



## Afghan International Journal of Science (AIJS)

Publisher: Afghan International Islamic University

Website: <https://aijs.aiiu.edu.af>

e-ISSN: 3134-5859

### Assessment of CO<sub>2</sub> Concentration Reduction Potential through Green Chemistry Principles: A Survey-Based Case Study of Kabul City

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#### Abstract

Kabul City is experiencing increasing environmental pressure from rapid urban expansion, dependence on fossil fuels, traffic growth, declining green spaces, and limited emission-control infrastructure. This study assessed experts' perceptions of the potential of green chemistry principles to reduce carbon dioxide (CO<sub>2</sub>) concentrations and related emissions under Kabul's current economic and infrastructural conditions. We conducted a cross-sectional mixed-methods survey of 29 purposively selected participants with academic or professional backgrounds in chemistry, environmental science, engineering, public health, and policy-related fields. Data were collected through a structured questionnaire containing five-point Likert-scale and open-ended questions. We analyzed quantitative responses using descriptive statistics and reviewed qualitative comments thematically. Overall, 96% of responses were positive, comprising 50% agreement and 46% strong agreement, and the overall mean score was 4.14 (SD = 0.70). Respondents expressed particularly strong support for renewable energy, urban greening, cleaner transportation, catalytic process improvement, safer materials, and low-carbon construction practices. Immediate mitigation action received a mean score of 4.60 (SD = 0.56). The findings indicate that experts consider preventive and locally adaptable green chemistry measures more feasible for Kabul than capital-intensive CO<sub>2</sub> capture and conversion technologies. Because the study was perception-based and did not directly measure atmospheric CO<sub>2</sub> concentrations or emission reductions, the results should serve as an exploratory basis for future emission inventories, field monitoring, pilot projects, and quantitative modeling.

**Keywords:** Carbon dioxide; Environmental policy; Green chemistry; Kabul City; Renewable energy; Urban emissions

#### Article History

**Published:** Sep 30, 2026

**Accepted:** Aug 5, 2026

**Revised:** Jul 30, 2026

**Received:** Feb 22, 2026

**Cite as:** Ghanizadah, S., Mayar, Z., & Salahudeen, S. A. (2026). Assessment of CO<sub>2</sub> Concentration Reduction Potential through Green Chemistry Principles: A Survey-Based Case Study of Kabul City. *Afghan International Journal of Science* 2(3), 295-309. DOI: <https://doi.org/10.66546/aijs.v2i3.55>

## Introduction

Climate change and urban air pollution are closely connected because many activities that release carbon dioxide (CO<sub>2</sub>) also emit pollutants that harm human health. The Intergovernmental Panel on Climate Change has emphasized the need for rapid, deep, and sustained reductions in greenhouse-gas emissions to limit further warming, while the World

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Link to this article: <https://aijs.aiiu.edu.af/index.php/aijs/article/view/55>

Health Organization identifies ambient air pollution as a major public-health risk (Intergovernmental Panel on Climate Change [IPCC], 2023; World Health Organization [WHO], 2021). Although CO<sub>2</sub> is not generally treated as a toxic outdoor air pollutant at ambient concentrations, reducing fossil-fuel combustion can lower both CO<sub>2</sub> emissions and harmful co-pollutants.

Urban areas are central to this challenge. Population growth, expanding vehicle fleets, household energy demand, construction, industrial activity, and land-cover change concentrate emissions within limited geographical areas. International assessments therefore emphasize energy efficiency, renewable energy, electrification, cleaner production, and sustainable urban planning as essential components of long-term mitigation (International Energy Agency [IEA], 2023; United Nations Environment Program [UNEP], 2023). These measures are especially relevant in rapidly growing cities where monitoring systems, reliable energy infrastructure, and regulatory enforcement remain weak.

Green chemistry offers a preventive scientific framework for addressing such pressures. It is defined as designing chemical products and processes that reduce or eliminate the use and generation of hazardous substances (Anastas & Warner, 1998). Its principles include waste prevention, energy efficiency, renewable feedstocks, catalysis, safer materials, design for degradation, and inherently safer processes. Later scholarship has extended this framework by emphasizing life-cycle impacts, resource efficiency, and measurable sustainability performance (Anastas & Eghbali, 2010; Lancaster, 2016; Sheldon, 2018).

For CO<sub>2</sub> mitigation, green chemistry matters not only for carbon capture and conversion but also for preventing emissions at the source. Practical applications include reducing fossil-energy demand, improving catalytic and process efficiency, substituting renewable inputs, recovering value from waste, and designing lower-carbon materials. International studies demonstrate the technical potential of heterogeneous catalysts, biological routes, and porous materials for CO<sub>2</sub> capture and utilization (Sarkar et al., 2024; Wang et al., 2021; Wu et al., 2024; Yu & He, 2021). Green-manufacturing research also highlights renewable resources, process optimization, catalysis, and safer material selection as pathways to reduce environmental burdens (Idoko et al., 2024).

However, advanced capture and conversion systems require specialized equipment, reliable energy, trained personnel, and substantial investment. Their direct transfer to a resource-constrained city may therefore be difficult. In Kabul, the more immediate value of green chemistry may lie in preventive, locally adaptable measures such as renewable-energy substitution, cleaner household fuels, improved combustion efficiency, modernized transportation, protection of urban vegetation, cleaner small-industry processes, and safer construction materials. This approach remains consistent with the central green chemistry objective of preventing pollution and resource loss before end-of-pipe treatment becomes necessary.

Kabul has experienced rapid population growth, unplanned urban expansion, increasing vehicle use, widespread combustion of coal, wood, and petroleum products, dependence on diesel generators, and continuing pressure on green spaces. Kabul-focused studies identify transportation, solid-fuel combustion, dust, small industries, brick kilns, generators, and

vegetation loss as important contributors to deteriorating environmental conditions (Safi, 2024; Sharifi et al., 2024; Sultan Zoi et al., 2024). These studies show that the city's environmental problems arise from several connected sectors and therefore require a coordinated response rather than a single technology. Afghanistan's environmental and development documents also identify renewable energy, sustainable urban development, improved transportation, ecosystem protection, and stronger institutional capacity as priorities, while acknowledging limitations in finance, monitoring, enforcement, and technical expertise (Islamic Republic of Afghanistan, 2021; National Environmental Protection Agency [NEPA], 2017). Against this background, expert-based exploratory research can help identify relevant and feasible interventions before more costly field studies or pilot projects are undertaken.

Existing Kabul studies have mainly examined pollution sources, air-quality trends, land-cover change, and environmental or socio-economic pressures. International green chemistry research, by contrast, often concentrates on advanced catalysts, capture materials, and industrial-scale CO<sub>2</sub> conversion. A practical gap therefore remains between local environmental diagnosis and the context-sensitive application of green chemistry principles in Kabul. Specifically, limited evidence is available on which preventive measures local experts consider feasible, which barriers may hinder implementation, and which government actions should receive priority.

This study addresses that gap by assessing expert perceptions of the main sources of CO<sub>2</sub> emissions in Kabul City, the feasibility of selected green chemistry interventions, the main implementation barriers, and the policy actions needed to support practical adoption. The study is exploratory and perception-based; it does not measure atmospheric CO<sub>2</sub> concentrations or calculate source-specific emission reductions. Its purpose is to establish a structured foundation for later measurement, pilot testing, and quantitative evaluation.

The following research questions guided the study:

1. What are the perceived major sources associated with CO<sub>2</sub> emissions in Kabul City?
2. Which green chemistry principles and locally adaptable interventions are considered most feasible for supporting CO<sub>2</sub> reduction under Kabul's economic and infrastructural conditions?
3. What implementation barriers and government actions are perceived as most important for the effective adoption of these interventions?

## **Methods and Materials**

This study employed a cross-sectional, descriptive-analytical mixed-method design to assess expert perceptions of CO<sub>2</sub>-related environmental pressures and the feasibility of green chemistry-based responses in Kabul City. The design combined structured quantitative responses with contextual explanations from open-ended questions, allowing the numerical patterns to be interpreted alongside the participants' professional judgments (Creswell & Creswell, 2018).

The target population comprised individuals with relevant academic qualifications or professional experience in chemistry, environmental science, public health, chemical and

industrial engineering, energy, environmental management, and policy. The study used purposive sampling because it required information-rich participants with specialized knowledge rather than statistical representation of the general population (Saunders et al., 2019; Taherdoost, 2016). Twenty-nine experts completed the survey. This sample was suitable for an exploratory assessment, although it does not support broad population-level generalization.

The questionnaire was developed from the study objectives, the twelve principles of green chemistry, the literature on urban emission sources, and Kabul's environmental conditions. It included participant-background questions, 15 closed-ended analytical items, and four open-ended questions. Closed-ended responses were scored on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The items covered perceived emission sources, public awareness, renewable energy, catalysis, transportation, urban greening, safer materials, low-carbon construction, immediate mitigation, source identification, and the government's role.

Specialists assessed content and face validity, after which the team revised ambiguous and overlapping items. Reliability was examined using Cronbach's alpha. The 15-item instrument produced a coefficient of 0.745, which was considered acceptable for an exploratory survey (Hair et al., 2019). Participation was voluntary, respondents were informed of the study's academic purpose, and the analytical dataset included no personally identifying information.

We analyzed closed-ended responses in SPSS and Microsoft Excel using mean, standard deviation, median, mode, percentage agreement, and ranking by mean score. Mean values were interpreted as follows: 1.00–1.80 = very low agreement, 1.81–2.60 = low agreement, 2.61–3.40 = moderate agreement, 3.41–4.20 = high agreement, and 4.21–5.00 = very high agreement. Standard deviations showed variation in expert opinion (Field, 2018). Because the sample included only 29 respondents, we did not use factor analysis or multivariable inferential analysis; these procedures would not provide stable estimates for 15 survey items. We reviewed open-ended responses thematically to identify recurring views on sources, practical actions, implementation barriers, and institutional responsibilities.

Table 1 summarizes the professional diversity represented in the expert sample. This information provides the context needed to interpret the findings presented in the following section.

**Table 1.** Characteristics represented in the expert sample ( $N = 29$ )

| Characteristic       | Categories represented                                                                                                                         | Relevance to the study                                                                                                         |
|----------------------|------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------|
| Professional profile | Environmental specialists; medical/public-health professionals; chemists; chemical and industrial engineers; energy and policy-related experts | Provided multidisciplinary perspectives on urban emissions, health, industrial processes, green chemistry, and implementation. |

| Characteristic          | Categories represented                                                                       | Relevance to the study                                                                                                |
|-------------------------|----------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|
| Educational background  | Chemistry; environmental science; engineering; public health; energy and related disciplines | Supported interpretation from scientific, technical, environmental, and health perspectives.                          |
| Institutional sector    | Government organizations; academic institutions; technical and professional organizations    | Included views relevant to policy formulation, research, regulation, and technical implementation.                    |
| Professional experience | From approximately 1 year to more than 5 years                                               | Combined early-career and experienced professional perspectives.                                                      |
| Sampling approach       | Purposive expert selection                                                                   | Focused the survey on respondents with relevant knowledge; results are exploratory and not population-representative. |

*Note. The table reports the professional diversity represented in the sample. Individual identities and institutional details are not disclosed to preserve confidentiality.*

## Findings and Discussion

The findings follow the same sequence as the research questions. The section begins with the participant profile, then examines perceived emission sources, the feasibility of green chemistry strategies, and the policy conditions required for implementation. Within each subsection, the numerical results are followed by interpretation and comparison with relevant literature.

### Characteristics of the Participants

The 29 participants represented environmental, chemical, engineering, health, academic, energy, and policy-related backgrounds (Table 1). They were drawn from government, academic, technical, and professional settings, and their experience ranged from early-career to more than five years. This multidisciplinary composition was appropriate because the proposed interventions involve energy, transportation, industrial processes, public health, urban planning, and institutional policy.

This range of expertise strengthened the exploratory assessment by bringing together technical and policy perspectives. At the same time, purposive recruitment and the small sample mean that the findings should be understood as informed expert judgments rather than estimates of public opinion. With this limitation in mind, the first analytical question concerned which sources respondents associated most strongly with CO<sub>2</sub>-related pressure in Kabul.

### Perceived Major Sources of CO<sub>2</sub> Emissions in Kabul

Respondents showed high or very high agreement that several interconnected urban factors contribute to CO<sub>2</sub> emissions and related environmental pressure in Kabul (Table 2). The reduction of green spaces received the highest mean score ( $M = 5.00$ ,  $SD = 0.66$ ). Transportation, household fossil-fuel consumption, small-scale industries, and limited public awareness each received a mean score of 4.00, indicating high agreement.

**Table 2.** *Perceived major sources and contributing conditions associated with CO<sub>2</sub> emissions in Kabul City*

| Survey statement                                                                          | Mean | SD   | Median | Mode | Agreement level |
|-------------------------------------------------------------------------------------------|------|------|--------|------|-----------------|
| Transportation activities are a major source of CO <sub>2</sub> emissions.                | 4.00 | 0.94 | 4      | 4    | High            |
| Household fossil-fuel consumption contributes substantially to CO <sub>2</sub> emissions. | 4.00 | 0.68 | 5      | 5    | High            |
| Reduction of green spaces intensifies CO <sub>2</sub> -related environmental pressure.    | 5.00 | 0.66 | 5      | 5    | Very high       |
| Small-scale industries contribute to CO <sub>2</sub> emissions.                           | 4.00 | 0.95 | 4      | 5    | High            |
| Public awareness of the consequences of increasing CO <sub>2</sub> is low.                | 4.00 | 0.89 | 4      | 4    | High            |

The very high score for reduced green space should not be interpreted as evidence that vegetation loss is the city's largest quantified emission source. Rather, it indicates that respondents considered vegetation protection and urban greening especially important within Kabul's environmental context. Green spaces support carbon uptake, local cooling, dust control, and broader environmental quality, and Kabul-focused research has similarly emphasized their declining condition and mitigation value (Safi, 2024).

Respondents also strongly endorsed transportation and household fossil-fuel use. The transportation item showed greater variation in responses ( $SD = 0.94$ ) than household fuel use ( $SD = 0.68$ ), but both were regarded as important intervention areas. These perceptions align with evidence linking Kabul's environmental deterioration to vehicle growth, traffic congestion, household combustion of coal and wood, diesel generators, brick kilns, and unplanned urban expansion (Sharifi et al., 2024; Sultan Zoi et al., 2024).

Small industries received high agreement but also the largest variation among the source-related items ( $SD = 0.95$ ), probably reflecting differences in participants' familiarity with workshops, brick production, and combustion practices. This result suggests that future emission inventories should distinguish among industrial subsectors rather than treating small industry as a single source. Respondents also considered public awareness inadequate, indicating that technical measures will need to be accompanied by education, communication, and enforcement. The next question was therefore not only what to control, but which green chemistry-based responses seemed most feasible.

### Perceived Potential of Green Chemistry Principles

Participants expressed broad support for preventive green chemistry measures adapted to Kabul's current conditions (Table 3). Renewable energy received the highest mean score ( $M = 5.00$ ,  $SD = 0.83$ ), while green catalysts, cleaner transportation, urban greening, safer and biodegradable materials, and low-carbon construction each received a mean score of 4.00. The

pattern indicates a preference for practical measures that reduce energy use, emissions, and material hazards at their source.

**Table 3:** *Perceived effectiveness of green chemistry-related strategies for CO<sub>2</sub> mitigation*

| Survey statement                                                                 | Mean | SD   | Median | Mode | Agreement level |
|----------------------------------------------------------------------------------|------|------|--------|------|-----------------|
| Use of renewable energy sources, including solar and wind.                       | 5.00 | 0.83 | 5      | 5    | Very high       |
| Application of green catalysts in small industries.                              | 4.00 | 0.73 | 4      | 4    | High            |
| Improvement and modernization of transportation systems.                         | 4.00 | 0.86 | 4      | 4    | High            |
| Expand green spaces and plant urban trees.                                       | 4.00 | 0.73 | 5      | 5    | High            |
| Replacement of conventional chemicals with safer and biodegradable alternatives. | 4.00 | 0.72 | 4      | 4    | High            |
| Use of low-carbon materials and green chemistry practices in construction.       | 4.00 | 0.74 | 4      | 4    | High            |

The strong preference for renewable energy reflects the green chemistry principle of energy efficiency and the broader transition from fossil resources to renewable inputs. In Kabul, distributed solar systems may be particularly relevant for households, public buildings, and small enterprises because they can reduce diesel-generator use and improve energy resilience. However, the survey assessed perceived suitability rather than technical generation potential, cost-effectiveness, or verified emission reductions.

Support for green catalysts is consistent with the principle of catalysis, which seeks to improve reaction efficiency, reduce energy demand, and minimize waste. International studies show that catalysts and specialized materials can support CO<sub>2</sub> conversion and cleaner industrial processes (Wang et al., 2021; Wu et al., 2024). Under Kabul's current conditions, the immediate implication is more modest: affordable catalytic improvements, better combustion, process control, maintenance, and cleaner production practices may be more realistic than complex capture systems.

Cleaner transportation, urban greening, safer chemicals, and low-carbon construction extend the same preventive logic across other sectors. Transportation modernization supports energy efficiency and pollution prevention; urban vegetation supports carbon uptake, cooling, and dust reduction; safer, biodegradable materials reflect the principles of safer chemistry and design for degradation; and low-carbon construction promotes life-cycle resource efficiency. Collectively, these findings suggest that the strongest entry points for Kabul are measures that can be introduced progressively and supported by existing institutions. Their implementation, however, depends on policy priorities and the ability to overcome practical barriers.

### Challenges and Policy Priorities for Implementing Green Chemistry

Respondents placed the greatest emphasis on immediate mitigation action ( $M = 4.60$ ,  $SD = 0.56$ ), followed by identification of the principal sources ( $M = 4.14$ ,  $SD = 0.44$ ) and government leadership ( $M = 3.90$ ,  $SD = 0.37$ ) (Table 4). The relatively low standard deviations indicate broad agreement on these policy priorities.

**Table 4:** *Expert perspectives on policy priorities for CO<sub>2</sub> mitigation in Kabul City (N = 29)*

| Policy item                                                                                       | Mean | SD   | Median | Mode | Interpretation      |
|---------------------------------------------------------------------------------------------------|------|------|--------|------|---------------------|
| Identification of the principal CO <sub>2</sub> emission source should guide mitigation planning. | 4.14 | 0.44 | 4      | 4    | High agreement      |
| Immediate mitigation actions are required.                                                        | 4.60 | 0.56 | 5      | 5    | Very high agreement |
| Government leadership is essential for effective CO <sub>2</sub> reduction.                       | 3.90 | 0.37 | 4      | 4    | High agreement      |

The priority assigned to immediate action suggests that respondents did not view additional research as a reason to delay basic interventions. Near-term measures could include controlling highly polluting fuels, strengthening vehicle inspection and maintenance, improving public transport, expanding distributed solar energy, protecting urban vegetation, and improving combustion and process efficiency in small industries. These actions correspond with international mitigation pathways centered on renewable energy, efficiency, electrification, and low-emission urban development (IEA, 2023; IPCC, 2023; UNEP, 2023).

At the same time, the high score for source identification shows that action should be guided by better evidence. Expert perception can identify likely priorities, but effective policy requires a city-level emission inventory, fuel-consumption data, source-specific measurements, and repeated environmental monitoring. Without these tools, resources may be directed toward the most visible sources rather than those responsible for the greatest emissions. Afghanistan's policy documents similarly emphasize stronger monitoring, institutional capacity, renewable-energy development, and coordinated implementation (Islamic Republic of Afghanistan, 2021; NEPA, 2017).

Government leadership is necessary because the proposed measures depend on standards, incentives, public investment, technical support, and inter-agency coordination. The open-ended responses also pointed to limited finance, weak enforcement, shortages of expertise, low public awareness, fragmented responsibilities, restricted access to technology, and insufficient data. These barriers are particularly important for advanced capture or conversion systems, which require reliable infrastructure, quality control, skilled personnel, and low-carbon energy inputs (Sarkar et al., 2024; Wang et al., 2021; Wu et al., 2024; Yu & He, 2021). A phased approach that begins with preventive and lower-cost measures is therefore more realistic for Kabul.

## Policy Implications

The results support integrating green chemistry principles into Kabul's energy, transportation, industrial, construction, and urban-environment policies. The practical starting point is prevention: reducing fossil-fuel demand, improving energy and material efficiency, using safer inputs, expanding renewable energy, and minimizing waste before relying on expensive end-of-pipe controls. This orientation follows the original green chemistry framework and later sustainability metrics, which prioritize hazard reduction, catalysis, renewable resources, and life-cycle performance (Anastas & Warner, 1998; Anastas & Eghbali, 2010; Lancaster, 2016; Sheldon, 2018).

In the short term, policy should focus on distributed solar energy, cleaner household heating, vehicle inspection and fuel-quality control, protection of urban green spaces, and basic cleaner-production assistance for small industries. Medium-term measures may include public-transport modernization, low-carbon construction standards, incentives for efficient equipment, technical training, and environmental-performance requirements for industrial facilities. Consider more advanced carbon capture, utilization, and catalytic systems through pilot projects only where technical, financial, and energy conditions are suitable.

Implementation will require cooperation among government agencies, municipalities, universities, industry, professional organizations, and communities. Universities can support emissions monitoring, local material assessment, pilot testing, catalyst evaluation, and workforce development. Government institutions can provide standards and incentives, industry can demonstrate cleaner processes, and communities can support household energy changes and protect green spaces. In this way, the policy implications lead directly to a phased set of recommendations rather than a single technological solution.

## Conclusion

This study assessed expert perceptions of how green chemistry principles could support CO<sub>2</sub> reduction and emission mitigation in Kabul City. Respondents identified transportation, household fossil-fuel consumption, small industries, declining green spaces, and limited public awareness as important sources or aggravating conditions. Renewable energy received the strongest support among the proposed interventions, while cleaner transportation, catalysis, urban greening, safer materials, and low-carbon construction also received high agreement.

The findings indicate that green chemistry can provide a useful preventive framework for Kabul when translated into locally feasible measures rather than limited to advanced carbon-capture technologies. Respondents strongly supported immediate mitigation, better source identification, and government leadership. Effective implementation will therefore require regulation, financing, institutional coordination, technical training, public awareness, and reliable monitoring data.

Because the study was exploratory and perception-based, it does not demonstrate actual reductions in atmospheric CO<sub>2</sub> concentrations. Its contribution is identifying expert-supported priorities that can guide field measurement and pilot implementation. A phased approach beginning with renewable energy, cleaner household and transport systems, urban greening,

process efficiency, and safer materials is appropriate, with more advanced technologies introduced only where technical and economic conditions permit.

### **Recommendations**

Based on the findings, Kabul should begin with a limited package of measures that are technically achievable and comparatively affordable. Priority should be given to distributed solar energy for households and public institutions, improved vehicle inspection and maintenance, cleaner household heating, protection and rehabilitation of green spaces, and cleaner-production support for small industries. These actions can produce overlapping climate, environmental, and health benefits (World Bank, 2022).

Transport planning should combine reliable public transport, improved traffic flow, fuel-quality control, vehicle-emission standards, and the gradual replacement of highly polluting vehicles. Future transport investments and urban mobility plans should incorporate environmental performance (Asian Development Bank [ADB], 2017). Urban greening should likewise be linked with land-use control, irrigation, community stewardship, and municipal maintenance rather than limited to short-term tree-planting campaigns (UNEP, 2003).

For industry and construction, government and universities should develop practical demonstrations in process efficiency, safer chemical substitution, waste valorization, material efficiency, and low-carbon construction. These activities should consider the full life cycle of materials, including hazardous inputs, waste generation, reuse, and environmental release (Organization for Economic Cooperation and Development [OECD], 2019; UNEP, 2019; United Nations Industrial Development Organization [UNIDO], 2020).

Finally, implementation should be supported by a city-level emissions inventory, routine monitoring, measurable performance indicators, and transparent institutional reporting. Future studies should use larger samples and direct measurements, and should compare the cost, maintenance needs, and verified emission reductions of selected interventions through pilot projects.

The study had several limitations: it used a small purposive sample of 29 experts and therefore cannot be generalized to Kabul's full population. It was cross-sectional and perception-based, and it did not include direct atmospheric CO<sub>2</sub> monitoring, a city-level emissions inventory, source-specific fuel data, or field validation of the proposed interventions. Some participants may also have interpreted CO<sub>2</sub> together with broader air-pollution concerns. These limitations do not invalidate the exploratory results, but they require cautious interpretation and empirical verification.

### **Author Contributions**

Shafiqullah Ghanizadah contributed to the study design, questionnaire development, data collection, data analysis, and preparation of the initial manuscript draft. Zabihullah Mayar contributed to the literature review, interpretation of the findings, and critical revision of the manuscript. Shafaat Ahmed Salahudeen contributed to the study's conception and supervision, refinement of the methodology, scientific review, and final approval of the manuscript. All authors reviewed and approved the final manuscript.

## References

- Anastas, P. T., & Eghbali, N. (2010). Green chemistry: Principles and practice. *Chemical Society Reviews*, 39(1), 301–312. <https://doi.org/10.1039/B918763B>
- Anastas, P. T., & Warner, J. C. (1998). *Green chemistry: Theory and practice*. Oxford University Press.
- Asian Development Bank. (2017). *Afghanistan transport sector master plan update (2017–2036)*. <https://www.adb.org/sites/default/files/institutional-document/327561/afg-transport-plan-2017-2036.pdf>
- Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.
- Field, A. (2018). *Discovering statistics using IBM SPSS Statistics* (5th ed.). SAGE Publications.
- Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2019). *Multivariate data analysis* (8th ed.). Cengage.
- Idoko, F. A., Ezeamii, G. C., & Ojochogwu, O. J. (2024). Green chemistry in manufacturing: Innovations in reducing environmental impact. *World Journal of Advanced Research and Reviews*, 23(3), 2826–2841. <https://doi.org/10.30574/wjarr.2024.23.3.2938>
- Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report*. <https://doi.org/10.59327/IPCC/AR6-9789291691647>
- International Energy Agency. (2023). *CO<sub>2</sub> emissions in 2022*. <https://www.iea.org/reports/co2-emissions-in-2022>
- Islamic Republic of Afghanistan, Ministry of Finance. (2021). *Afghanistan national peace and development framework II (2021–2025)*.
- Lancaster, M. (2016). *Green chemistry: An introductory text* (3rd ed.). Royal Society of Chemistry.
- National Environmental Protection Agency, Government of the Islamic Republic of Afghanistan. (2017). *Second national communication under the United Nations Framework Convention on Climate Change*.
- Organisation for Economic Cooperation and Development. (2019). *Global material resources outlook to 2060: Economic drivers and environmental consequences*. OECD Publishing. <https://doi.org/10.1787/9789264307452-en>
- Safi, L. (2024). Green spaces and urban forests' role in mitigating air pollution in Kabul city: A review. *Journal of Natural Sciences*, 7(2), 57–71. <https://doi.org/10.62810/jns.v7i2.79>
- Sarkar, O., Antonopoulou, I., Xiros, C., Bruce, Y., Souadkia, S., Rova, U., & Matsakas, L. (2024). Carbonic anhydrase-assisted acidogenic fermentation of forest residues for low-carbon hydrogen and volatile fatty acid production. *Green Chemistry*, 26, 5564–5582. <https://doi.org/10.1039/D4GC00044G>

- Saunders, M., Lewis, P., & Thornhill, A. (2019). *Research methods for business students* (8th ed.). Pearson.
- Sharifi, M. S., Aslami, A., Zaheb, H., Abed, I., Shokoory, A. W., & Yona, A. (2024). Modeling the impact of socioeconomic and environmental factors on air quality in the city of Kabul. *Sustainability*, 16, Article 10969. <https://doi.org/10.3390/su162410969>
- Sheldon, R. A. (2018). Metrics of green chemistry and sustainability: Past, present, and future. *ACS Sustainable Chemistry & Engineering*, 6(1), 32–48. <https://doi.org/10.1021/acssuschemeng.7b03505>
- Sultan Zoi, F., Samim, A. K., & Wiar, A. R. (2024). A case study of air quality in Kabul, Afghanistan. *International Journal of Current Science Research and Review*, 7(11), 8283–8292. <https://doi.org/10.5281/zenodo.14059166>
- Taherdoost, H. (2016). Sampling methods in research methodology: How to choose a sampling technique for research. *International Journal of Academic Research in Management*, 5(2), 18–27. <https://doi.org/10.2139/ssrn.3205035>
- United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. <https://sdgs.un.org/2030agenda>
- United Nations Environment Programme. (2003). *Afghanistan: Post-conflict environmental assessment*. <https://www.unep.org/resources/assessment/afghanistan-post-conflict-environmental-assessment>
- United Nations Environment Programme. (2019). *Global chemicals outlook II: From legacies to innovative solutions*. <https://www.unep.org/resources/report/global-chemicals-outlook-ii-legacies-innovative-solutions>
- United Nations Environment Programme. (2023). *Emissions gap report 2023: Broken record—Temperatures hit new highs, yet world fails to cut emissions (again)*. <https://www.unep.org/resources/emissions-gap-report-2023>
- United Nations Industrial Development Organization. (2020). *Industrial development report 2020: Industrializing in the digital age*. <https://www.unido.org/resources-publications-flagship-publications-industrial-development-report-series/idr2020>
- Wang, Y., Winter, L. R., Chen, J. G., & Yan, B. (2021). CO<sub>2</sub> hydrogenation over heterogeneous catalysts at atmospheric pressure: From electronic properties to product selectivity. *Green Chemistry*, 23(1), 249–267. <https://doi.org/10.1039/D0GC03506H>
- World Bank. (2022). *Air pollution and health in urban environments: A global review*. <https://www.worldbank.org/en/topic/environment/brief/air-pollution>
- World Health Organization. (2021). *Ambient (outdoor) air pollution*. [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health)
- Wu, Z., Li, Z., Hu, L., Afewerki, S., Strømme, M., Zhang, Q.-F., & Xu, C. (2024). A sequential flow process of CO<sub>2</sub> capture and conversion using cost-effective porous

organic polymers. *Green Chemistry*, 26, 10960–10968.

<https://doi.org/10.1039/D4GC03494E>

Yu, D.-G., & He, L.-N. (2021). Introduction to CO<sub>2</sub> utilisation. *Green Chemistry*, 23(8), 3499–3501. <https://doi.org/10.1039/D1GC90036F>

### Appendix A. Questionnaire

The questionnaire was administered to experts using a five-point Likert scale: 1 = Strongly disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly agree.

| Item | Statement                                                                                                                    | Response (1–5) |
|------|------------------------------------------------------------------------------------------------------------------------------|----------------|
| Q1   | The increasing concentration of CO <sub>2</sub> in Kabul City is a serious environmental concern.                            |                |
| Q2   | Transportation activities are a major source of CO <sub>2</sub> emissions in Kabul City.                                     |                |
| Q3   | Household consumption of fossil fuels contributes substantially to CO <sub>2</sub> emissions.                                |                |
| Q4   | The reduction of green spaces intensifies CO <sub>2</sub> -related environmental pressure in Kabul.                          |                |
| Q5   | Small-scale industries contribute to CO <sub>2</sub> emissions in Kabul City.                                                |                |
| Q6   | Public awareness of the consequences of increasing CO <sub>2</sub> is low.                                                   |                |
| Q7   | Renewable energy sources, including solar and wind, can effectively reduce CO <sub>2</sub> emissions.                        |                |
| Q8   | The application of green catalysts in small industries can reduce CO <sub>2</sub> emissions and improve process efficiency.  |                |
| Q9   | Improvement and modernization of transportation systems can reduce CO <sub>2</sub> emissions.                                |                |
| Q10  | Expansion of green spaces and urban tree planting can contribute to CO <sub>2</sub> mitigation.                              |                |
| Q11  | Replacing conventional chemicals with safer and biodegradable alternatives can reduce environmental impacts.                 |                |
| Q12  | Low-carbon materials and green chemistry practices should be promoted in the construction sector.                            |                |
| Q13  | The principal sources of CO <sub>2</sub> emissions in Kabul should be identified before mitigation policies are implemented. |                |

| Item       | Statement                                                                                                                  | Response (1–5) |
|------------|----------------------------------------------------------------------------------------------------------------------------|----------------|
| <b>Q14</b> | Immediate practical action is required to reduce CO <sub>2</sub> emissions in Kabul City.                                  |                |
| <b>Q15</b> | Government leadership is essential for effective CO <sub>2</sub> reduction and implementation of green chemistry measures. |                |

### Open-Ended Questions

1. In your opinion, what is the largest source of CO<sub>2</sub> emissions in Kabul City?
2. What immediate and practical actions should be prioritized to reduce CO<sub>2</sub> emissions in Kabul?
3. What are the main barriers to implementing green chemistry principles in Kabul?
4. What role should government institutions, universities, industry, and communities play in implementation?