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A scalable method for identifying key indicators to assess urban environmental sustainability: A case study in Norway

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A B S T R A C T

Urbanization presents numerous societal challenges and exacerbates environmental issues. It is crucial to comprehend the current state and future direction of cities to formulate strategies and actions that mitigate negative consequences while ensuring a prosperous future for citizens. This study presents a universally applicable method for selecting indicators to gauge urban environmental sustainability. It aims to aid in structuring thinking for understanding and implementing Sustainable Development Goals (SDGs) within urban settings, using Norway as a case study but with a clear potential for broader applications. To achieve this, a comprehensive literature survey was conducted to gain insight into how urban environmental sustainability is conceptualized and operationalized in Norway. This involved assessing the key environmental challenges, as well as the strategies and action plans associated with them. Standardized sustainable cities' indicators served as references, which were then tailored to the municipal level to address the identified environmental challenges specific to Norwegian cities. Furthermore, the study discussed the proposed indicators for tracking the progress and state of these specific environmental challenges. In doing so, it establishes a foundation for comprehending environmental issues and establishing connections between indicators and environmental strategies and action plans in the urban sustainability context. Importantly, the methodologies and indicators we have unveiled in this study are designed to be applicable to cities beyond Norway, offering a scalable and adaptable approach for evaluating environmental challenges internationally. This work proposes a novel approach for evaluating the status and trends of environmental challenges by employing targeted indicators. These indicators can be expanded to include social and economic dimensions, enabling decision-makers and stakeholders to prioritize actions towards urban sustainability.

Introduction

Currently, over 56 % of the world's population resides in urban areas, with Europe having a higher urbanization rate of 75 % [1]. Norway has an urbanization rate exceeding 83 % [2], and this figure continues to grow at a rapid pace. The process of urbanization and the expansion of cities present numerous societal challenges, further amplifying existing environmental, social, and economic problems. These challenges include issues such as inadequate waste management, life-threatening pollutants, economic disparities, social inequalities, significant changes in land use, increased demand for natural resources, and the need for expanded public services and urban infrastructure. Addressing these challenges, it is crucial for cities to identify effective solutions and adopt sustainable planning and governance practices.

Moreover, understanding the current state and future trajectory of cities in terms of urban sustainability is of utmost importance. This knowledge serves as a foundation for shaping strategies and taking actions that mitigate negative challenges while ensuring a prosperous future for citizens. To gain this understanding, it becomes necessary to employ instruments that assess the current standing of cities and provide guidance for sustainable urban development.

The shift from the eight United Nations' Millennium Development Goals (UN-MDGs) [3], targeted for completion by 2015, to the 17 Sustainable Development Goals (SDGs) [4] by 2030 still underscores the need for effective indicators to measure and drive progress in sustainable urban development. Indicators serve as valuable tools for comprehending the complexity of multidimensional issues, monitoring progress, and facilitating decision-making processes. However, several environmental indicators proposed in the UN-SDGs are too generic to capture specific challenges at the city and local levels [5,6]. For

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example, when addressing air pollution, the UN-SDGs focus solely on particulate matter (PM) concentrations (indicator SDG11.6.2), while other air pollutants are summarized in an indicator measuring mortality rates related to air pollution (indicator SDG3.9.1) [7]. Additionally, certain relevant indicators from an urban perspective, such as the availability and accessibility of green recreational areas and noise pollution, are missing from the current SDGs indicators [7]. Therefore, it is crucial to establish a suitable narrative of urban sustainability and identify relevant indicators to assess and apply them. This will support decision-makers in advancing sustainable development by aligning long-term goals with short-term actions.

Sustainability is a dynamic and multifaceted concept with the aim to prosper and thrive for generations to come while avoiding irreversible harms. It has continually evolved as our knowledge expands. Striking a balance between various sustainability narratives proves challenging, as different narratives call for different indicators [8]. For example, there are two narratives highlighting that climate change is going to negatively affect food production and poverty. One narrative emphasizes the urgent need for adaptation to climate change, while another calls for a radical shift in consumption patterns. Each narrative necessitates specific indicators aligned with its objectives. The first narrative might call for more of the same polices and measures, so indicators like 'proportion of agricultural area under productive and sustainable agriculture' could be useful [8]. In the second narrative, the indicators like 'sustainable consumption action plans and environmentally sound technologies developed or implemented' are more appropriate and could be used to measure the changes in the way the current food system works [8]. Therefore, it is crucial to establish an appropriate narrative of urban sustainability, identify relevant indicators, and determine how to assess and apply these indicators to assist decision-makers in achieving sustainable development.

A sustainable city should meet the needs of the present without compromising the ability of future generations to meet their own needs. Urban sustainability encompasses three pillars: environmental sustainability (resource consumption and environmental impact), economic sustainability (resource efficiency and economic returns), and social sustainability (social well-being and health). Policy initiatives in the European Union, such as the 7th Environment Action Programme (7th EAP) [9], EU Biodiversity Strategy for 2030 [10], and the European Green Deal Action Plan: 'Towards Zero Pollution for Air, Water and Soil' [11], reflect the need to break free from separate silos and integrate economic, social, and environmental considerations. As the work of the European Environmental Agency (EEA) on urban sustainability assessment is framed in terms of its core environmental sustainability remit [12], this study focuses primarily on the environmental dimension, it acknowledges the broader scope of urban sustainability. By examining the most significant environmental challenges faced by Norwegian cities, the study aims to connect these challenges and their indicators to strategies and action plans that yield co-benefits across various environmental concerns.

Existing sustainable cities' indicator frameworks incorporate environmental, economic, and social indicators to gauge progress in achieving sustainability objectives in a holistic sense [13]. Many European cities employ specific indicator sets to measure their success in reaching targets and communicate the results of their initiatives to citizens. For example, Statistics Norway (SSB) has developed a taxonomy for SDG indicators to sort, evaluate, and compare different indicators and indicator sets [14]. The DPSIR (Driving Forces-Pressure-State-Impact-Response) framework, adopted by the European Environment Agency (EEA), is often used to analyse major environmental issues along impact-causal chains [15]. Input-output models, widely used in economics and environmental science, have been employed to characterize smart city transformation and link desired outcomes [16–19]. Moreover, the input-process-output-outcome typology has been utilized by several UN organizations to measure the performance of their programs, strategies, and projects [20]. To date, a standard classification of indicator types is still absent, likely due to the integration of indicators from different fields, each with its own conventions [21]. Therefore, this study provides an overview of existing relevant indicator frameworks for sustainable cities, with a particular focus on the environmental dimension, aiming to develop indicator measures that assess urban environmental sustainability performance.

The objective of this study is to develop a method for identifying indicators including evaluating existing indicators and proposing new ones to comprehensively assess urban environmental sustainability by using Norwegian cities as case studies. The research aims to shed light on the extent to which standardized sustainability indicator frameworks adequately monitor Norwegian cities' progress in addressing their current environmental challenges. To achieve this, several research questions are addressed: **i)** What are the main environmental challenges faced by Norwegian cities? **ii)** What indicator frameworks are available for monitoring urban sustainability, and what environmental indicators do they provide? **iii)** Can the indicators suggested in existing frameworks assess the status and trends of environmental challenges in Norwegian cities? and **iv)** What additional indicators can be employed to monitor environmental challenges in Norwegian cities that are not addressed in existing indicator frameworks?

To answer these questions, the study first identifies the current key environmental challenges, as well as the associated strategies and action plans in Norway and Norwegian cities (Sections 2.1, 2.2.2, 3.1). Secondly, existing standardized sustainable cities' indicator frameworks, including the UN-SDGs framework, are examined to extract commonly used environmental indicators (Sections 2.2.3, 3.2.1). Finally, the study discusses each suggested indicator and its potential for monitoring the identified environmental challenges (Section 3.2.2). In doing so, it establishes a foundation for comprehending environmental challenges within urban areas, connecting the status of environmental indicators with environmental strategies and action plans in the context of sustainable development. Moreover, the study aims to propose new challenge-based approaches for formulating and illustrating the status of environmental indicators, which can be further expanded to incorporate social and economic indicators. Ultimately, these indicators can support policy decisions and stakeholder prioritizations toward urban sustainable development.

Materials and methods

Study area

This study focuses on Norwegian cities as the study area. Norway has made significant progress in implementing the 2030 Agenda for Sustainable Development at the national level. However, the country still faces challenges related to greenhouse gas (GHG) emissions (SDG13), biodiversity preservation (SDG15), and marine litter that threatens the health of Norwegian oceans (SDG14) [22]. At the city level, although Norwegian cities are relatively small on a global scale, they face similar challenges to larger cities worldwide, including the impact of population growth and climate change. For example, increased frequency of extreme precipitation events poses problems for stormwater management. Additionally, urban growth puts pressure on air quality, waste management, GHG emissions, energy consumption, species and natural habitats, and the availability of green space [23,24].

This study delves into 10 selected municipalities in Norway, including the five largest cities by population (Oslo, Bergen, Trondheim, Stavanger, Drammen) and five additional municipalities that explicitly work with the SDGs while considering geographical coverage (Asker, Kristiansand, Ålesund, Tromsø, Bodø) [25] (Fig. 1). Six of these municipalities have participated in the United for Smart Sustainable Cities (U4SSC) initiatives and adopted U4SSC key performance indicators (KPIs) for assessments towards smart sustainable cities (Asker, Bodø, Kristiansand, Stavanger, Trondheim, Ålesund) [26].

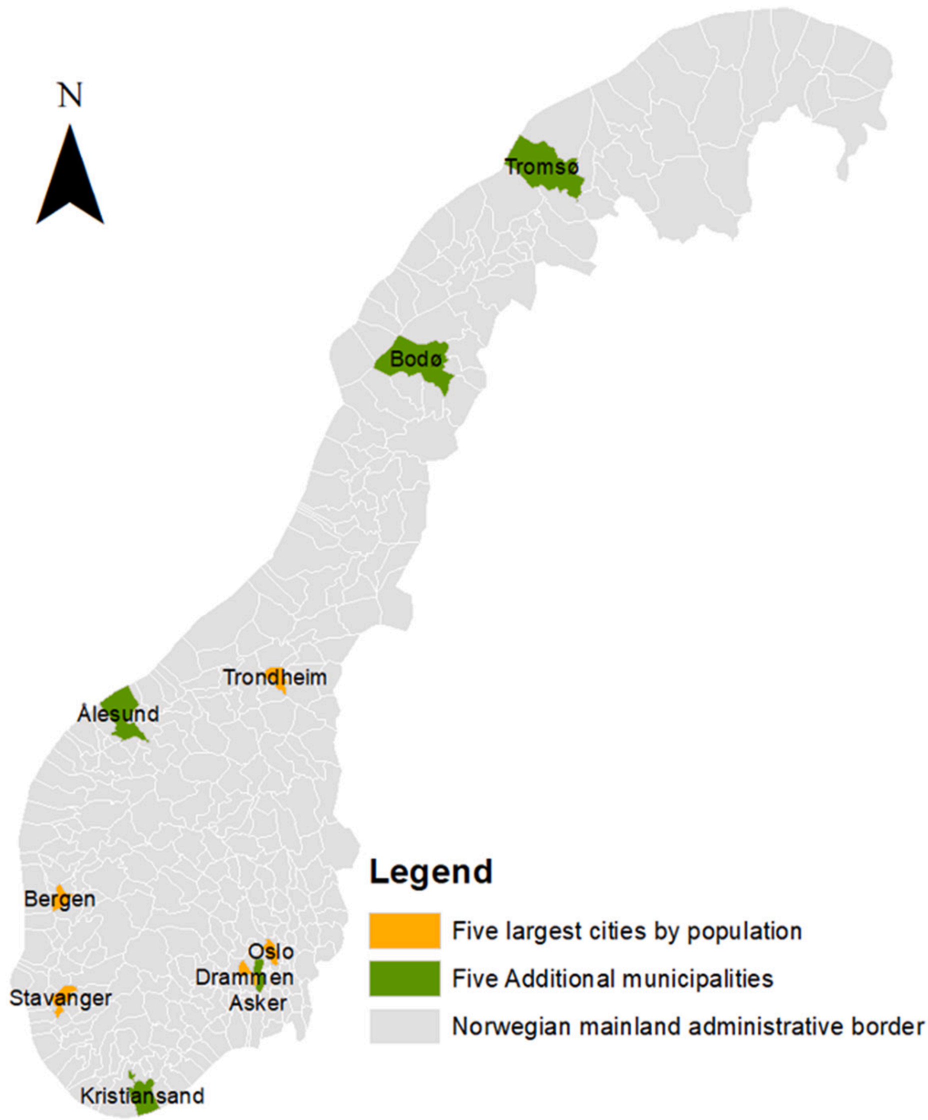

Fig. 1. Map of Norway with 10 selected municipalities (Orange: five largest cities by population; Green: five additional municipalities explicitly working with the SDGs). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Methodology

Overall methodology

The methodology consists of two steps, as illustrated in Fig. 2. In the first step, an in-depth literature survey was conducted to understand the key environmental challenges of Norwegian cities (Sections 2.2.2, 3.1), the associated strategies and action plans (Appendix A), and their linkages to the SDGs (Section 3.1). In the second step, existing standardized sustainable cities' indicator frameworks were identified, and the consistency of indicators across these frameworks was analysed (Sections 2.2.3, 3.2). Key indicators that could monitor the identified environmental challenges from Step 1 were extracted (Section 3.2.1).

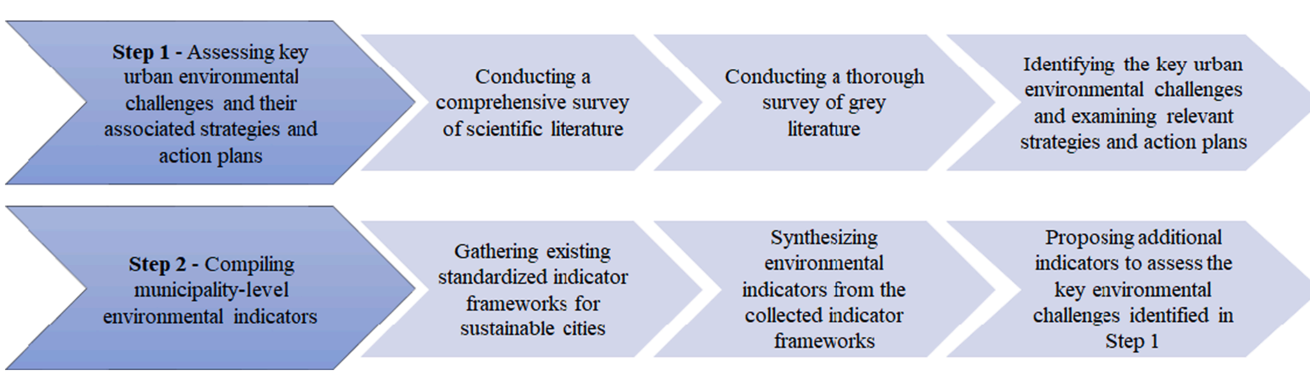

Fig. 2. Overall methodology.

Additionally, suggestions for additional indicators to assess the environmental challenges not covered by the existing indicator frameworks, were discussed (Section 3.2.2).

Step 1 – assessing key urban environmental challenges and their associated strategies and action plans

Conducting a comprehensive survey of scientific literature

To gather a wide range of scholarly articles, a comprehensive scientific literature review was conducted during the months of November 2022 and October 2023 using various databases, including Science Direct, Web of Science, Lens.org, and Wiley. The search strings used included keywords in the following: title-abstract-keywords ('sustainab*' or 'SDG*' or 'environmental challenges'), and ('city' or 'cities' or 'urban'), and ('Norway' or 'Norwegian'). These search strings were designed to capture articles that discussed sustainability, SDGs, or environmental challenges in the context of cities, with a focus on Norway. The resulting number of hits obtained from each database were as follows: 83 from Science Direct, 140 from Web of Science, 488 from Lens.org, and 29 from Wiley. After removing duplicates, the abstracts of 566 articles published between 1972 and October 2023 were screened for relevance. Subsequently, 113 selected articles published between 2000 and October 2023 were reviewed in full text for a deeper understanding of the content, findings and methodologies employed by the researchers (Fig. 3).

Conducting a thorough survey of grey literature

To ensure a comprehensive understanding of the environmental challenges, strategies, and action plans both at the national and municipal levels, an extensive collection of grey literature was obtained during the months of November 2022 and April 2023 from various sources, including government and ministry webpages, as well as individual municipal webpages. This process involved accessing reports, publications, policy documents, and other relevant materials that were not traditionally published in peer-reviewed journals.

To identify the key environmental challenges at the national level, as well as national environmental strategies and plans, the government and ministry webpages served as valuable sources of information [27,28]. These official platforms provided insights into the broader environmental concerns and the strategic approaches taken by the national authorities to address them. Similarly, to uncover the key environmental challenges specific to each municipality, as well as the corresponding municipal strategies and action plans, individual municipal webpages were consulted [29,30]. These webpages offered localized information on the environmental issues faced by each municipality and outlined the specific measures and initiatives being implemented to tackle them (see Appendix A).

Identifying the key urban environmental challenges and examining relevant strategies and action plans

The key environmental challenges in 10 Norwegian cities were primarily identified through a comprehensive review of scientific research and relevant grey literature. This involved analysing existing studies, reports, and publications that focused on urban environmental issues in these cities. Once the key environmental challenges were identified (Table 2), efforts were made to gather the relevant strategies and action plans that specifically targeted these environmental issues. The primary source for these strategies and action plans was the official webpages of each municipality. By leveraging scientific and grey literature review as well as the information shared on the municipal webpages, a comprehensive understanding of the environmental challenges and the corresponding strategies and action plans was attained (See Appendix A).

Step 2 - compiling municipality-level environmental indicators

Gathering existing standardized sustainable cities indicator frameworks

A wide variety of indicator frameworks exist to assess urban sustainability [15,17,31]. This study selected 10 international sustainable city indicator frameworks for evaluation and reporting purposes (Table 1, Appendix B and C). The selection was based on four criteria, including **i)** city target - targeting indicators at the city scale or having urban-based targets (e.g., UN-SDGs); **ii)** keywords - inclusion of specific keywords (*i.e.*, 'sustainable cities' and 'indicators' or 'index' or 'framework', or 'urban sustainability' and 'indicators' or 'index' or 'framework', or 'sustainable development goals') in the indicator framework title; **iii)** scalability - scalability for use in cities of various sizes; and **iv)** ease of use - ease of use in terms of data accessibility and scoring.

Synthesizing environmental indicators from gathered sustainability cities indicator frameworks

To identify commonly used indicators for addressing environmental challenges, a synthesis of 10 selected indicator frameworks on

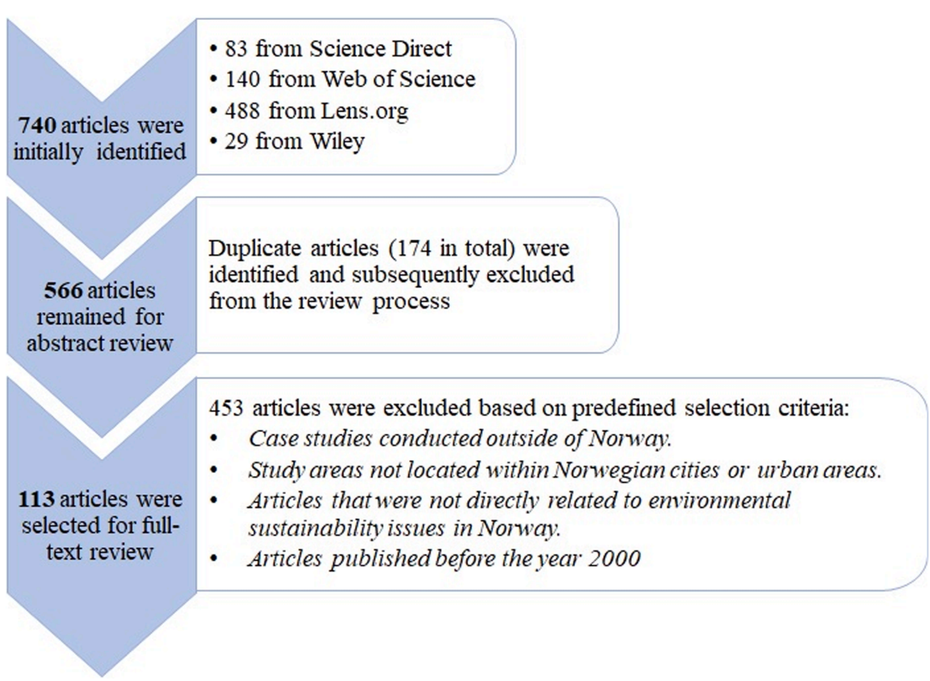

Fig. 3. Selection process for full scientific articles' review.

Table 1
An overview of the selected standardized sustainable cities' indicator frameworks, including their main thematic categories and the number of indicators they include.

Number	Indicator framework	Main thematic categories	Number of indicators
1	UN-SDGs [32	Productivity, Infrastructure, Quality of life, Equity and social inclusion, Environmental Sustainability, Governance, and legislation	232
2	International Organization for Standardization (ISO) 37120: 2018 – Sustainable cities and communities – Indicators for city services and quality of life [33]	Economy, Education, Energy, Environment and climate change, Finance, Governance, Health, Housing, Population and social conditions, Recreation, Safety, Solid waste, Sport and culture, Telecommunication, Transportation, Urban/ local agriculture and food security, Urban planning, Wastewater, Water	104
3	ISO 37122: 2019 – Sustainable cities and communities – indicators for smart cities [34]	Economy, Education, Energy, Environment and climate change, Finance, Governance, Health, Housing, Population and social conditions, Recreation, Safety, Solid waste, Sport and culture, Telecommunication, Transportation, Urban/ Local agriculture and food security, Urban planning, Wastewater, Water	79
4	The European Telecommunications Standards Institute (ETSI) technical specification (TS) 103 463 – Key performance indicators for sustainable digital multiservice cities [35]	People, Planet, Prosperity, Governance	76
5	International Telecommunication Union (ITU)'s Telecommunication Standardization Sector (ITU-T) Y.4903/L.1603 – Key performance indicators for smart sustainable cities to assess the achievement of sustainable development goals [36]	Economy, Environment, Society and culture	52
6	U4SSC collection methodology for key performance indicators for smart sustainable cities [37]	Economy, Environment, Society and culture	91
7	The European Reference Framework for Sustainable Cities [38]	Ecological, Social-cultural, Economic	28
8	Leadership in Energy and Environmental Design (LEED) for Sustainable Cities and Communities [39]	Energy, Water, Waste, Transportation, Education, Equitability, Prosperity, Health & Safety	14
9	Sustainable Cities International's indicator for sustainability list [15]	Economy, Environment, Social	32
10	China urban sustainability index [40]	Society, Environment, Economy, Resources	21

Table 2
Overview of eight main environmental challenges in Norwegian cities (Underlined text denotes primary challenge, and italicized text represents related sub-challenges), along with municipality actions.

Environmental challenges	Specification of environmental challenges	Examples of municipal's key actions
Climate change *GHG emissions in general* *GHG emissions from energy production*	· Human-induced emissions of GHG are the main cause of climate change [48]. Norwegian GHG emission decreased by around 2.3 % from 1990 to 2019. However, the total GHG emission is still very high. In 2019, the total emissions of GHG in Norway amounted to 50.3 million tonnes CO_2 equivalents [49]. Energy sector (*i.e.*, energy industries including oil and gas extraction, the transport sector, energy use in manufacturing and construction, fugitive emissions from fuels and energy combustion in other sectors) is the largest source of GHG, accounting for 70.6 % of the total Norwegian emissions [50]. Many changes caused by climate change have already been observed in the Norwegian cities, e.g., increased frequency of extreme precipitation events [51]. Climate change has been addressed as a problem in all 10 municipalities (Appendix A).	· Measures on reduction in GHG and mitigate climate change are most listed in 'cities' climate and Energy Strategy', and action plan for specific climate change related environmental issues, such as 'Action plan for stormwater management in the city of Oslo' [52]. All 10 municipalities have developed action plans towards climate change issues (Appendix A).
Nature and biodiversity degradation/loss *Change of land-use (from pristine to human influenced)* *Loss of species* *Invasive alien species* *Habitat reduction* *Habitat degradation*	Changes in land use are among the greatest threats to biological diversity [41,53]. Local variability in habitats and species composition is being reduced, and some species are being wiped out [53]. Almost 4000 species are on the current Norwegian Red List, and half of these are threatened [53]. Invasive alien species cause harm to local fauna and flora [54]. The extent of areas without major infrastructure development, including wilderness-like areas, is shrinking steadily. The proportion of wilderness-like areas has dropped from 48 % to less than 12	Measures on restricting the development of areas of natural habitat, ensuring that land use patterns are sustainable, and making better and more efficient use of existing infrastructure and built-up areas are most listed in 'cities' biodiversity action plan' [55]. Six out of 10 municipalities (Oslo, Stavanger, Drammen, Asker, Kristiansand, Tromsø) have developed strategies targeting at nature and biodiversity degradation/loss issues.

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Table 2 (*continued*)

Environmental challenges	Specification of environmental challenges	Examples of municipal's key actions
	% in the past 100 years [53]. Nature and biodiversity degradation have been addressed as a problem in all 10 municipalities (Appendix A)	
Air pollution *PM_{10}, $PM_{2.5}$ and NO_2 are the most important air pollutants*	Air quality has improved in recent years, but pollution levels are still high enough to be harmful in some Norwegian cities [56]. It was estimated that 1400 premature deaths in Norway occurred in 2018 due to air pollution [57]. Road traffic is the main source of local air pollution. [56]. Wood burning is another source of the local air pollution [58]. Air pollution has been addressed as a problem in all 10 municipalities (Appendix A).	Measures targeting at restricting the use of studded tyres and lowering speed limits [59]; increasingly cleaner cars; building more green, more bicycle paths and car-free urban space [60]; improving road maintenance and preventing road dust [59,61]; and encouraging the replacement of old wood-burning stoves [62] are most listed in 'cities' action plan for better air quality'. Five out of 10 municipalities (Oslo, Bergen, Stavanger, Drammen, Tromsø) have developed strategies to improve air quality.
Fresh water pollution *Water bodies without good ecological status (link to Nature and biodiversity degradation/loss)* *Hydro-morphological changes in water bodies (i.e., in rivers due to hydropower)* *(Local) pollution, i.e., seabed and sediment pollution, stormwater runoff, emissions from aviation, marine shipping, and agriculture* *Acid rain* *Salmon lice (parasite)*	According to the Nature Index, about one third of freshwater bodies do not meet the criteria for good ecological status [63]. The ecological status is best in central and northern parts of Norway, while it is poorer in the south and parts of west where it is more densely populated [63]. Key pressures are pollution, acid rain, hydropower production [64], urbanization, roads, the spread of alien species and high numbers of salmon lice [53,63]. Fresh water pollution has been addressed as a problem in two out of 10 municipalities (Oslo, Drammen) (Appendix A)	Measures to support integrated management of the country's river systems to minimise adverse impacts of activities that influence the freshwater environment as well as animals and plants and their habitats are most listed in 'cities' management plan for better freshwater quality' [63]. Two (Oslo and Drammen) out of 10 municipalities have developed strategies to improve freshwater pollution related issues (Appendix A).
Marine areas degradation *Extensive fishing* *Ocean acidification (link to climate change)* *Other climate change effects on oceans (i.e., increased temperatures)* *Pollution by aquaculture* *Contaminated sediments* *Release of hazardous substances to the ocean*	· Pressures on marine areas come directly from human activities such as aquaculture, extensive fishing, and oil and gas production. Other indirect pressures include climate change and ocean acidification [53,65]. Many cities' coastal areas and fjords are contaminated by hazardous substances from present and previous human activities [53,66]. Marine areas degradation has been addressed as a problem in all of 10 municipalities (Appendix A).	· Measures to support country's integrated marine management regime to achieve good environmental status of all its sea areas [65], reductions in emissions of hazardous substances, and the clean-up of contaminated marine sediments [53] are most listed in 'cities' strategies towards marine areas degradation'. Three of 10 municipalities (Oslo, Drammen, Tromsø) have developed strategies targeting at marine area degradation (Appendix A).
Waste management *Higher per capita waste production than EU average* *Waste from industrial activities* *Waste from construction industry* *Insufficient waste separation for later recycling*	Waste quantities are growing and total waste generation in Norway in 2020 was 11.6 million tonnes [67]. Norwegians produce more waste than the EU average (municipal waste). In 2019, each Norwegian produced in average 776 kg waste, while the average for the EU countries was 502 kg [68]. Economic growth is one reason for growth in consumption and rising waste quantities [53]. The largest source of waste is the construction industry [68]. Waste generation by industrial activities has increased in the last few years, while the amount of household waste has been relatively stable, both per capita and in total [67,68]. Insufficient waste separation: 70 % of Norwegian households are requested by municipalities to sort their food waste, only 42,5% of the food waste is sorted out at the household level [69]. Waste management has been addressed as a problem in eight out of 10 (Oslo, Bergen, Trondheim, Asker, Kristiansand, Ålesund, Tromsø, Bodø) municipalities (Appendix A).	Measures on ensuring waste collection followed by suitable treatment to avoid dumping and fly-tipping of waste and subsequent environmental pollution [68], increasing recycling rates [70], and restrictions on the types of waste that can be landfilled have been introduced [71] in 'cities' strategies towards waste management'. Seven out of 10 municipalities (Oslo, Trondheim, Asker, Kristiansand, Ålesund, Tromsø, Bodø) have developed strategies targeting at waste management (Appendix A)
Noise pollution *Noise is pollution under the Norwegian Pollution Control Act*	Noise remains a major problem with an estimated 2.1 million people are exposed to noise levels exceeding 55 Db(a) outside their homes [72], and more than 10 000 years of healthy life are lost every year because of sleep disturbance caused by road traffic noise [73]. Road traffic is the dominant source of noise annoyance, accounting for more than 80 % of estimated noise annoyance [73]. In Oslo, 61 % of the population are exposed to	Measures targeting road traffic management [74] and planning land use [75] to reduce people's exposure to noise are most listed in 'cities' pollution and noise action plan'. Four out of 10 municipalities (Oslo, Bergen, Stavanger, Asker) have developed strategies targeting at noise pollution issues (Appendix A).

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Table 2 (*continued*)

Environmental challenges	Specification of environmental challenges	Examples of municipal's key actions
	traffic noise, while 12 % are exposed to noise associated with trains, trams or subways [74]. In Stavanger, noise from railways affects 600 residents, 500 residents are exposed to noise in excess of 50 dB(a) from cruise ships [24]. Noise has been addressed as a problem in all 10 municipalities (Appendix A).	
Energy consumption *Total energy consumption per capita in Norway is almost double the EU average.* *Electricity consumption per capita that is over four times the EU average and the highest in the world.*	The transportation sector is the largest consumer of energy in Norway, accounting for approximately 40 % of the country's total energy consumption [76]. Total energy consumption in approximately 220 TWh (terawatt-hours) [76]. Energy consumption per capita in Norway was 63.7 gigajoules (GJ) in 2019 [77]. Norway's electricity consumption per capita in 2019 was 19,973 kW-hours (kWh) [77]. Energy consumption has been addressed as a problem in all 10 municipalities (Appendix A)	Bergen – improving energy efficiency in public buildings [78]. Trondheim – promoting renewable energy production [79]. Oslo – Encouraging sustainable transportation [80]. Kristiansand – promoting circular practices [81]. All of 10 municipalities have set a goal to reduce energy consumption (See Appendix A)

sustainable cities was conducted. This process involved three main steps, aimed at obtaining a comprehensive understanding of the indicators that are widely recognized and used for addressing environmental challenges. **Firstly**, an overview of each indicator framework was obtained, encompassing its primary focus, thematic categories, and the total number of indicators included. This information was compiled and presented in Table 1, and the detail can be found in Appendix B. **Secondly**, a specific focus was placed on the environmental category within each indicator framework. By referring to Appendix C, the indicators associated with the environmental category were selected for further analysis. This step ensured that the synthesis focused specifically on the indicators related to environmental challenges, aligning with the research objective. **Lastly**, the number of common indicators listed in the environmental category across the 10 indicator frameworks was determined. This involved counting and comparing the indicators identified in the previous step, and the results were presented in Table 3 and Fig. 4, also found in Appendix C. By identifying the indicators that appeared consistently across 10 indicator frameworks, we were able to ascertain the commonly used indicators for addressing environmental challenges in the context of sustainable cities.

Suggesting additional indicators to assess key environmental challenges identified in Norwegian cities

Using the results of the synthesis, the indicators that were found to be common across 10 indicator frameworks were extracted and compared with the environmental challenges identified in Norwegian cities. This matching process aimed to identify indicators that were relevant to the specific environmental challenges faced by the Norwegian cities. The outcomes of this analysis can be found in Table 3. Furthermore, in

Table 3

Indicators to address the eight main environmental challenges in Norwegian cities (* (x/10 means x out of 10 indicator frameworks).

Main environmental challenges	Indicators and how often they are suggested in the 10 indicator frameworks	Additional indicators suggested by the authors
Climate change *GHG emissions in general* *GHG emissions from energy production*	• GHG emissions measured in tons per capita (t CO_2e /capita/ yr.) [15,33,36–39] (6/ 10) * (2,5,6,7,8,9) CO_2 emission per unit of value added – for the sectors (1/10) * (1) Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population (1/10) * (1)Climate resilience strategy - The extent to which the city has developed and implemented a climate resilient strategy (3/10) * (1,6,7)	No additional indicator suggested.
Nature and biodiversity degradation/loss *Change of land-use (from pristine to human influenced)* *Loss of species* *Invasive alien species* *Habitat reduction* *Habitat degradation*	Ratio of land consumption rate to population growth rate (1/10) * (1) Proportion of local breeds classified as being at risk, not at risk or at unknown level of risk of extinction (1/10) * (1) Red List Index (1/10) * (1) Change in number of native species - Percentage change in number of native species (3/10) * (2,3,4) Proportion of countries adopting relevant national legislation and adequately resourcing the prevention or control of invasive alien species (1/10) * [1] Protected natural areas – size or proportion of areas under environmental protection (6/10) * [2,4,5,6,7,9] Change in the extent of water-related ecosystems over time - estimate percentage change in each major ecosystem present (1/10) * [1]	Number of invasive species recorded per ecosystem. Number/Area of ecosystems with invasive species. "Risk assessment of the species" per area/ ecosystem where they occur. Deterioration of habitat quality indicators – separately defined for each ecosystem or species under consideration.
Air pollution *PM10, PM2.5 and NO2 are the most important air pollutants*	Annual mean concentration of $PM_{2.5}$ (ug/m^3) (3/10) * [2,6,9] Annual mean concentration of PM_{10} (ug/m^3) (3/10) * [2,6,9] Annual mean concentration of NO_2 (ug/ m3) (3/10) * [2,6,10]	Maximum daily mean for PM_{10} (ug/m3) Maximum hourly mean for NO_2 (ug/m3)Air quality action plan (Yes/No)
Fresh water pollution *Water bodies without good ecological status (link to Nature and biodiversity degradation/loss)*	Ambient water quality - Proportion of bodies of water with good ambient water quality (1/10) * (1) Change in the extent of water-related ecosystems	Proportion of rivers / river stretches with (severe) hydro-morphological alterations. Pollutant accounting

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Table 3 (*continued*)

Main environmental challenges	Indicators and how often they are suggested in the 10 indicator frameworks	Additional indicators suggested by the authors
Hydro-morphological changes in water bodies (i.e., in rivers due to hydropower) *(Local) pollution, i.e., seabed and sediment pollution, stormwater runoff, emissions from aviation, marine shipping, and agriculture* *Acid rain* *Salmon lice (parasite)*	over time - estimate percentage change in each major ecosystem present (1/10) * (1) Many suggested indicators touch indirectly on the pollution problem, *i.e.*, Wastewater Treatment - Percentage of wastewater receiving treatment (Tertiary) (3/10) * [5,6,10]Wastewater monitoring - Percentage of the wastewater pipeline network monitored by a real-time data tracking sensor system (1/10) * [3]Index of coastal eutrophication (1/10) * [1]	systems for industries or receiving water bodies. Emission monitoring system for pollutants of relevance (*i.e.*, nitrate and phosphate for agriculture). Monitoring of stormwater quality/ pollution and runoff volumes. Continuous water quality monitoring in receiving water bodies. Rainwater pH and pH in local freshwater bodies Monitoring of acid rain precursors in the air Biological monitoring
Marine areas degradation *Extensive fishing* *Ocean acidification (link to climate change)* *Other climate change effects on oceans (i.e., increased temperatures)* *Pollution by aquaculture* *Contaminated sediments* *Release of hazardous substances to the ocean*	Proportion of fish stocks within biologically sustainable levels (1/10) * [1] Degree of implementation of international instruments aiming to combat illegal, unreported, and unregulated fishing (1/10) * [1] Degree of application of a legal/regulatory/ policy/ institutional framework which recognizes and protects access rights for small-scale fisheries (1/ 10) * [1]Average marine acidity (pH) measured at agreed suite of representative sampling stations (1/10) * [1] Index of coastal eutrophication (1/10) * [1]Index of plastic debris density (1/10) * [1]	Proportion of marine areas with good ambient water quality. Seasonal temperature deviation from long-term average. Marine area covered by monitoring programs (biological and physio-chemical indicators) Marine area [km2] with contaminated sediment Marine areas in good environmental status Regional pollution accounting established
Waste management *Higher per capita waste production than average EU* *Waste from industrial activities* *Waste from construction industry* *Insufficient waste separation for later recycling*	The amount of municipal solid waste generated per capita annually (3/10) * [4,8,9]Percentage of city's hazardous waste that is recycled (1/10) * [2]Percentage of total amount of plastic waste recycled in the city (1/10) * [2]	Amount of waste generated per sector Proportion of waste per sector, which is recycled/reused (for the construction sector, this should also include demolishment)
Noise pollution *Noise is considered to be pollution under the Norwegian Pollution Control Act*	• Exposure to noise - Proportion of the city inhabitants exposed to noise levels above international/national exposure limits (2/10) * [5,6] Noise pollution - Share of the population affected by noise > 55 dB(a) at night-time (2/ 10) * [4,7]	No additional indicator suggested.
Energy consumption *Total energy consumption per capita in Norway is almost double the EU average* *Electricity consumption per capita that is over four times the EU average and the highest in the world*	Total energy consumption per year (1/10) * [10]Total energy consumption per capita (1/10) * [2]Proportion of renewable energy consumed in the city (6/ 10) *[1,2,4,5,6,9]Electricity consumption per capita (3/10) * [5,6,10]	Energy consumption by sectors Total energy consumption by manufacturing and mining Total energy consumption by transport Total energy consumption by household Total energy consumption by other sectors (Commerce and public services, agriculture, and fishing)

addition to the indicators derived from the 10 indicator frameworks, suggestions were made for additional indicators that were not covered by these 10 indicator frameworks but could still be valuable in measuring the status and trends of specific environmental challenges. These suggestions aimed to fill potential gaps in the existing indicator frameworks and provide a more comprehensive understanding of the environmental challenges in Norwegian cities. The suggested additional indicators are also presented in Table 3.

Results and discussion

Key environmental challenges in Norwegian cities and prominent measures to address them

Through an extensive scientific and grey literature review, we have identified the key environmental challenges prevalent in Norwegian cities, many of which align with globally recognized environmental challenges. At the city level, Norway faces a range of environmental issues, including climate change (SDGs 7, 11, 12, 13, 15), natural and biodiversity degradation/loss (SDGs 14, 15, 6, 13, 2, 11, 17), air pollution (SDGs 3, 7, 11, 12, 13, 15, 17), fresh water pollution (SDGs 6, 14, 15, 12, 17), Marine areas degradation (SDGs 14, 12, 15, 11, 17), waste management (SDGs 12, 11, 6, 9, 17), noise pollution (SDGs 3, 11, 12, 15, 17), and energy consumption (SDGs 7, 12, 13, 11, 9). These challenges resonate with the SDGs, reflecting the interconnectedness of environmental issues with broader global sustainability objectives (SDGs 2, 3, 6, 7, 9, 11, 12, 13, 14, 15, 17).

Validation of these challenges at the municipal level is evident through multiple national sources, including the SDGs progress report in Norway [22], State of the Environment Norway [41], Norway country briefing in the European Environment State and Outlook reports for 2015 and 2020 [41,42], voluntary national review 2021 Norway [43], and U4SSC verification reports in 11 Norwegian cities [44]. Table 2 presents a summary of the eight specific environmental challenges, sub-challenges, and provides examples of key actions undertaken by municipalities to address these issues. At the national level, Norway has developed several strategies and action plans to address significant environmental concerns and foster the transition of Norwegian society towards sustainability. Noteworthy examples include Norway's Climate Action Plan [45], national biodiversity action plan [46], and strategy for developing a green, circular economy [47].

It is important to note that while Norway has established comprehensive strategies at the national level, not all municipalities have developed or updated their strategies and action plans to tackle their specific environmental challenges. For further insights on the strategies

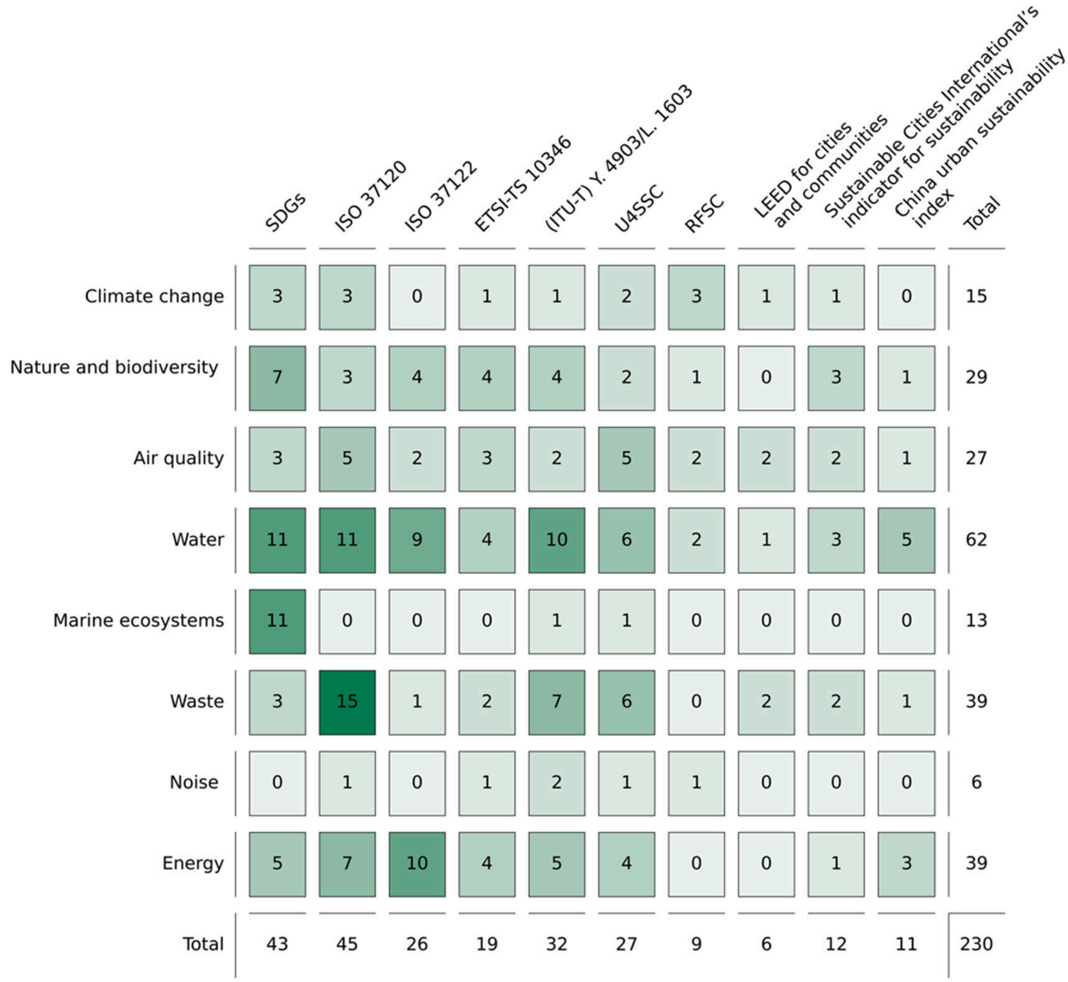

Fig. 4. Is 10 indicator frameworks and its number of indicators on eight environmental challenges identified.

and action plans developed by each municipality, please refer to Appendix A.

Climate change in Norwegian cities: Addressing GHG emissions

Climate change in Norway is primarily driven by human-induced GHG emissions [48]. Although there has been a slight reduction of approximately 2.3 % in Norwegian GHG emissions between 1990 and 2019, the total emissions remain at a high level. In 2019, the country's emissions reached 50.3 million tonnes of CO_2 equivalents [49]. The energy sector, encompassing activities such as oil and gas extraction, transportation, manufacturing, construction, and other fuel-related processes, emerges as the largest contributor, accounting for 70.6 % of total emissions in Norway [50]. These findings emphasize the importance of addressing GHG emissions from the energy sector to effectively combat climate change. Moreover, climate change impacts have already manifested in Norwegian cities, with an increased frequency of extreme precipitation events being one notable example [51].

Observing the urgency to combat climate change, all 10 municipalities in Norway have acknowledged climate change as a problem and implemented certain measures to tackle it (Appendix A). Their initiatives include the development of climate action plans that outline strategies for reducing GHG emissions, promoting renewable energy sources, implementing energy efficiency programs, and adapting to climate change impacts. One specific example is the "Action plan for stormwater management in the city of Oslo" [52], which highlights the city's targeted approach to addressing climate change-related issues.

Nature and biodiversity degradation/loss: strategies for conservation

Nature and biodiversity degradation/loss is a pressing concern in Norway, with several factors contributing to these issues. Changes in land use, particularly the conversion of pristine habitats to human-influenced landscapes, pose a significant threat to biological diversity [41,53]. This has led to a reduction in local variability in habitats and species composition, resulting in the loss of some species [53]. The current Norwegian Red List includes almost 4000 species, with half of them being threatened [53]. Invasive alien species further exacerbate the harm to local fauna and flora [54]. Additionally, the expansion of infrastructure development has led to the shrinking of areas without major human impact, including wilderness-like areas, which have decreased from 48 % to less than 12 % in the past century [53].

Addressing nature and biodiversity degradation has been recognized as a problem in all 10 municipalities in Norway (Appendix A). Strategies and measures have been developed to mitigate these issues, with six municipalities (Oslo, Stavanger, Drammen, Asker, Kristiansand, Tromsø) specifically targeting nature and biodiversity degradation/loss [55]. These strategies involve the protection and restoration of natural habitats, conservation of species, management of invasive species, and land-use planning designed to minimize habitat reduction. It prioritizes restricting the development of natural habitats, promoting sustainable land use patterns, and maximizing the use of existing infrastructure and built-up areas. By implementing these measures, municipalities aim to protect and preserve their natural heritage, restore local ecosystems, safeguard vulnerable species, and promote sustainable ecosystem management.

Air pollution: mitigating PM_{10}, $PM_{2.5}$, and NO_2

Air pollution is a significant concern in Norway, with particular focus on pollutants such as PM_{10}, $PM_{2.5}$, and NO_2. Although air quality has improved in recent years, pollution levels remain high enough to pose a risk in some Norwegian cities [56]. Alarmingly, it was estimated that 1,400 premature deaths in Norway occurred in 2018 due to air pollution [57]. Road traffic is identified as the primary local source of air pollution [56], while wood burning also contributes to local air pollution [58].

All 10 municipalities in Norway have recognized air pollution as a problem and have taken measures to address it (Appendix A). Out of the 10 municipalities, five (Oslo, Bergen, Stavanger, Drammen, Tromsø) have developed dedicated strategies to further enhance air quality [59]. These strategies encompass the implementation of air quality action plans, the promotion of clean transportation options, the enforcement of stricter emission standards, and public awareness campaigns aimed at reducing air pollution. Specific actions outlined in cities' air quality action plans include restricting the use of studded tires and lowering speed limits, promoting cleaner vehicles, expanding green spaces and bicycle paths, creating car-free urban areas, improving road maintenance to prevent road dust, and encouraging the replacement of old wood-burning stoves [59–62]. These strategies aim to mitigate the sources of air pollution and improve the overall air quality in the municipalities. By implementing these measures, the municipalities seek to safeguard public health, reduce the negative impacts of air pollution, and create healthier and more sustainable urban environments.

Freshwater pollution: challenges and management strategies

Freshwater pollution in Norway encompasses various aspects, including water bodies without good ecological status, hydromorphological changes in rivers due to hydropower, local pollution from sources such as seabed and sediment pollution, stormwater runoff, emissions from aviation, marine shipping, and agriculture, acid rain, and the presence of salmon lice as a parasite [63]. Approximately one-third of freshwater bodies in Norway do not meet the criteria for good ecological status, with better conditions observed in the central and northern regions compared to the more densely populated southern and western parts of the country [63]. Key pressures contributing to freshwater pollution include air pollution, acid rain, hydropower production, urbanization, road networks, invasive species, and salmon lice [53,63].

In response, two municipalities, Oslo and Drammen, have recognized freshwater pollution as a problem and have implemented measures to address it [63] (Appendix A). These efforts include water quality management programs, pollution reduction strategies targeting agriculture and urban runoff, restoration of degraded water bodies, and conservation of freshwater ecosystems. The cities' management plans prioritize integrated river system management and the protection of flora, fauna, and their habitats to improve freshwater quality [63]. By implementing these measures and strategies, Oslo and Drammen aim to enhance the ecological status of water bodies, safeguard freshwater resources, preserve biodiversity, and ensure long-term sustainability.

Marine areas degradation: addressing human-induced pressures

Marine areas degradation in Norway are caused by various factors, including extensive fishing, ocean acidification linked to climate change, increased temperatures, pollution from aquaculture, contaminated sediments, and the release of hazardous substances into the ocean [53,65]. These pressures primarily stem from human activities like aquaculture, extensive fishing, and oil and gas production, while climate change and ocean acidification contribute indirectly [53,65].

Coastal areas and fjords in many Norwegian cities are contaminated by hazardous substances from present and past human activities [53,66]. Addressing marine areas degradation is a concern for all 10 municipalities (as indicated in Appendix A). They have implemented measures to support integrated marine management, aiming to achieve good environmental status for all sea areas [65]. These measures include reducing hazardous substance emissions and addressing contaminated marine sediments [53]. Three municipalities, Oslo, Drammen, and Tromsø, have developed specific strategies to combat marine areas degradation [53] (as detailed in Appendix A), focusing on regulating fishing activities, controlling aquaculture pollution, remediating sediments, and reducing hazardous substance release. These efforts aim to protect and restore marine ecosystems, promote sustainable fishing, reduce pollution, and mitigate climate change impacts on marine environments.

Waste management: tackling high per capita waste production

Waste management in Norway faces several challenges, including high per capita waste production exceeding the EU average, industrial and construction waste, and inadequate waste separation for recycling [67]. In 2020, Norway generated 11.6 million tonnes of waste, with Norwegians producing more municipal waste per person than the EU average [67,68]. Economic growth contributes to increased consumption and waste generation [53], with the construction industry being a major waste source [68]. Insufficient waste separation is a concern, as only 42.5 % of food waste is sorted at the household level despite municipality requests [69].

Eight out of 10 municipalities recognize waste management as a problem, including Oslo, Bergen, Trondheim, Asker, Kristiansand, Ålesund, Tromsø, and Bodø [68] (Appendix A). Seven of these municipalities, namely Oslo, Trondheim, Asker, Kristiansand, Ålesund, Tromsø, and Bodø, have developed strategies targeting waste management [68]. These strategies prioritize comprehensive waste management, promoting recycling and waste separation, waste reduction, and circular economy practices. Key measures include proper waste collection, treatment to prevent environmental pollution, increased recycling rates, and restrictions on landfill disposal [68,70,71]. The goal is to minimize waste generation, enhance recycling rates, and foster a sustainable waste management approach, contributing to a cleaner environment and circular economy principles.

Noise pollution: affecting quality of life

Noise pollution is a significant concern in Norway, recognized as a form of pollution under the Norwegian Pollution Control Act. It poses a considerable problem, as around 2.1 million people are exposed to noise levels exceeding 55 dB(a) outside their homes, leading to sleep disturbance and the loss of over 10,000 years of healthy life annually [72,73]. Road traffic emerges as the primary source of noise annoyance, accounting for more than 80 % of estimated noise annoyance [73]. In Oslo, 61 % of the population is exposed to traffic noise, while 12 % are exposed to noise from trains, trams, or subways [74]. In Stavanger, 600 residents are affected by railway noise, and 500 residents endure noise levels surpassing 50 dB(a) from cruise ships [24]. Noise pollution is identified as a problem in all 10 municipalities in Norway (Appendix A). Four municipalities, namely Oslo, Bergen, Stavanger, and Asker, have implemented strategies specifically targeting noise pollution. These strategies encompass a range of initiatives, including the implementation of noise reduction measures, the formulation of traffic management strategies, urban planning interventions to mitigate noise impacts, and public awareness campaigns to address noise pollution. The cities' pollution and noise action plans prioritize measures such as road traffic management and land use planning to reduce people's exposure to noise [74,75]. These comprehensive strategies aim to mitigate noise pollution, enhance residents' quality of life, and create quieter and more liveable urban environments. By implementing these measures, municipalities strive to reduce noise levels, improve the acoustic environment, and promote the well-being of their residents.

Energy consumption: addressing high per capita consumption

Energy consumption in Norway is a significant concern, with the country's per capita energy consumption nearly double the EU average and per capita electricity consumption over four times the EU average, making it the highest in the world. The transportation sector plays a major role, accounting for about 40 % of Norway's total energy consumption [76]. In 2019, the country's total energy consumption was approximately 220 TWh, with per capita energy consumption reaching 63.7 GJ and per capita electricity consumption at 19,973 kWh [76,77]. Energy consumption is recognized as a problem in all 10 municipalities in Norway (Appendix A), leading to the implementation of various strategies to address it. These strategies include energy conservation programs, the promotion of energy-efficient technologies, incentives for renewable energy production, and the development of sustainable transportation systems.

For example, Bergen focuses on improving energy efficiency in public buildings, Trondheim promotes renewable energy production, Oslo encourages sustainable transportation, and Kristiansand emphasizes circular practices [78,79,80,81]. All 10 municipalities have set goals to reduce energy consumption, demonstrating their commitment to achieving energy efficiency targets (See Appendix A). These efforts aim to decrease overall energy consumption, promote renewable energy sources, enhance energy efficiency across sectors, encourage sustainable practices, and facilitate the transition to a more sustainable energy landscape in Norway.

Indicators synthesizing and identified to monitor environmental challenges in Norwegian cities

Synthesizing results of environmental indicators

Fig. 4 illustrates the total number of the indicators suggested by each of the 10 indicator frameworks for each of the eight environmental challenges identified in Norwegian cities. Appendix C provides an overview of the commonly used indicators within 10 indicator frameworks on each of eight environmental challenges identified. The total listed indicators and the most used indicators are as follows:

1) *climate change* – eight out 10 indicator frameworks have at least one indicator suggested (Fig. 4). A total of six indicators listed (Appendix C), and the indicator on 'GHG emissions measured in tons per capita' was used most (six out of eight indicator frameworks) (Table 3). Indicators on 'CO_2 emissions in tons per capita per year' and 'Climate resilience strategy - The extent to which the city has developed and implemented a climate resilient strategy' were used in three out of eight indicator frameworks ((Appendix C)).

2) *nature and biodiversity*: nine out 10 indicator frameworks have at least one indicator suggested (Fig. 4). A total of 15 indicators listed (Appendix C), indicator on 'protected natural areas - proportion of city area under environmental protection' was used most (six out of nine indicator frameworks) (Table 3). Indicator on 'Share of green areas - green area (hectares) per 100 000 population' was used in four out of nine indicator frameworks (Table 3). Indicators on 'Share of public spaces - area of total public recreational facilities per 100,000 inhabitants', 'Share of green and water spaces - share of green and water surface area as percentage of total land', and 'Change in number of native species - percentage change in number of native species' were used in three out of nine indicator frameworks (Appendix C).

3) *air quality* – all of 10 indicator frameworks have at least one indicator on air quality (Fig. 4). A total of 16 indicators listed (Appendix C), indicators on 'Annual mean concentration of SO_2', 'Annual mean concentration of NO_2', 'Annual mean concentration of PM_{10}', 'Annual mean concentration of $PM_{2.5}$' and 'Median AQI: based on PM_{10}, $PM_{2.5}$, NO_2, SO_2, O_3, CO' were used most (three out of 10 indicator frameworks) (Table 3).

4) *water*: all of 10 indicator frameworks have at least one indicator suggested (Fig. 4). A total of 43 indicators listed (Appendix C), indicators on 'Drinking water quality - index of compliance with standards relating to water quality parameters for drinking water (proportion of population using safely managed drinking water services)' and 'Water consumption – total water consumption per capita per day' were used most (four out of 10 indicator frameworks) (Table 3). Indicators on 'Household sanitation - proportion of the households with access to improved sanitation facilities', 'Wastewater treatment - percentage of wastewater receiving treatment (Primary)', 'Wastewater treatment - percentage of wastewater receiving treatment (Secondary)', 'Wastewater treatment - percentage of wastewater receiving treatment (Tertiary)' were used in three out of 10 indicator frameworks (Appendix C).

5) *marine ecosystems* – only UN SDGs, (ITU-T) Y. 4903/L. 1603, and U4SSC have indicator(s) on marine ecosystems (Fig. 4). A total of 11 indicators listed and indicator on 'Coverage of protected areas in relation to marine areas' was used in all these three indicator frameworks (Table 3). Other 10 indicators related to marine ecosystems were only suggested by UN SDGs (Appendix C).

6) *noise* – five out of 10 indicator frameworks have at least one indicator on noise (Fig. 4). A total of four indicators listed, indicators on 'Exposure to noise - proportion of the city inhabitants exposed to noise levels above international/national exposure limits' and 'Noise pollution - share of the population affected by noise > 55 dB(a) at night-time' were used most (two out of five indicator frameworks) (Table 3).

7) *waste* – nine out of 10 indicator frameworks have at least one indicator on waste (Fig. 4). A total of 20 indicators listed, and indicator on 'Solid waste treatment - percentage of the city's solid waste that is recycled' was used most (six out of nine indicator frameworks) (Table 3). Indicators on 'Solid waste treatment - percentage of the city's solid waste that is disposed of in a sanitary landfill' was used in four out of nine indicator frameworks. Indicators on 'The amount of municipal solid waste generated per capita annually', 'Solid waste treatment - percentage of the city's solid waste that is disposed of in an open dump' and 'Solid waste treatment - percentage of the city's solid waste that is disposed of by other means' were used in three out of nine indicator frameworks (Appendix C).

8) *energy* – eight out of 10 indicator frameworks have at least one indicator on energy (Fig. 4). A total of 29 indicators listed, indicators on 'Renewable energy consumption - proportion of renewable energy consumed in the city' was used most (six out of eight indicator frameworks) (Table 3). Indicators on 'Access to electricity - proportion of households with access to electricity', and 'Electricity consumption - electricity consumption per capita' were used in three out of eight indicator frameworks (Appendix C).

Overall, the 10 indicator frameworks covered some environmental challenges more extensively than others. Climate change, air pollution, and waste management were relatively well-covered, with a higher consistency of suggested indicators across frameworks. On the other hand, nature and biodiversity degradation/loss, marine areas degradation, freshwater pollution, noise pollution, and energy consumption had fewer indicators with cross-framework consistency.

Certain environmental challenges in Norwegian cities were not adequately covered by the existing indicator frameworks. For example, habitat degradation or alteration, hydro morphological changes in streams, and the pollution of coastal and marine areas were not specifically addressed. Therefore, the authors suggested additional indicators to fill these gaps, including indicators for habitat quality, pollution accounting systems, and monitoring programs for pollution in water bodies (see section 3.2.2). The additional indicators suggested by the authors have the potential to provide more comprehensive monitoring of the environmental challenges in Norwegian cities. They address specific aspects that are currently lacking in the existing indicator frameworks and focus on local context and ecosystem-specific indicators. However, implementing these new indicators may require additional data collection and monitoring efforts, which can be a challenge in terms of resources and coordination.

Indicators identified to monitor environmental challenges in Norwegian cities

Table 3 provides a summary of the commonly used indicators across 10 indicator frameworks and highlight areas where current frameworks fall short. Additional indicators are proposed by authors to fill these gaps, and ensuring a comprehensive monitoring of Norwegian cities' environmental sustainability. These indicators have been categorized according to various environmental issues, encompassing climate change, nature and biodiversity degradation/loss, air pollution, freshwater pollution, marine area degradation, waste management, noise pollution, and energy consumption.

Indicator identified to monitor climate change. In assessing the issue of climate change, **four indicators have been identified**. These include 'GHG emissions measured in tons per capita (t CO_2e/capita/yr.)', *'CO_2 emission per unit of value added – for the sectors'*, *'number of deaths, missing persons, and directly affected persons attributed to disasters per 100,000 population'*, and *'climate resilience strategy'*. These indicators have been suggested in multiple indicator frameworks. The most used indicator, found in six out of 10 indicator frameworks, is 'GHG emissions measured in tons per capita per year', providing insights into overall emissions levels [15,33,36–39]. The UN SDGs framework suggests the indicator 'CO_2 emissions per unit of value added' to understand sector-specific carbon intensity [32]. The UN SDGs framework also recommends the indicator 'number of deaths, missing persons, and directly affected individuals attributed to disasters per 100,000 population' to highlight vulnerability to climate-related events [32]. Additionally, the indicator 'climate resilience strategy' assesses a city's measures to enhance climate change resilience and is suggested by three indicator frameworks [32,37,38].

No additional indicators have been suggested by the authors to monitor climate change in Norwegian cities (Table 3), which emphasize the relevance of these identified indicators to international climate discourse. Such indicators are applicable beyond local contexts, and can be applied in other cities, regions, and countries as well. These indicators are generalized and can contribute to improving understanding of a city's responses to climate challenges.

Indicator identified to monitor nature and biodiversity degradation/loss. To effectively monitor nature and biodiversity degradation/loss, a set of **seven indicators has been identified** from the 10 indicator frameworks. These indicators cover various aspects and provide valuable insights into the state of the environment. Among these seven indicators, the "change in the number of native species" and "protected natural areas - size or proportion of areas under environmental protection" appeared in multiple indicator frameworks, indicating their significance in assessing nature and biodiversity degradation/loss across different contexts.

The first indicator, *'the ratio of land consumption rate to population growth rate'* used by UN SDGs framework [32], assesses the rate at which pristine land is being converted to human-influenced use in relation to population growth. This indicator helps evaluate the pressure on natural habitats and the balance between land use and population dynamics.

The second indicator, *'the proportion of local breeds at risk of extinction'* used by UN SDGs framework [32], examines the vulnerability of local breeds and their classification as at risk, not at risk, or with an unknown level of extinction risk. This indicator highlights the importance of preserving and safeguarding local biodiversity.

The third indicator, *'the red list index'* used by UN SDGs framework [32], provides a comprehensive assessment of species conservation status based on their extinction risk and population trends. This indicator offers insights into the overall health of species populations and the effectiveness of conservation efforts.

The fourth indicator, *'the change in the number of native species over time'* used by three indicator frameworks [33–35], tracks the percentage change in the number of native species, enabling the monitoring of biodiversity loss and the decline of species populations. This indicator helps identify the impact of human activities on species diversity.

The fifth indicator, *'the proportion of countries that have adopted relevant legislation for invasive alien species'* used by UN SDGs framework [32], assesses the adoption of national legislation and the allocation of adequate resources for the prevention or control of invasive species. This indicator highlights the importance of addressing the threats posed by invasive species to native ecosystems.

The sixth indicator focuses on *'protected natural areas'*, which were used by six of 10 indicator frameworks [15,33,35–38]. It measures the size or proportion of areas under environmental protection, providing insights into the extent of protected habitats and the effectiveness of conservation efforts. This indicator helps assess the coverage and management of protected areas.

The seventh indicator, *'the change in the extent of water-related ecosystems over time'* used by UN SDGs framework [32], calculates the percentage change in each major water-related ecosystem, reflecting the alterations and impacts on these ecosystems. This indicator emphasizes the need to monitor and protect water-related habitats.

In addition to these seven identified indicators, the authors proposed **four additional indicators as supplementary indicators** to enhance the monitoring of nature and biodiversity degradation/loss, provide further insights into specific threats and impacts on nature and biodiversity, enable a more comprehensive understanding of the challenges and guiding targeted conservation efforts, including:

1. *'Number of Invasive Species Recorded per Ecosystem*': This indicator is crucial in addressing the threat posed by invasive alien species, as mentioned in the challenges (See section 3.1, Table 2). The conversion of pristine habitats to human-influenced landscapes and the resulting reduction in local variability have heightened the risk of invasive species. By monitoring the number of invasive species per ecosystem, authorities can gain insights into the spread of these harmful species, helping to target conservation efforts where the threat is most significant. This aligns with the need to manage invasive species highlighted in the challenges.
2. *'Number/Area of Ecosystems with Invasive Species'*: In parallel with the concerns about changes in land use and the shrinking of areas without major human impact (See section 3.1, Table 2), this indicator quantifies the geographical extent of invasive species across different ecosystems. As habitats face degradation and reduction, understanding the number and area of ecosystems affected by invasive species becomes crucial. It provides valuable information for crafting conservation strategies, especially in areas where human activities have encroached upon pristine habitats, contributing to the loss of biodiversity.
3. *'Risk Assessments of Species in Specific Areas/Ecosystems'*: In line with the challenges of the Norwegian Red List highlighting threatened species (See section 3.1, Table 2), this indicator involves conducting risk assessments for species in targeted areas or ecosystems. The focus on species vulnerability aligns with the identified issue of species loss due to changes in land use. By identifying and prioritizing species most at risk, conservation efforts can be tailored to protect and preserve these key components of biodiversity.
4. *'Deterioration of Habitat Quality Indicators Tailored to Each Ecosystem or Species'*: Addressing the concerns about the expansion of infrastructure development and the associated habitat reduction (See section 3.1, Table 2), this indicator assesses the decline in habitat quality for various ecosystems or species in specific areas. As wilderness-like areas decrease, monitoring habitat quality becomes vital for understanding the health of ecosystems. This indicator provides a strategic approach to assess the degradation of habitats and guides conservation actions in areas where infrastructure development may threaten the quality of habitats.

It needs to note that the identified indicators to monitor nature and biodiversity degradation/loss issue from the existing indicator framework are applicable and beyond local contexts, and can be applied in other cities, regions, and countries as well. The suggested additional indicators are tailored to the specific challenges identified in the field of nature and biodiversity degradation/loss in Norwegian cities.

Indicator identified to monitor air pollution. **Three key indicators identified** in 10 indicator frameworks to monitor air pollution, including 1) *'annual mean concentration of $PM_{2.5}$'*; 2) *'annual mean concentration of PM_{10}'*; and 3) *'annual mean concentration of NO_2 (nitrogen dioxide)'*, respectively. The 'annual mean concentration of $PM_{2.5}$ (particulate matter with a diameter of 2.5 μm or less) in micrograms per cubic meter', is used by ISO 37128 [33], U4SSC [37] and Sustainable Cities International's indicator for sustainability list [15]. This indicator measures the average concentration of fine particulate matter in the air, which is crucial for assessing air quality and potential health impacts. The 'annual mean concentration of PM_{10} (particulate matter with a diameter of 10 μm or less) in micrograms per cubic meter', is used by ISO 37128 [33], U4SSC [37] and Sustainable Cities International's indicator for sustainability list [15]. This indicator assesses the average concentration of coarse particulate matter in the air, which includes larger particles that can also impact air quality and human health. The 'annual mean concentration of NO_2 in micrograms per cubic meter' is used by ISO 37128 [33], U4SSC [37] and China urban sustainability index [40]. This indicator measures the average concentration of NO_2, which is primarily emitted from burning fossil fuels and is a key contributor to air pollution and respiratory issues.

In addition to these three identified indicators, the authors suggested considering the following **three indicators as supplementary indicators**, including:

1) *'maximum daily mean for PM_{10} in micrograms per cubic meter'* - Monitoring the 'maximum daily mean concentration of PM_{10}' helps gauge the overall air quality in terms of particulate matter, which is one of the key pollutants in Norwegian cities from sources like vehicle emissions, industrial processes, and natural sources like dust. This indicator provides insights into the general air quality levels over a day, identifies the highest daily average concentration of coarse particulate matter, provides insights into peak pollution levels and potential short-term health risks, and helps authorities identify trends and initiate interventions when pollution levels exceed safe thresholds.

2) *'maximum hourly mean for NO_2 in micrograms per cubic meter'* - measuring the highest hourly average concentration of NO_2, which helps evaluate short-term exposure to this air pollutant. NO_2 is a common air pollutant in Norwegian cities primarily emitted from vehicle exhaust and industrial activities. It can cause respiratory problems, aggravate asthma, and contribute to the formation of smog. Monitoring the 'maximum hourly mean concentration of NO_2' is critical because short-term exposure to high levels can have immediate health effects. This indicator helps identify areas with elevated pollution levels, guiding policies and actions to reduce emissions and improve air quality.

3) *'air quality action plan (Yes/No)'* – assessing whether a city or region has implemented an action plan to address air pollution, indicating their commitment to improving air quality through targeted measures and policies. An air quality action plan outlines strategies and measures to address specific air quality issues. It serves as a comprehensive approach to mitigating air pollution and improving overall air quality. The plan might include initiatives such as promoting cleaner transportation options, enhancing emission controls in industries, encouraging urban planning that reduces vehicle use, and raising public awareness about air quality. Implementing an air quality action plan is essential to translate monitoring data into effective policies and actions that protect human health and the environment.

Both identified and suggested additional indicators are applicable and beyond local context and can be applied in other cities, regions, and countries where air pollution is an issue. By monitoring these identified and suggested indicators, policymakers and environmental agencies can gain a comprehensive understanding of air pollution levels, identify areas of concern, and develop appropriate strategies to mitigate the impacts on public health and the environment.

Indicator identified to monitor fresh water pollution. **Two indicators identified** that directly address freshwater pollution issues. One is the *'ambient water quality - proportion of bodies of water with good ambient water quality'*, used by UN SDGs framework [32]. This indicator measures the percentage of water bodies that meet established standards for good water quality. It assesses the overall ecological health and pollution levels in freshwater environments. Another indicator is the *'change in the extent of water-related ecosystems over time - estimate percentage change in each major ecosystem present'*, also used by UN SDGs framework [32]. This indicator tracks the percentage change in the size and extent of water-related ecosystems, such as lakes, rivers, and wetlands, over time. It helps monitor habitat loss and degradation caused by pollution.

In addition, **three indictors identified** that indirectly address freshwater pollution problem. One is the *'wastewater treatment - percentage of wastewater receiving treatment (Tertiary)'*, used by ITU-T Y.4903/L.1603 [36], U4SSC [37], and China urban sustainability index [40]. This indicator measures the proportion of wastewater that undergoes tertiary treatment, which is a higher level of treatment that removes pollutants more effectively. It assesses the level of pollution reduction from wastewater discharge into freshwater bodies. Second one is the *'wastewater monitoring - percentage of the wastewater pipeline network monitored by a real-time data tracking sensor system'*, used by UN SDGs framework [32]. This indicator evaluates the extent to which the wastewater pipeline network is equipped with real-time monitoring systems. It helps detect and address potential pollution incidents promptly. The third one is the *'index of coastal eutrophication'*, used by UN SDGs framework [32]. This indicator measures the level of nutrient enrichment in coastal waters, which can lead to excessive algae growth and oxygen depletion. It assesses the risk of eutrophication, a significant issue for freshwater ecosystems.

In addition to **the five identified indicators,** the authors propose **eight additional monitoring** indicators that indirectly address freshwater pollution challenges in Norwegian cities, including:

1. *'Proportion of Rivers or River Stretches with Hydro-morphological Alterations'*: This indicator is crucial in identifying changes in the physical structure of rivers, particularly due to hydropower projects. Hydropower-induced alterations can impact the ecological balance of freshwater ecosystems, and monitoring this proportion helps pinpoint areas with hydro-morphological changes, guiding targeted intervention.
2. *'Pollutant Accounting Systems for Industries or Receiving Water Bodies'*: To combat local pollution, especially from industrial sources, implementing pollutant accounting systems is essential. This indicator aids in tracking pollutants released by industries and their impact on receiving water bodies. It provides a comprehensive understanding of industrial contributions to freshwater pollution.
3. *'Monitoring Emissions of Relevant Pollutants from Agricultural Sources'*: Given the connection between agriculture and freshwater pollution, monitoring emissions of pollutants like nitrate and phosphate is critical. This indicator helps assess the impact of agricultural activities on water quality, providing insights into the sources of nutrient pollution in freshwater bodies.
4. *'Monitoring Stormwater Quality and Runoff Volumes'*: Stormwater runoff is a significant contributor to freshwater pollution. This indicator focuses on assessing the quality and volume of stormwater runoff, enabling authorities to identify areas with high pollution risk. It guides strategies to manage and treat stormwater to prevent pollution.
5. *'Continuous Water Quality Monitoring in Receiving Water Bodies'*: Regular monitoring of water quality in receiving bodies is essential for understanding the ongoing state of pollution. This indicator facilitates real-time data collection, helping authorities respond promptly to pollution events and implement timely corrective measures.
6. *'Measuring Rainwater pH and pH in Local Freshwater Bodies'*: pH levels directly impact freshwater ecosystems. Monitoring rainwater pH and

pH in local bodies provides insights into acid rain effects on water quality. This indicator aids in assessing the impact of acid rain on freshwater ecosystems.

7. *'Monitoring Acid Rain Precursors in the Air'*: Understanding air quality is key to addressing acid rain. This indicator focuses on monitoring precursors in the air, helping assess the potential impact of acid rain on freshwater bodies and guiding efforts to mitigate airborne pollutants.
8. *'Utilizing Biological Monitoring to Assess the Health and Biodiversity of Freshwater Ecosystems'*: Biological monitoring is a valuable tool for evaluating the overall health and biodiversity of freshwater ecosystems. This indicator involves studying the presence and abundance of aquatic organisms to gauge the impact of pollution on the ecosystem.

By employing these identified and suggested indicators, policymakers and environmental agencies in Norwegian cities can comprehensively evaluate the state of freshwater pollution, identify pollution sources, and implement targeted measures to protect and restore freshwater ecosystems. The identified indicators are applicable and beyond the local context and can be applied in other cities, regions, and countries where fresh water pollution is an issue. The suggested additional indicators are tailored to the specific challenges identified in the field of fresh water pollution in Norwegian cities.

Indicator identified to monitor marine areas degradation. There is very limited coverage of indicators in the selected 10 indicator frameworks to monitor marine area degradation issue. **Six indicators identified** from UN-SDGs framework address issues such as extensive fishing, ocean acidification, climate change effects on oceans, pollution by aquaculture, contaminated sediments, and release of hazardous substances to the ocean, respectively. These include: 1) *'proportion of fish stocks within biologically sustainable levels'* - measures the percentage of fish stocks that are managed and harvested sustainably, ensuring their long-term viability and preventing overfishing; 2) *'degree of implementation of international instruments aiming to combat illegal, unreported, and unregulated fishing'*- assesses the extent to which international agreements and measures to combat illegal fishing practices are implemented effectively, promoting responsible and legal fishing practices; 3) *'degree of application of a legal/regulatory/ policy/institutional framework which recognizes and protects access rights for small-scale fisheries'* - evaluates the implementation of legal and policy frameworks that protect the rights of small-scale fisheries and ensure their sustainable management and access to resources; 4) *'average marine acidity (pH) measured at agreed sampling stations'* - monitors the average acidity level of the marine environment, specifically the pH level, to assess the impacts of ocean acidification, which is a consequence of increased CO_2 absorption by the oceans; 5) *'Index of coastal eutrophication'* - measures the level of nutrient enrichment in coastal waters, which can lead to excessive algae growth and oxygen depletion. It helps assess the risk of eutrophication and its impacts on marine ecosystems; and 6) *'Index of plastic debris density'* - quantifies the density of plastic debris in marine areas, providing insight into the extent of plastic pollution and its potential impacts on marine organisms and ecosystems.

In addition to these **six identified indicators**, an additional **six monitoring indicators** can be utilized to assess marine areas degradation, including:

1. *'Proportion of Marine Areas with Good Ambient Water Quality'*: This indicator is vital for evaluating the overall health of marine areas, addressing concerns related to pollution, aquaculture, and hazardous substances. Monitoring water quality provides insights into the presence of contaminants and the impact on marine ecosystems, allowing policymakers to initiate targeted conservation efforts.
2. *'Seasonal Temperature Deviations from Long-Term Averages'*: Monitoring temperature variations is essential in the face of increased temperatures and climate change impacts. This indicator helps assess the resilience of marine ecosystems to temperature fluctuations, providing crucial information for adapting conservation strategies to climate-driven changes.
3. *'Coverage of Monitoring Programs for Biological and Physio-Chemical Indicators in Marine Areas'*: This indicator ensures a robust understanding of marine ecosystem dynamics by evaluating the extent of monitoring programs. By tracking biological and physio-chemical indicators, policymakers gain insights into the health and functioning of marine areas, facilitating informed decision-making on conservation measures.
4. *'Extent of Marine Areas with Contaminated Sediment'*: Addressing the challenge of contaminated sediments, this indicator focuses on measuring the extent of pollution in coastal areas and fjords. Monitoring sediment quality provides a direct assessment of the impact of hazardous substances, supporting efforts to remediate sediments and protect marine biodiversity.
5. *'Environmental Status of Marine Areas'*: This overarching indicator evaluates the overall environmental status of marine areas, offering a consolidated view of the multiple pressures they face. Assessing the environmental status provides a baseline for measuring the effectiveness of conservation measures, guiding policymakers in their efforts to achieve good environmental status for all sea areas.
6. *'Regional Pollution Accounting Systems'*: To tackle issues related to pollution from various sources, this indicator involves establishing regional pollution accounting systems. Such systems allow authorities to trace and manage pollution sources, contributing to targeted strategies for reducing hazardous substance emissions and controlling pollution from human activities.

Both identified and suggested additional indicators to assess marine areas degradation are application and beyond local context. By utilizing these identified and suggested indicators, policymakers and environmental agencies can gain a comprehensive understanding of the state of marine areas degradation, the issues related to overfishing, illegal fishing, pollution, and climate change impacts. These indicators offer valuable insights to guide effective management and conservation measures, support the overarching goal of protecting and restoring marine ecosystems, promoting sustainable fishing practices, reducing pollution, and mitigating climate change impacts on the marine environment.

Indicator identified to monitor waste management. **Three indicators identified** by the existing indicator frameworks to monitor waste management issue are as follows: 1) *'amount of municipal solid waste generated per capita annually'*; 2) *'percentage of city's hazardous waste that is recycled'*; and 3) *'percentage of total amount of plastic waste recycled in the city'*. These identified waste management indicators not only offer insights into local waste practices but also hold broader implications for international contexts, aligning with global sustainability goals.

The first indicator on *'amount of municipal solid waste generated per capita annually'* is used by ETSI-TS 103 463, LEED for Sustainable Cities and Communities, and Sustainable Cities International's indicator for sustainability list. This indicator is to quantify the average amount of non-hazardous solid waste that is produced by everyone in a specific area, typically measured over a year. It helps track the quantity of waste produced by the population, allowing authorities to understand how much waste is generated and identify any significant changes over time. The amount of waste generated per capita can reflect consumption patterns within a society and assists cities in evaluating their progress toward waste reduction targets.

The second indicator on *'percentage of city's hazardous waste that is recycled'* is used by ISO 37120. This indicator is used to assess the proportion of hazardous waste generated by a city that is effectively recycled instead of being disposed of through conventional waste management practices. This indicator reflects the city's ability to manage and reduce the environmental impact of hazardous waste. Monitoring the recycling of hazardous waste ensures that cities are meeting legal requirements and contributing to a responsible waste management system.

The third indicator on *'percentage of total amount of plastic waste recycled in the city'* is also used by ISO 37120. It is an indicator used to assess the effectiveness of a city's recycling programs and its commitment to sustainable waste management practices, specifically in relation to plastic waste. A higher percentage in this indicator implies that the city has a more efficient and successful recycling system in place, which can have several positive outcomes, such as reduction in environmental impact, conservation of resources, economic benefits, reduced landfill use, etc.

To monitor waste management issue in Norwegian cities, the authors suggested considering the following **two supplementary indicators**, including 1) The indicator *"the amount of waste generated per sector"* is used to quantify the amount of waste produced by different sectors within a specific city. This indicator provides insights into waste generation patterns across various sectors, helping to identify which sectors are the major contributors to waste generation and target interventions; and 2) The indicator *'the proportion of waste per sector that is recycled/reused'* is used to assess the extent to which different sectors within a specific city or region are effectively recycling or reusing their generated waste. It breaks down waste recycling and reuse rates by sectors such as residential, commercial, industrial, and institutional. This allows for an understanding of which sectors are successfully implementing sustainable waste management practices. This indicator aligns with circular economy principles by showcasing sectors that are actively participating in recycling and reuse and helps assess progress toward waste diversion targets set by cities or regulatory bodies.

By considering these indicators, policymakers can gain a comprehensive understanding of waste management in Norwegian cities, identifying major contributors to waste generation and assessing progress toward waste diversion targets. It needs to note that the indicators identified from the existing indicator frameworks and suggested by authors on waste management issues can be applied in other cities as well. By emphasizing the broader implications of these indicators, the waste management framework becomes more generalizable, appealing to an international audience, and advancing the understanding of sustainable waste practices on a global scale.

Indicator identified to monitor noise pollution. **Two indicators identified** to monitor noise pollution issues, including 1) *'exposure to noise'*; and 2) *'noise pollution - share of the population affected by noise > 55 dB(a) at night-time'*. Indicator on *'exposure to noise'* is used by ITU-T Y.4903/L.1603 and U4SSC. This indicator quantifies the proportion of city inhabitants exposed to noise levels above international or national standards. It provides a clear and measurable way to assess the severity of noise pollution, considering both the intensity of noise and the number of people affected. It helps identify areas where health risks may be higher, allows for the identification of areas or demographic groups disproportionately affected by noise pollution, helps identify areas where noise-reducing measures are needed to create healthier and more liveable urban environments.

Indicator on *'noise pollution - share of the population affected by noise > 55 dB(a) at night-time'* is used by ETSI-TS 103 463 and The European Reference Framework for Sustainable Cities. This indicator specifically targets nighttime exposure, reflecting the potential impact on sleep quality and overall well-being. It assesses the extent of noise pollution during nighttime within a city by determining the percentage of its population exposed to noise levels exceeding 55 dB(a) on the A-weighted scale. The World Health Organization (WHO) recommends that night-time noise levels not exceed 40 dB(a) for outdoor areas, with higher levels having potential health impacts. The indicator provides a means to assess whether the city is compliant with such recommendations.

No additional indicators have been suggested by the authors to monitor noise pollution in Norwegian cities (Table 3).

The identified noise pollution indicators from the existing indicator frameworks extend beyond local implications, addressing universal concerns and contributing to a global understanding of urban environmental health.

Indicator identified to monitor energy consumption. **Four indicators identified** to monitor energy consumption issue, including 1) *'total energy consumption per year'* – used by China urban sustainability index, which can be used to assess and understand the overall energy usage within a specific region or country over a given period, providing valuable insights into energy trends, efficiency, and sustainability; 2) *'total energy consumption per capita'* – used by ISO 37120, assess the average energy usage of individuals within a specific geographic area, provides valuable insights into the energy consumption habits of a population and can have implications for sustainability, development, and environmental impact; 3) *'proportion of renewable energy consumed in the city'* – used by six indicator frameworks (UN-SDGs, ISO 37120, ETSI-TS 103463, ITU-T Y.4903/L.1603, U4SSC, Sustainable Cities International's indicator for sustainability list), assess the share of energy derived from renewable sources in the overall energy consumption of a city, can be used for evaluating the sustainability and environmental impact of a city's energy consumption; and 4) *'electricity consumption per capita'*- used by three indicator frameworks (ITU-T Y.4903/L.1603, U4SSC, China urban sustainability index), assess the average amount of electricity used by each individual within a specific geographic areas, provides valuable insights into energy consumption patterns, lifestyle trends, and the efficiency of energy use.

In addition to these **four identified indicators**, the authors proposed **four additional indicators on energy consumption by sectors**, as potential supplementary indicator, to assess energy consumption issue in Norwegian cities. This indicator breaks down energy consumption by sectors such as residential, commercial, industrial, transportation, and others, which can offer a detailed and sector-specific view of energy use, provides the information needed for targeted interventions, ultimately contributing to energy efficiency, environmental sustainability, and improved quality of life.

By considering these indicators, policymakers can gain a detailed understanding of energy consumption in Norwegian cities, facilitating informed decision-making for energy efficiency and sustainable practices. It needs to note that all these identified and suggested indicators on energy consumption are applicable beyond local contexts and can be applied to other cities as well.

In summary, while the study initially focuses on Norwegian cities, the identified challenges, strategies, and indicators have significant international relevance. They provide a template for other urban areas to assess and address their environmental sustainability challenges. The study contributes to a broader understanding of urban environmental sustainability, offering a framework that can be adapted and applied globally.

Conclusions and recommendations

Cities globally continue to face significant environmental challenges, ranging from climate change and biodiversity loss to various forms of pollution, and high energy consumption. Addressing these issues requires effective measurement of environmental performance. However, there isn't a single, widely accepted way to measure how well cities are doing in terms of their environmental sustainability. Existing indicator frameworks are diverse, generic, and not tailored to specific city needs.

In response to this gap, this study introduces a scalable methodology to identify and develop indicators to assess urban environmental sustainability, demonstrated through case studies in Norway.

This methodology combines an in-depth literature review with an analysis of environmental strategies and action plans from selected case study cities. It begins by identifying key environmental challenges and its relevant environmental strategies and action plans, then aligns these challenges with corresponding strategies and action plan to develop relevant indicators. Our method merges indicators that were commonly used across 10 selected indicator frameworks with the additional suggested indicators. It incorporates indicators that measure and monitor human activities or anthropogenic pressures, such as GHG emissions. It includes indicators that can be used to assess the state of the environment, such as the concentration of air pollutants, and indicators to tracks political responses to environmental issues, such as climate and energy action plans. The underlying concept of our resulted indicators relies on comparing the pressures or statuses of each environmental challenge to set values by either environmental control regulations or defined in cities environmental strategies and action plans. In this way, these indicators are presented as indices, enable to offer a comprehensive approach to measuring and monitoring environmental challenges over time. They facilitate inter-city comparisons, allowing for the ranking of city environmental sustainability and providing insights for gaps identification and prioritization of objectives.

While initially applied in Norwegian cities, our methodology is inherently scalable and globally applicable. By combining universally recognized indicators with additional context-specific ones, our approach presents a comprehensive and adaptable framework for monitoring environmental challenges internationally. We emphasize the method's universal relevance in identifying indicator, aiming to contribute to the development of standardized approaches for assessing urban environmental sustainability.

Despite the comprehensive nature of our study, the reliability of our proposed indicators depends on the availability of reliable data. Thus, there's a critical need for standardized methods of data collection to ensure data accessibility and comparability. Future research should focus on refining these methods to enhance the reliability and robustness of the indicators.

Moreover, our approach, synthesizing literature reviews with city-specific strategies and action plans, might have biases and variations in policy depth. While our set of indicators is comprehensive, there's a chance we may miss some that are crucial for specific environmental challenges in diverse urban contexts. Acknowledging these potential biases in our approach, future research should conduct extensive literature review and a detailed look at environmental policies in diverse contexts and involve stakeholders more deeply to create a set of indicators that fits city-specific needs. Furthermore, continuous refinement of indicators, improvements in data collection, and an understanding of real-world factors affecting policy success are essential to guide cities globally toward increased environmental sustainability.

In summary, while this study primarily focuses on presenting a method for identifying indicators to assess urban environmental sustainability and applying the method by developing indicators within the context of Norwegian cities, it also provides a scalable method that holds promise for global applications. Cities around world can leverage this study to identify environmental challenges and determine how optimizing existing initiatives for a more sustainable future. The approach is replicable, with the potential for future refinements that include social and economic dimensions in urban sustainability assessments.

CRediT authorship contribution statement

Hai-Ying Liu: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Babak Ebrahimi:** Writing – review & editing, Visualization, Data curation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cacint.2024.100144.

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