
Article	[24]	2021	GCI utilization outcomes in Panama City for conducting problem-based research approach, regeneration model, SWOT analysis and a questionnaire survey
Article	[25]	2021	A comparative review of seven extant sustainability appraisal tools that include the GCI.
Conference paper	[26]	2020	City sustainability assessment via (Asian) GCI
Book Chapter	[27]	2019	Analysis of various global sustainability initiatives and the GCI.
Article	[28]	2019	No usage, just mentioned in the Abstract
Article	[29]	2018	Not utilize, just mention
Article	[30]	2017	African GCI utilization for environmental assessment of three young Egyptian cities
Conference paper	[31]	2017	Not utilize, just mention
Article	[32]	2017	Utilized for the ranking and classification of selected cities in Hungary with a particular focus on social and environmental pillars
Article	[33]	2015	Various indices, including the GCI, were selected for correlation analysis of the Blue City Index and Trends and Pressure Index.
Article	[34]	2014	Development of an Index that used selected GCI indicators and another ranking tool.
Article	[35]	2014	An assessment of the relationship between four selected indices in the United States of America (USA), including the GCI.
Article	[22]	2014	A critical review of six indices that include the GCI

environmental sustainability appraisal towards carbon neutrality, there is the need for a hybrid framework with analysis of the grey area between selected indicators. The following sub-section briefly reviews one technique known as the grey relation analysis.

2.3. Grey relation analysis

Among the various multi-criteria decision-making techniques, not too many have been utilized by scholars in extant literature for national, regional or city sustainability appraisal from a complex grey system perspective. The GRA was first formulated in the early 1980s and was a broadly utilized weighting method for appraising the correlation and interconnections between variables [37–39]. The advantage of this method lies in its strength of generating a good outcome with a limited dataset without undermining normal distribution [40]. The pragmatic utilization of the model in extant studies includes but are not limited to ranking sustainable development strategy [41], sustainable urban development [38], and sustainability performance [42]. In this study, the GRA was incorporated into the design of the proposed framework and composite index for computing the grey relational degree matrix (i.e., the correlation between the selected case study and the selected indicators based on the available dataset). Unlike other extant indicator weighting methods, the utilization of this framework and composite index is moderately straightforward and uncomplicated.

2.4. Towards a carbon neutrality in Saudi Arabia and the need for a composite index

Saudi Arabia houses the headquarters of the Gulf Cooperation Council (GCC) nation and is located at coordinates 23.8859° N and 45.0792° E. Nearly 35 million people live within an area of 2.2 million km^2. Within the last 100 years, the nation's capital city, with an area of one km^2, has developed to become one of the most crowded cities in the world. Saudi Arabia has been the center of rapid development in the GCC and MENA. The country has championed several environmental sustainability strategies to make urban planning sustainable, such as the Saudi and Middle East green initiatives. Therefore, Saudi Arabia's smart and sustainable city planning, design, and growth are essential to the nation's climate change mitigation approach. Recently, the country launched Riyadh Sustainability Strategy, which includes 68 initiatives covering five main sectors [17]. These key sectors are (i) air quality, (ii) water management, (iii) waste management, (iv) natural areas and biodiversity, and (v) energy and climate change.

The strategy intends to transform the nation's capital into one of the most sustainable cities in the world by the year 2030 [17]. The plan will help achieve SDGs through water recycling, a shift toward public transportation, halving the production of CO_2 emissions, as well as a massive investment in renewable energy, which is expected to meet 50% of the city's energy demand. On the other hand, the green initiative executed by Riyadh city is planned to increase the green spaces to reach 541 km^2, including the plantation of 7.5 million trees across the city.

Although the strategy is not yet finalized, its main features are as follows: (i) an increase in the population's use of public transit from 5% to 20%, i.e., of all vehicles on the road, 30% will be electric by 2030, (ii) fifteen million trees are to be planted in Riyadh, i.e., 1.7 m^2–28 m^2 increase in per capita share of green space within the city center, (iii) increase water recycling from 11% to 100%, (iv) reduce carbon emissions by 50% with an annual reduction of 1.5 million tons of GHG emissions, (v) deliver enough renewable energy to meet 50% of the city's needs, and (vi) reduce the demand for landfills and recycle 94% of waste into energy. As such, the country needs a climate change strategy and an environmental-dimension sustainability appraisal. Notwithstanding, national sustainability appraisal is embedded with the potential to assist governmental and non-governmental decision-makers. This assistance could be in the form of guiding the monitoring of innovative, sustainable projects to ensure quality lifestyle and livability of the populace.

2.5. Extant studies towards net-zero emissions in Saudi Arabia

The preceding sub-sections revealed the relevance, criticism and existing studies that utilized the GCI. The above discussion revealed the absence of studies based on the GCI procedure and complex grey system perspective in Saudi Arabia. The need for a composite indicator index was also established due to various initiatives and strategies currently being implemented that deserve monitoring and evaluation. In line with this study's objectives and research question, a comprehensive review of extant studies aimed at ensuring Saudi Arabia's vision 2060 net zero emissions was conducted. In 2020, two scholars from the University of Jeddah assessed the effect of CO_2 emissions in Saudi Arabia [18]. Data such as CO_2, education, GDP, governance effectiveness, industrialization, oil consumption, and regulatory quality of Saudi Arabia were extracted from the World Development Indicators for a timeline of 1970–2018. The ordinary least square and quantile regression was employed for in-depth analysis and accurate outcomes reflecting their study's aim. The study's significant findings revealed that efficient governance in Saudi Arabia decreases CO_2 emissions.

In 2022, scholars from Saudi Electronic University and the University of Jeddah conducted a collaborative study to understand the correlation between life expectancy and CO_2 emissions in Saudi Arabia [19]. The extracted data between 1996 and 2019, ranging from governance indicators and population to CO_2, were collected from the World Development Indicators. The autoregressive distributed lag estimation technique and tests such as (i) Zivot and Andrews Unit Root Test and (ii) Cointegration Test were utilized to assess the impacts of the selected indicators in ensuring net-zero emissions in Saudi Arabia. The outcomes are slightly similar to the previous study, with few astonishments. Recently, similar research was carried out with data on the tech industry [43]. All these studies have been conducted with various aims and objectives targeted towards net zero emissions in Saudi Arabia. However, there is a knowledge gap in the literature regarding developing a composite indicator index with a complex grey system that monitors or assesses the status and progress of the environmental dimension of sustainability across Saudi cities. To bridge this identified knowledge gap, (i) a framework was proposed, (ii) indicators selection criteria and a novel hybrid GCI and GRA composite index were developed as contained in the methodology section.

3. Methods

The indicator weighting techniques utilized in diverse sustainability frameworks, indexes, or tools are developed to meet the nature of their selected variables [44]. The incident and circumstances of sustainability indicators linkages, interconnection, and interrelationships are prevalent in many countries [45]. In answering the research question (i.e., what is the status and progress of the environmental dimension of sustainability across Saudi cities?), this study concentrates on identifying GCI quantitative indicators and, after that, compiling them into a single index applicable to the national context of Saudi Arabia based on the GRA stages of (i) grey relational generating, (ii) grey relational coefficient calculation, and (iii) grey relational grade calculation. Therefore, considering the interrelationship between selected GCI indicators via weighting techniques is pertinent [46] and in line with this study's aim. This study's proposed framework/novel composite index advances the GCI that utilizes the normalization technique (involving max-min for quantitative indicators and scoring the qualitative indicators by the Index's in-house analysts) [47]. Fig. 1 illustrates the proposed framework.

3.1. Developing composite index for national context

A composite indicator/index is an assemblage of all utilized categories, aims, independent/discrete indicators and variables [48]. This means the conventional definition of a composite indicator signifies a "set of properties underlying its aggregation convention" [49]. A composite indicator is established, after which independent social, economic or environmental indicators are put together into a single index based on an implicit/inherent framework. All things being equal, a composite indicator is designed to appraise complex/multifaceted/intricate/complicated phenomena with difficulty being assessed by an individual indicator.

There are several relevances of composite indexes, such as (i) benchmarking urban/city or national performance, (ii) statistical aggregate for change measurement, (iii) implication of interpretation, and (iv) all-inclusive/broad visualization for policymakers. Other benefits of composite indices include but are not limited to (i) measurement of either qualitative or quantitative indicators from reliable sources for comparative analysis and (ii) interpretation of urban, national, or regional trends. An excellent composite index is characterized by its specificity, robustness, efficient measurement, essential indicators capturing effectiveness, relevance etc. [48].

As such, a composite index can generate results and outcomes with insights that could be used for formulating urban or national sustainability policies with climate change mitigation strategies. Moreover, environmental-dimension indicators were collected from GCI and integrated into the established composite index to derive quantitative data related to climate change and environmental sustainability appraisal within the national context of Saudi Arabia. In this study, extant studies [50–52] are adapted to develop the novel composite index while maintaining all the required elements/steps of designing a composite index by the European Commission.

3.2. Indicators selection criteria

To achieve the first study objective (i.e., comprehensively review an extant index and its corresponding indicators for environmental sustainability assessment indicators), this study adopted the European GCI indicators for environmental sustainability performance measurement [47]. Thus, this study differs from extant studies [50–53] assessing the sustainability of their selected cities using different sets of indicators. It also differs from recent studies on carbon emission minimization and carbon neutrality in Saudi

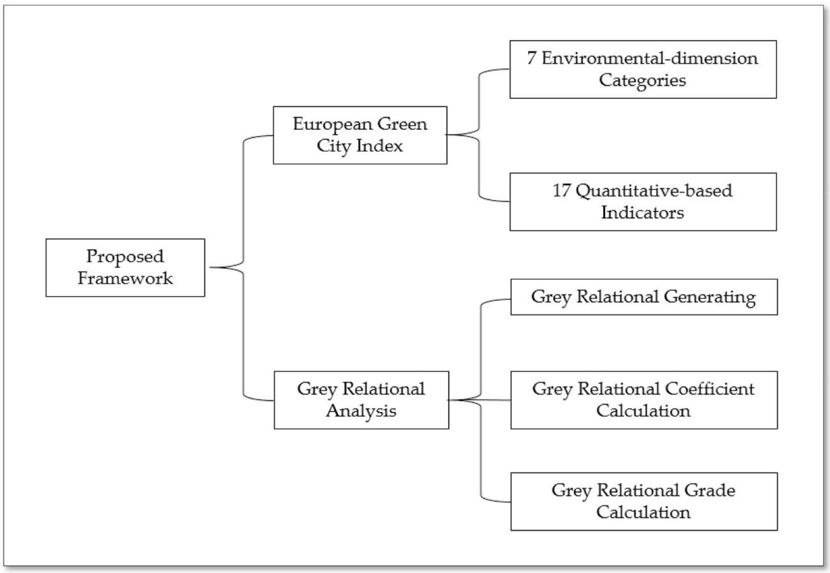

Fig. 1. The flowchart of the proposed framework. Source: Authors (2023).

Arabia, which primarily focuses on governance indicators [18,19]. The European GCI considers 30 indicators (both quantitative and qualitative) into eight categories. The indicators of the GCI were utilized in this study because more than 120 cities in Europe, the USA, Canada, Latin America, Africa, and Asia were measured using the index [20]. As such, they provided insight into the strengths and weaknesses of individual countries while ranking them according to their performance in environmental sustainability. However, the utilization of these indicators within MENA and the Gulf region is missing in the existing literature.

In this proposed framework, there were a total of 17 indicators grouped under seven categories due to the exclusion of the GCI qualitative indicators. For instance, the following indicators were excluded due to qualitative indicators criteria: (i) clean and efficient energy policies, (ii) energy-efficient buildings standards, (iii) energy-efficient buildings standards, (iv) green transport promotion, and (v) congestion reduction policies underneath the GCI categories of CO_2, "Energy", "Building" and "Transport". Likewise, indicators such as (i) Waste reduction policies, (ii) Green land use policies, (iii) Water efficiency and treatment policies, and (iv) Clean air policies underneath the GCI categories of Waste and land use, Water, and Air quality were also excluded because of the qualitative exclusion criteria. Contrastingly, all indicators that fall under the "environmental governance" category, which are (i) Green management, (ii) Green management, and (iii) Public participation in green policy, were qualitative.

3.3. Grey relational analysis – normalization, weightage and aggregation

To achieve the second study objective (i.e., propose a hybrid GCI and GRA composite index), this section presents the data analysis/computation/calculations involved in arriving at the sustainability appraisal outcome. The following steps illustrate the data analysis and its justifications. To appraise environmental sustainability towards mitigating climate change, one must first ascertain the selected indicators' weights by examining the correlation between them [50–52]. After the computation, the higher weight will be allocated to the indicators with higher correlation and vice versa. This study proposes the GRA technique for determining the correlation between the selected indicators. The fundamental theme of the GRA is ascertaining the closeness level via the similarity degree of reference series/sequence in addition to other comparison series/sequences. To ensure that the proposed framework assessment outcome reflects linear and nonlinear relationships, the geometry-based GRA technique was adopted [38,54] for computing the grey relational degree matrix. The GRA evaluation techniques and procedure for arriving at this study's desired objective are based on the following steps [52,55,56].

Step 1: Grey Relational Generating: This step could also be referred to as data pre-processing. Here, the overall procedure is similar to normalization [57] in which all the selected indicators in various units are within the range of [0, 1] to ensure uniform comparison.

This initial uniform value is derived using the following equations.

$$x_{ij} = \frac{y_{ij} - Min\left\{y_{ij}, i = 1, 2, \ldots, m\right\}}{Max\left\{y_{ij}, i = 1, 2, \ldots, m\right\} - Min\left\{y_{ij}, i = 1, 2, \ldots, m\right\}} \text{ for } i = 1, 2, \ldots, m \; j = 1, 2, \ldots n \tag{1}$$

$$x_{ij} = \frac{Max\left\{y_{ij}, i = 1, 2, \ldots, m\right\} - y_{ij}}{Max\left\{y_{ij}, i = 1, 2, \ldots, m\right\} - Min\left\{y_{ij}, i = 1, 2, \ldots, m\right\}} \text{ for } i = 1, 2, \ldots, m \; j = 1, 2, \ldots n \tag{2}$$

In this study, equation (1) is utilized to obtain the values of these beneficial indicators (see Table 2) because the larger their value, the better for the study area in ensuring sustainability and corresponding climate change mitigation. However, in calculating the value of the study's selected non-beneficial indicators (see Table 2), whereby the smaller their values, the better for the study area's quality of life, equation (2) is utilized.

Step 2: Grey Relational Coefficient Calculation: The closeness between the selected GCI indicators was determined at this step.

Table 2
The index categories and their underlying indicators, units, and environmental impacts. Prepared by the Authors.

Category	Indicators	Unit	Beneficial/Non-beneficial
Air quality	Nitrogen dioxide (NO_2)	Yearly daily average	Non-beneficial
	Sulphur dioxide (SO_2)	Yearly daily average	Non-beneficial
	Ozone (O_3)	Yearly daily average	Non-beneficial
	Carbon monoxide (CO.)	Yearly daily average	Non-beneficial
Buildings	Energy consumption of residential buildings (*E*-CRB)	Per m^2	Non-beneficial
CO_2	CO_2 emission (E-CO_2)	Tonnes/head	Non-beneficial
	CO_2 intensity (I–CO_2)	Grams/real GDP	Non-beneficial
Energy	Energy consumption (EC)	Gigajoules/head	Non-beneficial
	Energy intensity (EI)	Mega joules/real GDP	Non-beneficial
	Renewable energy consumption (REC)	% in terajoules	Non-beneficial
Transport	Use of non-car transport (UNT)	%	Beneficial
	Size of non-car transport network (*S*-NTN)	Km/m^2	Beneficial
Waste and land use	Municipal waste production (MWP)	kg/head	Non-beneficial
	Waste recycling (WR)	%	Beneficial
Water	Wastewater treatment (WT)	%	Beneficial
	Water System Leakages (WSL)	%	Non-beneficial
	Water consumption (WC)	m^3/head	Non-beneficial

Here, a larger grey relational coefficient signifies a relative closeness between the indicators (i.e., x_{ij} and x_{oj}). The grey relational coefficient calculation value is derived using equation (3) in this study [58].

$$\gamma(x_{0j}, x_{ij}) = \frac{\Delta_{min} + \zeta\ \Delta_{max}}{\Delta_{ij} + \zeta\ \Delta_{max}} \text{ for } i = 1, 2, \ldots, m\ j = 1, 2, \ldots n \tag{3}$$

Where $\gamma(x_{0j}, x_{ij})$ represents the grey relational coefficient that exits between x_{ij} and $x_{0j}\Delta_{ij} = |x_{0j} - x_{ij}|$ represents the deviation sequence$\Delta_{min} = Min\{\Delta_{ij}, i = 1, 2, \ldots, m; j = 1, 2, \ldots n\}\Delta_{max} = Max\{\Delta_{ij}, i = 1, 2, \ldots, m; j = 1, 2, \ldots n\}\zeta$ represents the distinguishing coefficient, $\zeta \in [0, 1]$

The ζ is utilized for the enlargement or the compression of the grey relational coefficient range. In this study, a value of ζ as 0.5 was utilized based on extant studies [50,55].

Step 3: Grey Relational Grade Calculation: Upon obtaining the grey relational coefficient values, the calculation of the grey relational grade [57] in step 3 is carried out using equations (4) and (5) below.

$$\Gamma(X_0, X_i) = \sum_{j=1}^{n} w_j \gamma(x_{0j}, x_{ij}) \text{ for } i = 1, 2, \ldots, m \tag{4}$$

$$\Gamma(X_0, X_i) = \frac{1}{n} \sum_{j=1}^{n} w_j \gamma(x_{0j}, x_{ij}) \text{ for } i = 1, 2, \ldots, m \tag{5}$$

In equation (5), n represents the summation of the assessment period, i.e., nine years in this study. w_j represents the weights of the selected indicators. In most studies, the values of w_j are based on the opinion of the scholars or policymakers conducting the analysis. Likewise, these weighting values could be derived based on convenience or available weighting techniques to the appraisal decision-makers. In this study, the weights from the European GCI [47] were adopted for obtaining the weightings' value.

Finally, the GRA has been utilized by scholars [59–65] in diverse research areas and sectors. The GRA utilization ranges from system restoration, marking inspection, optimization [66], organization performance [58], relationship [67], simulation, and assessment. However, studies that utilized this method in its direct approach or hybrid format for national sustainability performance, grades or ranking are rare in the Gulf region.

4. Results

The following sections present the study's outcomes in line with the research question (i.e., what is the status and progress of the environmental dimension of sustainability across Saudi cities?) and the third objective (i.e., assess the Kingdom of Saudi Arabia based on available data via the proposed composite index).

4.1. Hybrid GCI-GRA composite index

One of the aims of this proposed tool is the drive towards a paramount remedy to the challenges of climate change and related environmental impact. This aim is actualized via the identification of seven categories which are (i) air quality, (ii) buildings, (iii) CO_2, (iv) energy, (v) transport, (vi) water, and (vii) waste and land use. These seven categories were extracted from the GCI based on the quality/relevance/analytical soundness of their underlying indicators to this study's objectives and the availability of quantitative-based indicators.

The first category is "air quality". This category concentrates on exponentially reducing pollution, poisonous emissions and particles with adverse climatic and environmental effects. As contained in Table 2, there are four underlying indicators in the index under this category. The second is "buildings". There is only one indicator underneath this category with emphasis on the climate and environmental impacts of residential structures within the selected national context. The third category is "CO_2". Here, two indicators focus on the number of released emissions into the atmosphere based on the individuals in the selected nation's gross domestic product (GDP). The fourth is "energy". Underneath this category are three indicators focusing on the chosen national context based on individuals, real GDP and percentages. The fifth category is "transport". To mitigate the change effect and negative environmental impact within a selected study area, two underlying indicators in this category concentrate on the distance the working-class populace covers in percentages/km. The next category is "water". This category has three indicators for measuring and rating environmental performance in cubic meters/percentages—lastly, the "waste and land use" category. Here, two underlying indicators are assessed based on individuals within a national context in kg and percentages.

The proposed index's outcome also revealed four beneficial and 13 non-beneficial indicators (see section 3.3). Based on steps 1–3 and equations (1)–(5) in section 3.3, the proposed composite index is depicted in Fig. 2 below.

4.2. Application to Saudi Arabia

This section addresses the third research objective (i.e., assess the Kingdom of Saudi Arabia based on available data via the proposed composite index). Based on one of the identified knowledge gaps (climate and environmental performance tools utilization lag) in the extant literature, Saudi Arabia was chosen as this article's study area. In assessing the sustainability status of Saudi Arabia, the indicators from the proposed index were used to measure the nation's performance [47]. Thus, this study differs from extant studies [50–53] assessing the sustainability of their selected cities using different sets of indicators. However, after the completion of the data collection phase, there were a total of 14 indicators grouped under seven categories (see Table 3) due to the (i) non-availability of substantive data for sustainability analysis and (ii) missing data or data availability in the Arabic language for the study's sustainability assessment period.

Regarding the non-availability of substantive data for sustainability analysis, two indicators (i.e., (i) renewable energy under the Energy category and (ii) water system leakages under the water category) were excluded. According to the Saudi General Authority for Statistics, based on the information gathered from the Saudi Electricity and Cogeneration Regulatory Authority, the Percentage of energy consumption for electricity are from (i) crude oil, (ii) diesel, (iii) heavy fuel oil, and (iv) natural gas [69]. Although, as of 2020, 13 National Renewable Energy Program projects were generating 4,870 MW with a projection of an annual 15, 108, 701 MWh by 2024 [78]. Likewise, there are extant studies with estimations on water loss in the distribution systems in some selected parts of Saudi Arabia [79,80], but the data are not substantive. Lastly, concerning the indicator (i.e., use of non-car transport underneath the Transport category), the percentage of the annual passenger travelling via public transportation is partly provided by the Saudi Public Transport Company (SAPTCO) in English and Arabic. Therefore, this indicator's data is unsuitable for this study's analysis.

The selected indicators are symbolic because they appraise diverse components of a nation's environmental sustainability with a corresponding impact on climate change. For instance, indicators concerning CO, CO_2, NO_2, O_3, SO_3 emissions, energy and water consumption, waste generation and recycling were utilized to appraise the study area's environmental sustainability. Unlike the European GCI, certain adjustments were made to the selected indicators based on the context of Saudi Arabia's available data. In Table 3, under the air quality category, the indicator "particulate matter," measuring the yearly daily average of PM^{10} emissions, is replaced with "carbon monoxide". As for the indicator "energy consumption of residential buildings", Gigawatt/Hour (GWH) was adopted rather than the GCI energy consumption per m^2 of residential floor space. Under the CO_2 category, "Kilotons" and "Metric Tons per Capita" was the adopted units rather than the GCI units of "total CO_2 emissions, in tonnes per head" and "total CO_2 emissions, in grams per unit of real GDP (2000 base year)" for "CO_2 emission" and "CO_2 intensity" simultaneously.

Regarding the indicators, i.e., (i) energy consumption and (ii) energy intensity underneath the Energy category, GWH and Kwh were adopted instead of "energy consumption, in gigajoules per head" and "megajoules per unit of real GDP" provided in the European GCI. Concerning the indicator "Size of non-car transport network" in km/m^2 of city area, the authors used data on the length of completed paved roads in km. Also, unlike the two indicators (i.e., (i) "municipal waste production" in kg/head and (ii) "waste recycling" in Percentage) under the Waste and land use category, this study utilized the per capita daily waste generation in kg, and industrial waste disposal with the unit in Ton per year in one of the study area's industrial cities. Finally, for the two indicators (i.e., (i) waste consumption and (ii) wastewater treatment) underneath the water category, in this study, a summation of Water consumption from three sectors (i.e., agricultural, industrial and municipal) in a million m^3/year and Percentage of wastewater to fresh Water treated for use were utilized. This utilized data is an adjustment to the European GCI recommendation of m^3/head for water consumption and the Percentage of housing linked to the sewage system for wastewater treatment.

Consistent with the indicators in Table 3, the sustainability of Saudi Arabia within the last decade (i.e., 2010 to 2018) was appraised in this study. This duration was covered because available data before 2010 and after 2018 were not evenly available across the selected indicators. The substantial indicators values were derived from the General Authority for Statistics (Saudi Arabia) webpage, macrotrends.net, and statista.com. The indicator values from macrotrends.net are from the World Bank data source. Likewise, the actual values collected from statista.com are backed by data sources from the (i) General Authority for Statistics (Saudi Arabia) and (ii)

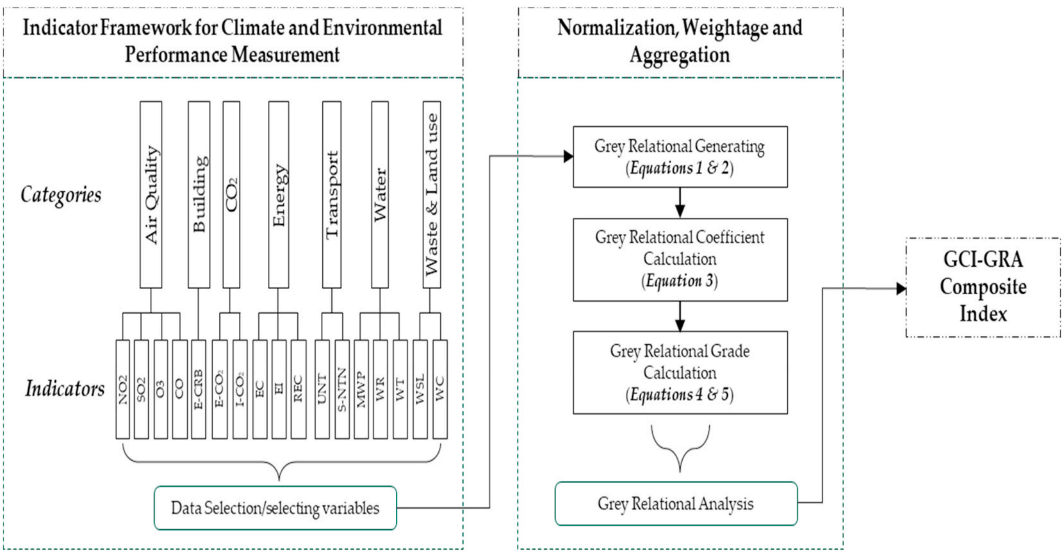

Fig. 2. The hybrid GCI-GRA composite index. Source: Authors (2023).

Table 3
Selected indicators for assessing Saudi Arabia's environmental sustainability. Prepared by the authors.

Category	Indicators	Saudi Arabia	Unit	Indicator Data Collection Source
Air quality	NO_2	✓	–	[68]
	SO_2	✓	–	
	O_3	✓	–	
	CO	✓	–	
Buildings	*E*-CRB	✓	Gigawatt/Hour	[69]
CO_2	E-CO_2	✓	Kilotons	[70]
	I–CO_2	✓	Metric Tons/Capita	
Energy	EC	✓	G.W·H.	[71,72]
	EI	✓	Kwh	
	REC	x	–	–
Transport	UNT	x	–	–
	S-NTN	✓	Km	[73]
Waste and land use	MWP	✓	kg	[74]
	WR	✓	Ton per year	[75]
Water	WT	✓	%	[76]
	WSL	x	–	–
	WC	✓	Million m^3/year	[77]

Ministry of Transport and Logistic Services (Saudi Arabia). As such, the utilized data are derived from official and legitimate national and international databank authorities, guaranteeing the reliability and integrity of this study's analysis and findings.

Table 4 contains this study's 14 indicators across an assessment period of 2010–2018, detailing the study's original reference series/sequences and the original comparison series/sequences. Therefore, the decision matrix is designed as 14 indicators across nine assessment periods.

4.2.1. *Grey relational generating*

The grey relational generating results were derived using equations (1) and (2), as illustrated in section 2.4. For instance, under the NO_2 indicator, the maximum value was 514 in 2016, and the minimum value was 96 during the year 2010. Since NO_2 is categorized as a non-beneficial indicator, using equation (2), the outcome of the grey relational generating for 2011 is (514–112)/(514–96) = 0.9617. The overall outcomes of the grey relational generating are contained in the upper part of Table 5.

4.2.2. *Grey relational coefficient calculation*

After determining the values of the deviation sequence Δ_{ij}, Δ_{min}, and Δ_{max}. The overall grey relational coefficient was computed using Equation (3). As an illustration, the E-CO_2 indicator in 2014 is $\Delta_{2014} = |1 - 0.2072|$, $\Delta_{min} = 0$, $\Delta_{max} = 1$, with a value of ζ as 0.5, therefore $\gamma = (0 + 0.5 \times 1)/(0.7928 + 0.5 \times 1) = 0.3868$. The overall outcomes of the grey relational coefficient are contained in the lower part of Table 5.

4.2.3. *Grey relational grade calculation*

At this step, rather than allocating equal or different weights to the selected indicators based on the subjectivity of the authors or the summation of the grey relational coefficient via the arithmetic mean with a follow-up weighting procedure, the authors utilized the European GCI indicators weights in calculating the grey relational grade values [47]. This approach is one of the benefits of this study's proposed method of GRA-GCI. Equations (4) and (5) were utilized to calculate the grey relational grade contained in Table 6.

The results revealed that the latest sustainability assessment period, 2018, is ranked 4th. At the category level, the grade's outcomes and ranking are slightly similar to the overall sustainability. While (i) CO_2 and (ii) Energy ranked 1st in 2010, the assessment period 2012 received a favourable air sustainability ranking under the air quality category. In actualizing Saudi Arabia's aim of net zero by 2060, the outcomes of this GRA-GCI appraisal would recommend advancing on the 2010 assessment period that ranked 1st in almost the rankings.

5. Discussion

This study is primarily based on developing a composite indicator index within the context of climate change mitigation and environmental sustainability appraisal via a novel analysis and developmental stages. As such, its outcomes are significant with a sufficient contribution to identified gaps in extant studies. The extraction and analysis of this study's quantitative data support the conventional framework for sustainability assessment [56], sustainability measurement within multiple cities within a country [51], and sustainability investigation within a cityscape [52]. The selected underlying indicators are underneath climate change/environmental-dimension sustainability categories. At the same time, the methodology of the GRA is efficient and reliable for the normalization and aggregation of the selected indicators. Hence, this demonstrates the developed index capacity and the ability for sustainability appraisal and climate change mitigation by policy/decision makers.

The proposed framework and composite indicator index comprise seven categories of "air quality", "buildings", "CO_2", "energy", "transport", "waste and land use", and "water", which were adapted from the European GCI putting into considerations only

Table 4
The Study's selected GCI indicators across assessment period. Prepared by the authors.

Category	Indicators	Assessment Period								
		2010	2011	2012	2013	2014	2015	2016	2017	2018
Air quality	NO2	96	112	103	195	193	453	514	426	439
	SO2	1	1	1	3	4	7	10	8	13
	O3	46	64	76	165	161	419	473	256	229
	CO	96	91	72	119	107	166	197	140	115
Buildings	*E*-CRB	109,021	109,623	120,652	126,113	136,368	144,513	143,660	143,473	130,428
CO2	E-CO2	446,130.00	463,769.99	492,470.00	503,209.99	540,520.02	565,190.00	561,229.98	545,070.01	521,260.01
	I–CO2	16.27	16.41	16.89	16.74	17.48	17.82	17.30	16.47	15.47
Energy	EC	218,254	225,509	246,610	262,685	281,155	294,612	296,673	298,439	299,188
	EI	7962	8004	8534	8871	9267	9485	9333	9151	8954
Transport	*S*-NTN	58,036	59,143	60,336	61,376	62,735	64,412	64,412	65,964	66,419
Waste and land use	MWP	1.15	1.16	1.18	1.20	1.22	1.26	1.36	2.04	1.72
	WR	51,000	54,000	55,000	59,900	75,000	108,440	113,172	137,879	195,907
Water	WT	45	46	50	46	51	49	51	49	49
	WC	17,447	19,193	20,884	22,260	23,416	24,833	23,933	23,350	25,992

Table 5
The outcomes of the grey relational generating and grey relational coefficient. Prepared by the Authors.

Assessment Period	Air quality				Buildings	CO_2		Energy		Transport	Waste and land use		Water	
	NO_2	SO_2	O_3	CO	*E*-CRB	E-CO2	I–CO_2	EC	EI	*S*-NTN	MWP	WR	WT.	WC
Grey Relational Generating														
2010	1.0000	1.0000	1.0000	0.8080	1.0000	1.0000	0.6596	1.0000	1.0000	0.0000	1.0000	0.0000	0.0000	1.0000
2011	0.9617	1.0000	0.9578	0.8480	0.9830	0.8518	0.6000	0.9104	0.9724	0.1321	0.9888	0.0207	0.1667	0.7957
2012	0.9833	1.0000	0.9297	1.0000	0.6723	0.6108	0.3957	0.6496	0.6244	0.2744	0.9663	0.0276	0.8333	0.5978
2013	0.7632	0.8333	0.7213	0.6240	0.5184	0.5206	0.4596	0.4510	0.4032	0.3984	0.9439	0.0614	0.1667	0.4367
2014	0.7679	0.7500	0.7307	0.7200	0.2295	0.2072	0.1447	0.2228	0.1431	0.5605	0.9213	0.1656	1.0000	0.3015
2015	0.1459	0.5000	0.1264	0.2480	0.0000	0.0000	0.0000	0.0565	0.0000	0.7606	0.8764	0.3964	0.6667	0.1356
2016	0.0000	0.2500	0.0000	0.0000	0.0240	0.0332	0.2212	0.0311	0.0998	0.7606	0.7640	0.4290	1.0000	0.2410
2017	0.2105	0.4167	0.5082	0.4560	0.0293	0.1690	0.5745	0.0093	0.2193	0.9457	0.0000	0.5996	0.6667	0.3092
2018	0.1794	0.0000	0.5714	0.6560	0.3968	0.3670	0.3690	0.0000	0.3487	1.0000	0.3596	1.0000	0.6667	0.0000
Grey Relational Coefficient														
2010	1.0000	1.0000	1.0000	0.7225	1.0000	1.0000	0.5949	1.0000	1.0000	0.3333	1.0000	0.3333	0.3333	1.0000
2011	0.9289	1.0000	0.9222	0.7667	0.9672	0.7714	0.5556	0.8480	0.9477	0.3655	0.9780	0.3380	0.3750	0.7099
2012	0.9676	1.0000	0.8768	1.0000	0.6041	0.5623	0.4528	0.5880	0.5711	0.4080	0.9368	0.3396	0.7500	0.5541
2013	0.6786	0.7500	0.6421	0.5708	0.5094	0.5105	0.4806	0.4767	0.4559	0.4539	0.8990	0.3476	0.3750	0.4702
2014	0.6830	0.6667	0.6500	0.6410	0.3935	0.3868	0.3690	0.3915	0.3685	0.5322	0.8641	0.3747	1.0000	0.4172
2015	0.3693	0.5000	0.3640	0.3994	0.3333	0.3333	0.3333	0.3464	0.3333	0.6762	0.8018	0.4531	0.6000	0.3665
2016	0.3333	0.4000	0.3333	0.3333	0.3388	0.3409	0.3910	0.3404	0.3571	0.6762	0.6794	0.4669	1.0000	0.3971
2017	0.3878	0.4615	0.5041	0.4789	0.3400	0.3757	0.5402	0.3354	0.3904	0.9021	0.3333	0.5553	0.6000	0.4199
2018	0.3786	0.3333	0.5385	0.5924	0.4532	0.4420	1.0000	0.3333	0.4343	1.0000	0.4384	1.0000	0.6000	0.3333

Table 6
The Outcomes of the GRA-GCI for Air Quality, CO_2, Energy, and overall sustainability ranking. Prepared by the Authors.

Assessment Period	Overall Sustainability		Air Quality		CO_2		Energy	
	Grade	Rank	Grade	Rank	Grade	Rank	Grade	Rank
2010	0.3127	1	0.1861	2	0.2632	1	0.2500	1
2011	0.2868	2	0.1809	3	0.2190	3	0.2245	2
2012	0.2550	3	0.1922	1	0.1675	4	0.1449	3
2013	0.2048	5	0.1321	4	0.1635	5	0.1166	4
2014	0.2040	6	0.1320	5	0.1247	7	0.0950	6
2015	0.1641	9	0.0816	8	0.1100	9	0.0850	9
2016	0.1709	8	0.0700	9	0.1208	8	0.0872	8
2017	0.1740	7	0.0916	7	0.1511	6	0.0907	7
2018	0.2132	4	0.0921	6	0.2379	2	0.0960	5

underlying indicators with quantitative attributes for national context. The index is embedded with 17 environmental aspect indicators that a country should seriously consider when addressing climate change challenges and actualizing net zero carbon emissions/national carbon neutrality. Also, the composite index reveals the positive relationship existing between GRA and the selected seven categories – illustrating the criticality of the grey relational generating, grey relational coefficient calculation, and grey relational grade calculation for the weights/grades of the indicators to effectively and efficiently reflect the assessed study area. An individual indicator is with a unique unit and environmental impact. Extant studies [50–53] evaluate the sustainability of their selected cities using different sets of indicators based on diverse literature reviews. However, this study is unique based on the explicit consideration of environmental dimension/GCI, focusing on climate change mitigation and carbon neutrality.

The application of the proposed index and its corresponding outcomes in this paper's study area (i.e., Saudi Arabia) was revealed in section 4.2. The identified/selected indicators for Saudi Arabia based on the developed index were outlined in the section. Due to the availability of data for public usage on the General Authority for Statistics (Saudi Arabia) webpage, macrotrends.net, and statista.com, some underlying indicators data between 2010 and 2018 were achieved. Although, the unit and characteristics of some of these indicators were modified for the index utilization. The extraction of the index underlying indicators data led to the identification of 14 indicators within the Saudi context due to the non-availability of data in the English language as well as within 2010–20108 for the remaining three indicators. As such, this data availability challenge is one of the setbacks for advancing the utilization of the developed composite indicator index within Saudi Arabia.

5.1. *Saudi Arabia's performance, comparison with other cities, and a focus on the capital city*

This section discussed Saudi Arabia's performance in green/environmentally sustainable assessment with reference to selected categories of GCI developed by Siemens [20]. The discussion is also tailored to Saudi Arabia's capital city to ensure a similar comparison with the European cities. In line with the ambition to "transform Riyadh into one of the most sustainable cities in the world" and pave the way to Saudi Arabia's net zero emissions by 2060, Riyadh's climate change strategies and the authors' practical recommendations were discussed according to the main findings.

5.1.1. *Air quality*

With a grade of 0.1922 out of 1.0000, the 2012 air quality sustainability level of Saudi Arabia ranked 1st out of nine years based on the GCI-GRA methodology, slightly ahead of 2011. As depicted in Fig. 3, there was a gradual increase in NO_2, SO_2, O_3, and CO in the country's air from 2012 until 2016, when the Kingdom started experiencing a decrease in the quantity of these elements in the atmosphere. This decrease in these elements after 2016 might be the effect of the Saudi Vision 2030 declaration in 2016.

However, the December 2022 air quality rating varies between "moderate" to "good" in the capital city [81]. The current air quality

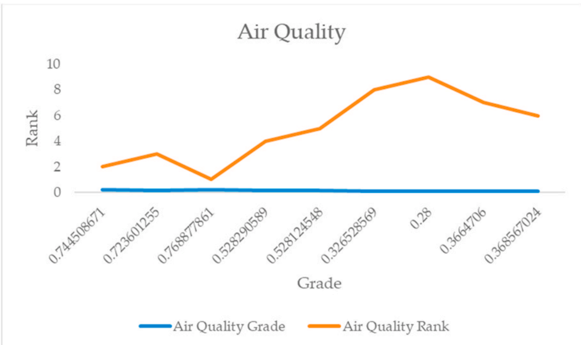

Fig. 3. Saudi Arabia GCI-GRA 2010–2018 air quality grade and rank. Source: Authors (2023).

rating shows an improvement over the 2020 ratings, where air quality was unhealthy for sensitive groups [81]. Compared with other European cities, Riyadh scored 3.8 compared to an average of 6.7 for the 30 European cities (see Fig. 4). At a concentration of 51.6 μg/m^3, NO_2 levels were higher than the benchmark of 40 μg/m^3 European target, as well as PM_{10} concentration with 54 μg/m^3 compared to a standard of 50 μg/m^3. SO_2 and O_3, on the other hand, were way below the European benchmark of 40 μg/m^3 and 120 μg/m^3, with concentrations of 25.3 μg/m^3 and 54.91 μg/m^3, respectively.

In addressing the air quality challenges, clean air policies in the city primarily focus on measuring air quality levels. Clean air policies in Saudi Arabia are governed by the General Authority of Meteorology and Environmental Protection, and the city of Riyadh follows the same regulations and guidelines issued by the authority. In 2012, the administration published a new set of environmental standards to increase air quality and limit the release of pollutants in the atmosphere. In 2014, the city launched 32 air quality monitoring stations that measure six primary pollutant levels (SO_2, O_3, CO, NO_2, PM_{10}, and $PM_{2.5}$). This paper authors' practical recommendations include but are not limited to the adoption, incorporation, and implementation of (i) green building initiatives and design across both new and refurbished construction and (ii) lifecycle-based innovative sustainable city strategic framework [82]. Expanding the current Saudi wind farm project and adherence to the World Health Organization (WHO) selected air quality indicators guidelines and levels could also improve the Kingdom's air quality.

5.1.2. CO_2 emissions

With a grade of 0.2632 out of 1.0000, the 2010 CO_2 emissions sustainability level of Saudi Arabia ranked 1st out of nine years based on the GCI-GRA methodology, a rank outcome similar to the overall sustainability. Fig. 5 revealed a CO_2 emission pattern that continued to increase after 2010 until after 2015, when the Kingdom started experiencing a decrease in CO_2 emissions. This trend differs from air quality, where there was an initial decrease in harmful elements in the atmosphere in 2012 and later in 2016. This situation might be attributed to Saudi Arabia's dependence on fossil fuels as the primary energy source and cars as the main mode of transportation. In this study, insufficient transport data was extracted for data analysis. However, promoting green transport is one of the objectives of Riyadh's Sustainable City Strategy. By 2030, the capital city aims to increase the use of public transit from 5% to 20%, capitalizing on King Abdulaziz Project for Public Transport in Riyadh, in addition to a plan to have 30% of the vehicles in the city running on electricity.

Saudi Arabia produced 16.27 metric tons per capita CO_2 in 2010, with its capital city (Riyadh) generating approximately 17.4 tons per head in 2020 [83]; this is more than triple the average of 5.2 tons per head for European cities. However, the country has initiated a promising strategy to address CO_2 emissions with a series of investments; for instance, the capital city aspires to reduce CO_2 emissions to 50% by 2030. In this study, Saudi Arabia's overall sustainability level for 2015 ranked lowest, with a 0.1641 grade out of 1.000. One of the justifications for this low sustainability performance might be its low performance across the energy sector. With an energy consumption of 365,190 GWH, 5.8 MJ per unit of real GDP across Saudi Arabia in 2015, and 360 MJ per head in the capital city, the city consumes more than three times the average of other European cities. On the other hand, renewable energy consumption is at 0% compared to an average of 7.2% for European cities. Regarding policies, the new electricity tariffs [84] and the massive investment of 30 billion riyals to enable Riyadh city to meet 50% of the energy demands through renewable energy resources by 2030 have been initiated to promote energy efficiencies.

5.1.3. Energy

With a grade of 0.2500 out of 1.0000, the 2010 energy sustainability level of Saudi Arabia ranked 1st out of nine years based on the GCI-GRA methodology, a rank outcome also similar to the overall sustainability and the CO_2 emission sustainability. Fig. 6 revealed an energy pattern that continued to increase from 2010 until after 2015, when the Kingdom started experiencing a decrease in CO_2

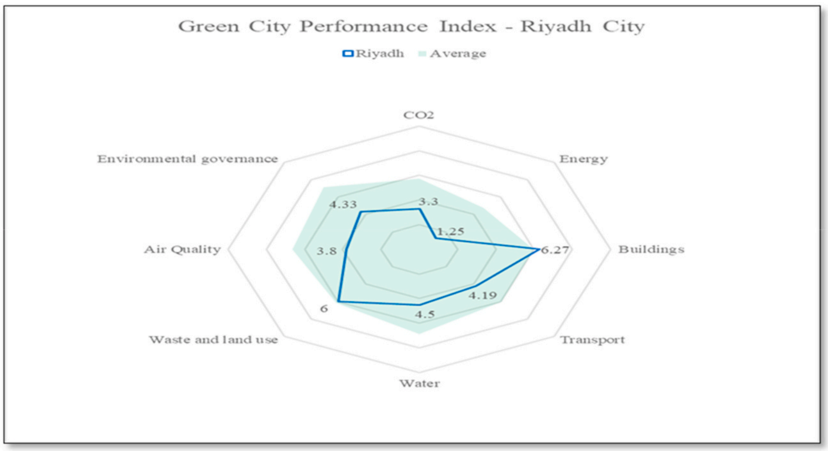

Fig. 4. Green city performance index- riyadh city results. Source: Authors (2023). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

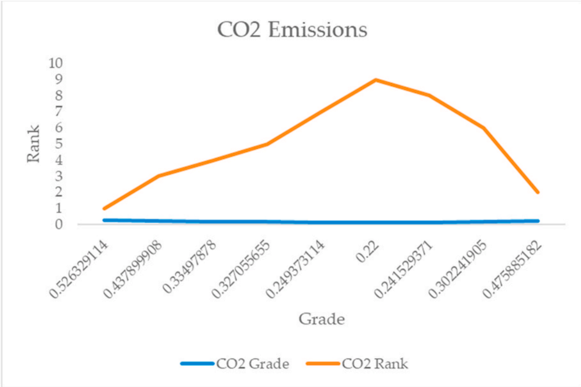

Fig. 5. Saudi Arabia GCI-GRA 2010–2018 CO2 emissions grade and rank. Source: Authors (2023).

emissions. This trend is slightly similar to CO_2 emission but different from air quality. There was an initial decrease in harmful elements in the atmosphere in 2012 and later in 2016.

As per the available records from the 2017 Riyadh Urban Observatory report, the total energy consumption per head in Riyadh City was estimated at 32.5 Gigajoules. Energy intensity measures the energy inefficiency of a country's economy; the higher the number indicates the higher cost of converting energy into real GDP. For Riyadh City, there is a lack of data on energy intensity measures. However, the country's energy intensity per unit of real GDP in 2015 was recorded at 5.8 MJ per unit of real GDP. Compared to the 30 European countries included in the study, Saudi Arabia ranked 26th, indicating high energy intensity compared to the other European countries. Thus, the government did not have good performance in this category. The weakest category was energy, where Riyadh scored the lowest among the 30 cities due to its low performance across the energy sector. With an energy consumption of 360 MJ per head, the city consumes more than three times the average consumption of the other cities. Renewable energy consumption is at 0% compared to an average of 7.2% for the remaining cities.

Besides a small percentage of 1.82% of houses in Riyadh using solar energy, most electricity is produced using non-renewable resources. As part of the country's strategy to achieve net zero carbon emission, shifting towards renewable energy is considered across the Kingdom. In 2018, phase 1 of the National Renewable Energy Program was launched. It covers a solar power station in Skaka and a wind power station in Domat Aljandal with a capacity of 700 MW which will be used to power 115,000 houses. Phase 2 of the program was launched in 2019 with seven renewable power stations with an overall capacity of 3.7 GW of energy. Phase 3 of the program was established in 2020, promising to provide 1200 MW through investing in four solar power stations. Riyadh city has a share of renewable energy with the announcement of the Sa'ad solar power station project, with a power generating capacity of 300 MW, which is expected to be completed by 2024.

5.1.4. Other categories

In 2015, the overall water consumption was 24,833 million m^3 per year [77], with water consumption of 143 cubic meters per head in Riyadh city, above the average of 105 cubic meters for the 30 European cities. Water leakage is an issue for the city, and it is estimated that 25%–40% of Water is lost in the distribution network compared to an overage of 22.6% for the rest of the cities. Dwelling units connected to a sewage network are one of the indicators to determine the performance in the water sectors. The average for the 30 European cities is 95%, while Riyadh scored 73.2% of dwellings connected to a sewage network. Water efficiency and treatment policies are emerging in the city, and water tariffs have been revised to encourage less water consumption and a penalty system to discourage unnecessary water waste. With an investment of 30 billion riyals, Riyadh's Sustainable City strategy is to have

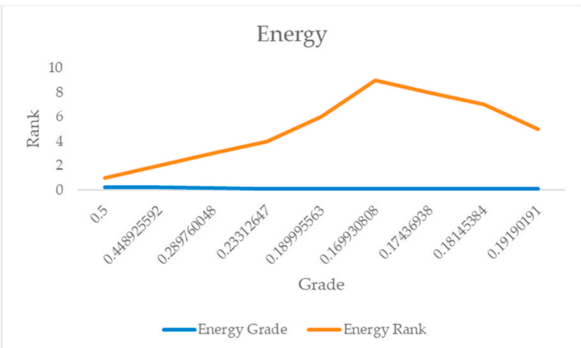

Fig. 6. Saudi Arabia GCI-GRA 2010–2018 Energy grade and rank. Source: Authors (2023).

100% water recycling by 2030.

Regarding waste and land use, Saudi Arabia generated 20,930 (1000 tons) in 2018 [74]. Riyadh city produces 475.5 kg of waste per head, while the average for European cities is 511 kg per head. At a percentage varying between 5% and 10%, waste recycling is below the average of 17.61% for European cities. Nevertheless, there is a good plan to convert 94% of the city's waste into energy, reducing demand for landfills and increasing the share of waste recycling. The capital city is investing heavily in green spaces. From a current per capita share of green areas of 1.7 square meters, the city aims to increase the allocation to 28 square meters per capita by 2030. This increase involves building more than 3300 parks in neighbourhoods and 43 major parks across the city. Multiple measures are being taken to limit the urban sprawl of Riyadh city. Annual fees on undeveloped lands are enacted to encourage development within the urban boundary of the town, while the city does not permit development beyond the urban boundaries.

In summary, the appraisal outcomes and the study's recommendations could serve as the basis or model for various Saudi ministries, agencies, and departments in advancing and implementing environmental sustainability strategies and climate change-related policies.

5.2. Study limitations and direction for future research

In this study, not all the 30 GCI indicators were considered in appraising the sustainability performance of Saudi Arabia. For instance, all qualitative indicators were excluded, such as CO_2 reduction strategy, clean and efficient energy policies, and congestion reduction policies with no measurement unit. With Saudi Arabia's updated data availability, utilization of surveys, satisfaction reports, and responses from experienced policymakers in the future, the selected indicators for assessing the study area would be enhanced. Also, sustainability appraisal of the study area considering socio-economic sustainability dimensions should be carried out in future research. In addition, a sustainability appraisal of the 13 provinces and-or selected Saudi cities using the GRA or other multi-criteria decision-making techniques in the future should be embarked upon. Due to the available data in Saudi Arabia, indicators from other appraisal schemes, such as sustainability city index indicators' could be utilized in future studies.

While the country is rapidly progressing towards achieving sustainable development goals in different social, environmental, and economic aspects, the absence of a comprehensive tool to assess Saudi cities' performance in sustainable development would make it hard to evaluate the performance of cities and their related sectors. Thus, it is recommended to establish an assessment tool that enables various city officials and authorities to measure their cities' performance in sustainable cities while designing the tool to be compatible with the different natures of Saudi cities.

6. Conclusions

The GCI is established to benchmark cities' environmental sustainability performance and share best practices. However, its utilization lags in Saudi Arabia despite its high global GHG emissions ranking. The authors saw the need for policymakers and decision-makers within the Saudi government and non-governmental institutions to address the nation's climate change issues and the 2060 net-zero carbon emissions actualization. The research question below was formulated to ensure a pragmatic measure of achieving this.

What is the status and progress of the environmental dimension of sustainability across Saudi cities?

In answering the question, this paper developed a composite indicator index and, after that, utilized it to assess the environmental sustainability level of Saudi Arabia within the last decade using selected European GCI indicators and weights. In addressing the critique of the European GCI, a novel approach was utilized, combining the GCI with a grey relational analysis (GRA) technique. While the GRA was used to grade and rank Saudi Arabia's environmental sustainability level between 2010 and 2018, the appraised indicators and their corresponding weightings were adopted from the European GCI.

Recall that climate change is driving environmental changes in our planet, increasing the earth's temperature rate and intensity of natural disasters while negatively impacting the air quality and surrounding environment. Countries worldwide are starting to address climate change issues and taking measures to limit the temperature increase to 2 °C. Saudi Arabia is one of the countries taking extensive steps to address climate change with many initiatives, including the target to achieve net zero emissions by 2060. Saudi capital city's sustainable strategy is a promising plan that aims to convert the city into one of the most sustainable cities in the world by 2030 with initiatives related to air quality, water, waste, energy, and biodiversity. Yet, there is a lack of measures to assess the current green city performance. Thus, this article appraised the environmental sustainability performance of Saudi Arabia within the past decade. The outcome of the analysis revealed that sustainability grades and ranking in Saudi Arabia based on the selected indicators are low. Compared with European GCI cities, the overall Saudi sustainability level and the capital city ranked higher and lower in various categories.

The study's significant contributions to knowledge are (i) the utilization of GRA-GCI to ascertain the weights and grey linkages, interconnection, and interrelationships between the selected indicators; (ii) Saudi Arabia's environmental sustainability insight between 2010 and 2018 that decision-makers might utilize in actualizing the 2060 net zero carbon emissions; and (iii) discussion on this study's outcome/utilize methods in comparison with studies and index. Saudi Arabia's policy and decision-makers should advance climate change mitigation and environmental sustainability across the country by reducing the value of the study's selected non-beneficial indicators (i.e., NO_2, SO_2, O_3, CO, *E*-CRB, E-CO_2, I–CO_2, EC, EI, MWP, and WC) while simultaneously increasing the values of the beneficial indicators (i.e., *S*-NTN, WR, and WT). Despite several government environmental sustainability initiatives and strategies in the capital city and across the Kingdom, it is recommended that more follow-up is required to ensure the use and modification of this framework.

Author contribution statement

Habib M. Alshuwaikhat, Yusuf A. Adenle and Turki N. Alotaishan: conceived and designed the experiments.
Habib M. Alshuwaikhat, Yusuf A. Adenle and Turki N. Alotaishan: performed the experiments.
Habib M. Alshuwaikhat, Yusuf A. Adenle and Turki N. Alotaishan: analyzed and interpreted the data.
Habib M. Alshuwaikhat, Yusuf A. Adenle and Turki N. Alotaishan: contributed materials, analysis tools or data.
Habib M. Alshuwaikhat, Yusuf A. Adenle and Turki N. Alotaishan: wrote the paper.

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Data availability statement

The substantial indicators values were derived from the General Authority for Statistics (Saudi Arabia) webpage, macrotrends.net, and statista.com. The indicator values from macrotrends.net are from the World Bank data source. Likewise, the actual values collected from statista.com are backed by data sources from the (i) General Authority for Statistics.

(Saudi Arabia) and (ii) Ministry of Transport and Logistic Services (Saudi Arabia).

Additional information

Supplementary content related to this article has been publish online at [URL].

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.

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Appendix A. Supplementary data

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