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Design and Development of a Web-Based Platform to Track Carbon Footprint

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Abstract

Climate change is a critical global challenge demanding both systemic change and localized, individual action. Climate change poses a growing threat to Zambia's social, economic, and environmental systems, yet carbon footprint literacy and access to personalized sustainability tools remain limited. This study presents the design and development of a web-based carbon footprint tracking platform specifically tailored to bridge this awareness-action gap in the Zambian context, integrating global carbon accounting standards with local emission factors and national climate policies. A baseline study involving Zambian respondents assessed climate change awareness, understanding of carbon footprint concepts, environmental attitudes, digital readiness, and acceptance of AI guided recommendations. The findings revealed that although awareness of climate change is moderately high, knowledge of carbon footprint principles remains low. Digital readiness is increasing particularly among educated and urban groups yet there is still a strong need for simplified interfaces, localized examples, and clear explanations to support meaningful engagement.

The system was developed using a Design Science Research methodology and implemented as a modular web platform built in React. Emissions calculation followed the Greenhouse Gas (GHG) Protocol, IPCC 2006 Guidelines, and Zambia's Carbon Market Framework, using national emission factors. The calculator supports multiple sectors including electricity, transport, agriculture, waste, and forestry. A Retrieval-Augmented Generation engine was integrated to deliver personalized, Zambia-specific sustainability recommendations, combining local mitigation practices, national policy guidelines, and empirically validated behavioral insights. The tool effectively bridges the gap between users' limited carbon literacy and the need for localized climate-action guidance at individual and community level.

This research contributes a validated methodological framework and a practical digital solution that aligns with Zambia's Measurement, Reporting, and Verification requirements under the Green Economy and Climate Change Act. The system has significant potential for use in households, schools, businesses, and community programs, supporting national low-carbon development and climate education initiatives. Future work will focus on expanding datasets, integrating real-time energy, enhancing AI explainability, and aligning the platform with emerging carbon market opportunities in Zambia.

Keywords: Carbon Footprint, Climate Change, Greenhouse Gas Protocol, IPCC Guidelines, Emission Factors, Zambia, Artificial Intelligence, RAG Systems, Sustainability, Digital Climate Tools, Carbon Accounting, Environmental Awareness, Climate Education, Green Economy and Climate Change Act, Web-Based Application, Sustainable

1. Introduction

Climate change remains a major global challenge with profound effects on the environment, economies, and society as a whole. A critical factor fueling this crisis is the steady rise in greenhouse gas (GHG) emissions, predominantly resulting from human pursuits such as energy use, transportation, and waste production (Chuvieco *et al*., 2021; Holka *et al*., 2022). Central to addressing this issue is the concept of the carbon footprint, defined as the total GHG emissions directly and indirectly linked to individual, collective, or organizational activities. This metric has become increasingly prominent in climate change discourse, having evolved from the broader ecological footprint by specifically targeting carbon emissions instead of overall resource use (Purwanto *et al*., 2019; Ji *et al*., 2024). Notably, carbon footprint calculations can be applied at various scales, including products, households, cities, and even entire nations (Han *et al*., 2022). The carbon footprint concept, defined as the total GHG emissions attributable directly or indirectly to activities or entities, remains central to climate action strategies worldwide

(Klaaßen & Stoll, 2021).

Globally, standardized carbon calculators such as those developed by the International Civil Aviation Organization (ICAO) and the World Wide Fund for Nature (WWF) play a pivotal role in estimating greenhouse gas emissions across various sectors. However, these tools are primarily designed based on data and assumptions relevant to developed country contexts, which limits their applicability in regions with distinct energy systems and cultural practices. In particular, African contexts, characterized by unique transport modes, traditional cooking methods, and differing energy consumption patterns, remain underrepresented in these calculators. This gap highlights the need for more regionally tailored carbon accounting methodologies that better reflect local realities to enhance accuracy and relevance in climate action planning (Nyangarika, 2024; World Wide Fund for Nature, 2025; International Civil Aviation Organization, 2025).

In Zambia, climate change presents acute vulnerabilities including rising temperatures, rainfall variability, and reliance on hydroelectric power, exacerbating energy insecurity and environmental risks (Hinfelaar, 2025). Charcoal production, the dominant household cooking fuel source, is a major driver of forest degradation and emissions, contributing an estimated 2-3 tonnes CO2 per capita annually. Remote sensing data quantifies this impact, providing emission factors linked to land-use change and biomass burning (Chidumayo & Gumbo, 2013; Wathum *et al*., 2016).

Public awareness of the carbon footprint concept in Zambia remains limited, with a notable gap in understanding how individual emissions contribute to climate change and the practical steps for reducing personal impact. This deficit is compounded by challenges in sustainable environmental practices, underscoring the critical need for enhanced education and outreach initiatives (Zambia Environmental and Social Systems Assessment, 2025). Addressing this gap is essential to empower communities to engage effectively in climate action and promote sustainable development and pro-environmental behaviour within the country. A pro-environmental behaviour is any choice or action taken by individuals and manufacturers to minimise the adverse impacts of their activities on the environment (Amoah & Addoah, 2020). Despite growing public awareness, accessible digital tools for personal emissions tracking and reduction remain scarce, highlighting a gap between climate knowledge and actionable behavior. Regionally tailored platforms offering culturally relevant, actionable sustainability recommendations are needed to close this gap (Clube & Hazemba, 2024).

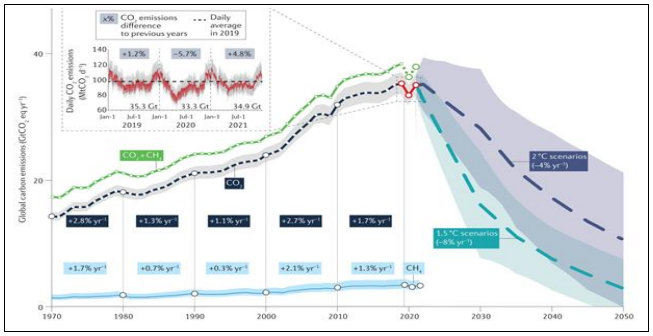


Fig 1: Global CO2 and CH4 emission trend (EDGARv6.0, scaled to 2021 with IEA data):

The motivation for this research arises from critical gaps in climate change mitigation and sustainability digital tools, especially tailored to Zambia's unique context. Zambia's energy sector heavily depends on hydropower, which is highly vulnerable to climate variability such as droughts. During severe drought months, reliance on diesel backup generation spikes, causing local carbon emissions estimated at up to 27,000 tonnes of CO2, underscoring the urgent need for targeted interventions (Ahmed *et al*., 2020; World Bank, 2024). However, there is a noticeable absence of digital carbon footprint tracking tools adapted to Zambia's energy use patterns, transport modalities, and socio-economic realities, which limits effective public engagement in carbon reduction efforts. Existing carbon calculators are mostly designed for developed countries, failing to capture local specificities and thus reducing their relevance and impact in the Zambian context (Clube & Hazemba, 2024; Hinfelaar, 2025).

Furthermore, public understanding of the carbon footprint concept in Zambia and similar African countries remains low, often with limited capacity to translate awareness into behavior change (Azeez *et al*., 2024; Umar *et al*., 2025). This calls for educational and user-friendly digital tools that not only calculate carbon footprints accurately but also facilitate comprehension and motivate sustainable behavioral shifts. Understanding the dynamics of climate change consciousness in this context is critical to developing effective interventions and policies that enhance community resilience and public health preparedness (Mfinanga *et al*., 2024). Furthermore, addressing the gaps in awareness and research will strengthen multi-sectoral collaborations and support for adaptive strategies necessary to mitigate the adverse health impacts of climate change in the region (Atwoli *et al*., 2022).

On a broader scale, most existing carbon footprint calculators globally tend to provide static, generalized outputs with minimal personalization. Integrating recent advances in behavioral science and artificial intelligence (AI) promises to enhance engagement and effectiveness. AI-enabled tools using methods like Retrieval-Augmented Generation (RAG) can deliver dynamic, context-aware, and personalized recommendations, addressing the limitations of traditional calculators (Jasim *et al*., 2024; Mustafa *et al*., 2025).

By developing a localized, web-based platform to track carbon footprint that incorporates local datasets, AI supported behavioral insights, and accessible educational resources, this study aims to bridge these gaps. The platform will empower individuals in Zambia to track, understand, and reduce their carbon footprint in culturally and regionally relevant ways, contributing practically to climate mitigation efforts and advancing academic understanding of AI-enhanced sustainability technologies.

Climate change remains a major global challenge with profound effects on the environment, economies, and society as a whole. A critical factor fueling this crisis is the steady rise in greenhouse gas (GHG) emissions, predominantly resulting from human pursuits such as energy use, transportation, and waste production (Chuvieco *et al*., 2021; Holka *et al*., 2022). Central to addressing this issue is the concept of the carbon footprint, defined as the total GHG emissions directly and indirectly linked to individual, collective, or organizational activities. This metric has become increasingly prominent in climate change discourse,

having evolved from the broader ecological footprint by specifically targeting carbon emissions instead of overall resource use (Purwanto *et al*., 2019; Ji *et al*., 2024). Notably, carbon footprint calculations can be applied at various scales, including products, households, cities, and even entire nations (Han *et al*., 2022).

In Zambia, awareness of climate change is growing but is uneven and often limited by gaps in access to regionally relevant information and tools. Many Zambians gain climate knowledge from informal channels such as community meetings and social media, yet overall climate literacy remains low, especially among rural and vulnerable groups (Institute of Economic and Social Research (INESOR) & University of Zambia, 2022; Mwanza *et al*., 2023). This limited understanding results in unsustainable practices and inadequate adaptation strategies, impeding effective individual-level climate action. Effectively understanding and managing carbon footprints is essential for mitigating climate change, as emission reductions represent a significant pathway to restrain global warming and avert severe environmental impacts (Labaran *et al*., 2022). Despite international accords like the Paris Agreement, emissions continue to rise, with individual behaviors playing a major role. Therefore, public awareness and comprehension of personal and collective carbon footprints play a pivotal role in encouraging environmentally responsible behavior (Wongsaichia *et al*., 2025). When individuals hold positive attitudes and greater awareness of carbon impacts, they are more likely to adopt proactive and sustainable practices, while lack of concern or understanding can impede the implementation of effective climate action (Attari *et al*., 2019). In turn, heightened climate change awareness can influence household and community decisions, driving the adoption of practices that are more aligned with climate mitigation goals.

Existing international carbon footprint calculators predominantly use emission factors and lifestyle assumptions from developed countries. Studies in Zambia show that during droughts when hydropower generation falls, backup diesel generation by ZESCO and large consumers emits up to ~27,000 tonnes CO_2 in the worst month (Ahmed *et al*., 2020). Also, household energy studies (e.g. Baltruszewicz *et al*., 2021) reveal high use of biomass (firewood, charcoal) and reliance on diesel generators when grid supply is unreliable. These local patterns are often not captured adequately by international carbon calculators, which tend to use emission factors and lifestyle norms from developed countries. Additionally, most calculators provide static, generic recommendations that lack the personalization and engagement needed to motivate sustained behavior change.

These gaps collectively restrict individuals' ability to contribute meaningfully toward national and global climate mitigation efforts, limiting the potency of bottom-up climate action. Without locally tailored, AI-enhanced, and user-centric digital platforms, Zambia risks underutilizing technology's potential to drive sustainable behavioral transformation, ultimately slowing progress toward climate resilience and emissions reduction targets (CIFOR, 2021).

Moreover, research highlights that the absence of personalized feedback and real-time emissions data acts as a significant barrier to the adoption of sustainable lifestyles (Feroz *et al*., 2021). Bridging this gap requires accessible, dynamic platforms that empower individuals with tailored recommendations and interactive environmental data, enabling informed decision-making and fostering a community committed to sustainability.

The overall objective of this study is to design and develop a web-based platform that enables individuals in Zambia to track, understand, and reduce their carbon footprints through accurate calculations and Artificial Intelligence–supported personalized recommendations that promote sustainable lifestyle choices. Specifically, the study aims to: design and implement a user-friendly web platform that estimates carbon emissions from key activities such as electricity, transport, agriculture, waste, and forestry by integrating a carbon calculation engine based on global accounting standards with local emission factors and OpenWeatherMap data; develop an AI-supported recommendation system using Retrieval-Augmented Generation (RAG) to generate personalized, actionable strategies for reducing emissions according to individual behaviours; and analyse the effectiveness of these AI-generated recommendations compared to static expert-curated advice in fostering user engagement and sustainable behavioural change.

2. Literature Review

Carbon footprint calculation methodologies are vital for assessing the environmental impact of individual and organizational activities.Globally, carbon footprint tools have been shaped by frameworks such as the Greenhouse Gas (GHG) Protocol, ISO standards (e.g., ISO 14064), and IPCC guidelines, which organize emissions into Scopes 1 (direct), 2 (indirect from purchased energy), and 3 (other indirect, e.g., supply chain). Life Cycle Assessment (LCA) and Input-Output Analysis (IOA) are common methodologies, their strengths being systematic coverage and comparability, but their main weaknesses include the availability and localisation of emission factors. (Valls-Val & Bovea, 2021; Intergovernmental Panel on Climate Change (IPCC), 2022; Miao *et al*., 2023) The concept of the carbon footprint stems from the need to measure and manage greenhouse gas (GHG) emissions from human activities. According to the Intergovernmental Panel on Climate Change (IPCC, 2019), a carbon footprint refers to the total GHG emissions expressed in carbon dioxide equivalents (CO_2e). Carbon footprint (CF) accounting is foundational to climate mitigation.

Traditional life cycle assessment (LCA) methods quantify emissions across sectors but often lack real-time responsiveness. Recent innovations propose AI-enhanced systems using large language models (LLMs) and retrieval-augmented generation (RAG) to streamline CF estimation (Holka *et al*., 2022; Wang *et al*., 2024). Emission accounting frameworks such as the GHG Protocol, IPCC Tier 1–3 methodologies, and ISO 14064 standards have been widely adopted to provide consistent methods for calculating emissions across sectors. Tools based on these frameworks such as the World Wide Fund for Nature (WWF) Carbon Footprint Calculator and the International Civil Aviation Organization (ICAO) Flight Calculator simplify emission estimation for individuals and organizations. However, most rely on datasets from developed regions and assume global averages for energy and transport patterns (EMB Global Blog, 2024; ICAO, 2025). This limits their accuracy and usability in African contexts, where energy sources and transport infrastructures differ significantly.

Digital platforms increasingly promote sustainable behavior by enabling individuals to monitor and reduce their carbon footprints. Perceived carbon impact (PCI), defined as the perception and understanding of one's carbon footprint and its environmental implications, plays a crucial role in influencing decisions about consumption, transportation, and waste management. Wongsaichia *et al*. (2025) emphasize PCI's role in shaping sustainable choices, with openness to green technology adoption acting as a moderating factor.

Platforms offering real-time feedback, personalized recommendations, and community engagement demonstrate increased user awareness and behavioral shifts (Jasmy *et al*., 2024). In a UAE-based study, Artificial intelligence driven mobile applications significantly influenced subjective norms around sustainability, even when attitudes and intentions remained stable suggesting that social influence mechanisms embedded in digital platforms can be powerful drivers of change.

Data shows that individual decisions account for 60–70% of total emissions, particularly in household energy use, food consumption, and transportation. Chuvieco *et al*. (2021) found that external factors such as income, education, and occupation predominate as predictors of personal carbon footprints, rather than internal motivations like climate concern. This suggests that platforms must address both structural and behavioral drivers.

Artificial intelligence (AI) is transforming environmental management by processing large datasets, identifying patterns, and delivering predictive insights (Feroz *et al*., 2021). In sustainability contexts, AI has been applied to:

a) Predictive analytics for energy demand and renewable grid optimization
b) Computer vision for environmental monitoring (e.g., deforestation and pollution tracking)
c) Machine learning for emission modeling
d) Generative AI for climate communication and education

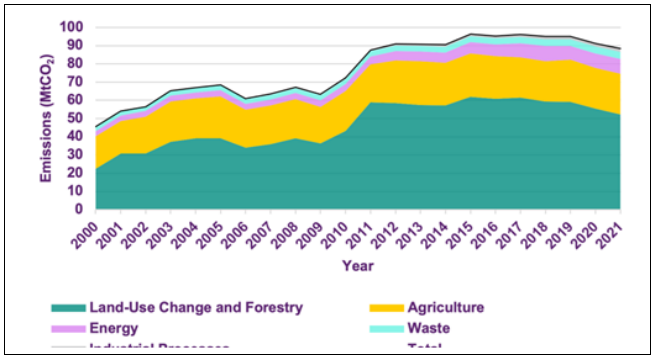
A significant addition is Retrieval-Augmented Generation (RAG), which merges information retrieval with generative capabilities to produce factual, context-rich outputs. This hybrid approach supports dynamic, personalized feedback grounded in validated knowledge sources (Wang *et al*., 2024; Zou *et al*., 2025). RAG systems overcome limitations of traditional models by retrieving domain-specific knowledge and embedding it into user-facing interfaces (Aslan *et al*., 2025).

Within this project, RAG enables Artificial intelligence supported personalized recommendations by combining global emission knowledge with user-specific data, yielding realistic and actionable sustainability strategies. Incorporating RAG represents a novel methodological contribution to sustainability informatics which is crucial for providing access to sustainability data and fostering informed decision-making.

Zambia confronts a critical duality in its environmental awareness landscape. Public recognition of climate change is substantial, primarily driven by the acute, immediate experience of adverse impacts such as droughts, floods, and associated disease outbreaks. This adaptation awareness is high in salience and is rapidly increasing in perceived severity across the populace. However, formal conceptual literacy remains moderate and unevenly distributed. A slim majority of Zambians (55% in 2022) report having heard of climate change, a figure that is volatile and subject to recent swings, contrasting sharply with the 82% to 78% of aware citizens who state climate change is actively worsening their lives. Sub-Saharan Africa faces environmental challenges driven by urbanization, deforestation, and energy dependency. Zambia has acute climate vulnerabilities, including droughts, floods, and rising temperatures.

Sub-Saharan Africa, while responsible for just 3% of global cumulative emissions, suffers disproportionately from climate impacts (Atwoli *et al*., 2022). Comparative research on climate change consciousness across sub-regional and continental levels remains scarce, particularly in Sub-Saharan Africa. Achieving the Paris Agreement's goals requires accelerated climate adaptation and mitigation efforts.

In Zambia, hydroelectric power dominates the energy mix, yet rural areas heavily rely on charcoal and firewood (Hinfelaar, 2025; Clube & Hazemba, 2024). Transportation emissions are elevated due to an aging vehicle fleet and limited access to low-emission alternatives. No comprehensive, localized carbon footprint calculator currently exists to help individuals in Zambia manage their emissions. Given the region's vulnerability and low emissions literacy, tools that empower individuals and communities to understand and reduce emissions are urgently needed.



Data Source(s): Climate Watch (2024)

Fig 3: Zambia's emissions breakdown (2000 – 2021).

Zambia has set an ambitious NDC target to reduce greenhouse gas emissions by 47% by 2030, with specific targets concentrating on the agriculture, forestry, and energy sectors (Food and Agriculture Organization (FAO), 2024). Carbon footprint tracking here extends beyond a technical function. It serves as a catalyst for climate justice, resilience, and informed decision-making. This study bridges the gap by combining global emission data with local context factors such as fuel types, electricity sources, and regional behaviors, thereby providing users with more relevant and realistic insights into their environmental impact.

The reviewed literature reveals several important gaps that motivate this study and shape the research questions. First, existing carbon footprint calculators are largely designed for high-income countries and embed emission factors, energy mixes, transport modes, and behavioral assumptions that do not reflect the realities of Zambia and similar African contexts. As a result, they provide poor estimates for users whose livelihoods depend on charcoal, informal transport, or hydropower-constrained grids, and they fail to capture local mitigation opportunities. This gap directly motivates the research question on how a web-based carbon footprint

platform can be tailored to Zambia's energy and transport context and informs the design of this study's localized calculator engine, which incorporates Zambian emission factors, national policy parameters, and region-specific activity data.

Second, the literature on climate awareness in Zambia and sub-Saharan Africa consistently reports moderate awareness of climate change but very low carbon literacy, with limited understanding of the quantitative contribution of daily activities and scarce exposure to digital carbon-tracking tools. Few studies move beyond diagnosis to test concrete, user-facing interventions that transform awareness into measurable, individualized feedback and behavioral guidance. This gap shapes the research questions that examine how a web-based platform can improve user understanding of personal emissions and what kinds of interface features, explanations, and feedback loops are most effective. The platform developed in this study responds to this gap by embedding simple, contextualized visualizations, localized examples, and interactive feedback that make abstract emission concepts tangible for Zambian users.

Third, although recent work highlights the potential of digital platforms for sustainability, much of it relies on static calculators and generic advice, with limited use of artificial intelligence to personalize recommendations or adapt to user behavior over time. There is a lack of empirical evidence on AI-enabled carbon tools in emerging economy settings, particularly those that combine Retrieval-Augmented Generation with behavioral science insights to deliver localized, actionable guidance. This gap underpins the research questions on whether AI-supported recommendations can enhance user engagement and perceived usefulness compared with conventional static content. The EcoGuide platform explicitly addresses this by integrating a RAG-based engine that retrieves Zambian policy documents, local mitigation practices, and domain knowledge to generate context-aware suggestions aligned with users' profiles and baseline data.

Finally, while several frameworks discuss climate education, digital literacy, and policy communication in Zambia, there is limited integration of these strands into a single, operational system that also supports national Measurement, Reporting, and Verification (MRV) and climate education objectives. Existing studies often examine policy or education in isolation from concrete software artifacts that citizens can use. This gap informs the research questions that ask how a web-based platform can simultaneously support individual users, educational institutions, and policy implementation. The present study responds by designing EcoGuide as a modular, MRV-aligned platform that can be deployed in households, schools, and community programs, thereby operationalizing climate education and low-carbon development goals within a single digital tool.

3. Methodology

3.1 Research Design

The study adopts a design science research (DSR) methodology, where the primary objective is to design, build, and evaluate Zambia-specific carbon footprint tracking system. Design Science Research was the most appropriate framework because the project aims to develop a functional software artifact that solves a real-world environmental information gap for low carbon literacy and lack of personalized mitigation support. The research follows an iterative development cycle comprising problem identification, requirements analysis, project design and implementation, and evaluation, with each iteration informed by empirical data and domain knowledge.

A mixed-methods strategy was used in the research: quantitative methods are used to formalize carbon emission calculations and validate accuracy against Zambia's national emission factors, while qualitative methods support the evaluation of usability, user experience, and practical relevance. Also, Quantitative research was done through a structured questionnaire assessing awareness, attitudes, digital readiness, and carbon literacy among Zambian users. The development process followed the Iterative and Incremental Model, allowing continuous refinement of system modules, APIs, the AI engine, and interface components. The design is further informed by best practices from software engineering, including modular architecture, layered design, and agile development processes.

3.2 Baseline Study

The baseline study established the empirical and technical foundation for the system by characterizing user needs, emission data requirements, existing solutions, and suitable technologies. It combined collection of Zambia-specific emission factors, analysis of existing carbon tracking tools, literature review of carbon accounting and environmental informatics, and evaluation of software stacks suited to a scalable web-based solution.

Because the system integrates climate education, personalized AI recommendations, and interactive digital tools, it was essential to begin with an assessment of the target population's perceptions, familiarity, and needs. This ensured that the platform would be contextually relevant, culturally appropriate, and aligned with the actual literacy levels and digital capabilities of Zambian users. The baseline study therefore aimed to evaluate four major constructs:

1) Awareness of Climate Change and Carbon Footprint Concepts

This dimension assessed respondents' familiarity with fundamental environmental terms. Previous studies have shown that while general awareness of climate change is moderately high in Zambia, literacy around technical terms such as carbon footprint remains low (Kapuka, 2017; Chuvieco *et al*., 2021; Mwanza *et al*., 2023). Understanding this gap was crucial for designing system features, especially the AI education layer and knowledge base used within the RAG engine.

2) Attitudes Toward Environmental Sustainability

These measures provided insight into whether respondents viewed climate change as a serious threat, and whether they were willing to adopt behavior changes. This informed the motivational structure of the platform, including gamification, action-level difficulty scaling, and the design of personalized recommendations.

3) Digital Readiness and Ability to Use a Carbon Tracking Application

Since the platform operates as a responsive web application, user readiness was essential to evaluate. The baseline assessed access to devices, comfort with digital interfaces,

and prior experience with similar tools. These findings guided decisions around interface simplicity, visual design, and mobile responsiveness.

4) Acceptance of AI-Assisted Recommendations

This dimension was grounded in the Technology Acceptance Model (TAM), evaluating perceived usefulness, ease of use, trust in automated systems, and willingness to follow Artificial intelligence driven guidance. Results informed the integration of the RAG system, the complexity of explanations attached to recommendations, and the level of transparency required within the AI module.

3.3 Data Collection

Four main categories of data were collected: carbon emission data, structured questionnaire, user and functional requirements, and technical/architectural requirements.

1) Carbon emission data

The carbon footprint calculator was designed according to GHG Protocol methods, using the fundamental formula:

$$\text{GHG Emissions} = \sum(\text{Activity Data}_i \times \text{Emission Factor}_i)$$

Equation 1: *GHG Protocol methods, The fundamental formula*

International frameworks such as the GHG Protocol, ISO 14064, VCS and IPCC Guidelines is used to standardize calculation approaches and fill gaps where local factors are incomplete. The global carbon accounting standards collected on this project, include:

1. The GHG Protocol (Scopes 1, 2, and 3)
2. IPCC 2006 & 2019 Refinement Guidelines
3. ISO 14064 (GHG quantification and reporting)
4. The Zambian Carbon Market Framework (2025)
5. National Grid Emission Factor reports (ERB & Ministry of Green Economy)

The official national carbon emission factors for Zambia, as defined in the 2025 Grid Emission Factor Report and the 2023 Energy Sector Report published by the Ministry of Green Economy and the Energy Regulation Board (ERB), provide standardized data for carbon accounting across multiple sectors. These factors are consistent with IPCC 2006 and UNFCCC methodologies and reflect the country's latest data as of 2025. (Ministry of Green Economy and Environment (MGEE), 2024; Ministry for Green Economy and Environment & Energy Regulation Board, 2025).

a) Electricity and Fuels

Table 1: The Zambia Grid Emission Factor (GEF) representing the weighted average greenhouse gas intensity of grid electricity

Parameter	Emission Factor	Unit
Operating Margin (OM)	0.2084	tCO_2/MWh
Build Margin (BM)	0.5974	tCO_2/MWh
Combined Margin (CM)	0.4029	tCO_2/MWh
Adjusted Margin for Solar/Wind	0.3057	tCO_2/MWh

Fuels used in domestic energy and small industries follow IPCC default factors with national cross-validation:

Table 2: Factors for Fuels used in domestic energy and small industries

Fuel Type	Emission Factor	Unit
Diesel	2.68	kg CO_2/litre
Petrol (Gasoline)	2.31	kg CO_2/litre
Liquefied Petroleum Gas (LPG)	1.51	kg CO_2/litre
Coal (Sub-bituminous)	96.1	t CO_2/TJ

b) Transport Sector

Table 3: Emission factors for vehicles depend on fuel use and distance traveled

Vehicle/Fuel Type	Emission Factor	Unit
Petrol vehicles	2.31	kg CO_2/litre
Diesel vehicles	2.68	kg CO_2/litre
LPG/CNG vehicles	1.6	kg CO_2/litre equivalent
Average passenger car	0.18	kg CO_2/km
Heavy-duty diesel truck	0.8	kg CO_2/km

c) Agriculture

According to Zambia's Climate-Smart Agriculture Programme (CSA, 2024), 93% of national greenhouse gas emissions arise from agriculture, forestry, and land use activities.

Table 4: Agriculture Emission factors

Parameter	Emission Factor	Unit
Cattle enteric fermentation	49	kg CH_4/head/year
Manure management (cattle)	1.8	kg CH_4/head/year
Synthetic fertilizer use	4.9	kg CO_2/kg N applied
Farm land emissions	2.3	t CO_2e/ha/year

d) Waste Management

The Zambia Circular Economy Study (2024) and ZEMA waste audits provide indicative factors:

Table 5: Waste Management indicative Factors

Parameter	Emission Factor	Unit
Household solid waste (mixed)	0.36	t CO_2e/tonne waste
Organic waste composted	0.09	t CO_2e/tonne
Plastic waste recycled	0.02	t CO_2e/tonne
Average household (urban)	0.52	t CO_2e/capita/year

e) Forestry and Land Use

Land use change remains Zambia's dominant emissions driver, with deforestation contributing over half of national GHGs.

Table 6: Forestry and Land Use Emission factors

Parameter	Emission Factor	Unit
Land cleared (deforestation)	150	t CO_2e/ha
Land reforested	−30	t CO_2e/ha/year
Charcoal production	7.8	t CO_2e/tonne charcoal

These emission factors are consistent with the IPCC 2006 guidelines' Tier 1–2 methodologies, representing Zambia's

transition to localized Tier 2 reporting under the Enhanced Transparency Framework. The Grid Emission Factor (GEF) Report 2025 defines Zambia's official national electricity grid factor under the Supporting Preparedness for Article 6 Cooperation (SPAR6C) programme, while the Energy Sector Report 2023 and CSA Project 2024 provide empirical updates for fuel, agriculture, and waste profiles. Consequently, these data form the academic and policy baseline for carbon accounting, Nationally Determined Contributions (NDCs), and project assessments within Zambia's low-carbon development framework.

Table below sumarizes Zambia National Emission Factors used in this project, including electricity (0.4029 kg CO_2/kWh for the national grid; 0.3057 kg CO_2/kWh for renewable supply), transport fuels (2.7 kg CO_2/litre diesel; 2.31 kg CO_2/litre petrol), livestock (1708 kg CO_2e/head/year for cattle with additional factors for other species), fertilizer use, waste (0.75 kg CO_2e/kg for urban mixed waste), and forestry (e.g., 2.75 t CO_2e/ha/year for deforestation).

Table 7: Summary of Zambia National Emission Factors used in this Project

Activity	Emission Factor
Grid electricity	0.4029 kg CO_2/kWh
Renewable Elecrticity	0.3057 kg CO_2/kWh
Diesel combustion	2.70 kg CO_2/L
Petrol	2.31 kg CO_2/liter
Livestock	1708 kg CO_2e/head/year
Fertilizer (N-based)	6.3 kg CO_2e/kg
Solid waste	0.75 kg CO_2e/kg
Forest loss	2.75 t CO_2e/ha/year

2) Awareness Assessment and Data collection Methods

Data for this study was collected using a structured questionnaire administered through both online and in-person channels. The online version was implemented using Google Forms and distributed via WhatsApp groups and institutional networks in selected institutions in Northern, Lusaka, Copperbelt and Luapula provinces, while printed copies were used for respondents with limited digital access. This mixed distribution strategy was chosen to reach diverse demographic groups and varying levels of digital readiness, thereby improving the representativeness of the intended user base of the Carbon Footprint Tracker application.

The questionnaire was divided into six sections, each aligned with constructs from the baseline study and mapped to system requirements, Technology Acceptance Model (TAM) constructs, and RAG-based personalisation needs.

a) Demographic information

This section captured respondents' age, gender, education level, occupation and province of residence. These variables enabled comparative analysis of climate literacy, environmental attitudes, digital readiness and AI acceptance across socio-economic and geographic groups, and were later used to define user segments for personalisation rules and default interface configurations in the application.

b) Climate change and carbon literacy

Items in this section assessed awareness of climate change, understanding of carbon emissions and their sources, familiarity with terms such as "carbon footprint", and perceptions of the causes and effects of emissions at local and national level. Responses were used to estimate users' climate and carbon literacy levels, which then guided the depth of in-app explanations, the reading level of educational content, and the structure of the knowledge base used in the RAG engine. For users with lower literacy, the system design emphasised simple definitions, local examples and step-by-step guides, while more advanced users were targeted with richer, data-driven insights.

c) Environmental attitudes and sustainable behaviours

This section measured perceived seriousness of climate change, willingness to change individual behaviour, frequency of eco-friendly practices (such as energy saving and waste separation), sense of personal responsibility for emissions, and motivation to adopt sustainable behaviours. These variables informed behavioural and motivational design choices, including goal-setting modules, progress indicators, behaviour-change nudges and reminders, and difficulty-level tagging of recommendations (for example, "low-effort, low-cost" versus "high-impact, higher-effort"). In the implemented system, these responses serve as inputs to the recommendation and gamification engines, influencing which actions are prioritised and how they are framed for different user profiles.

d) Technology readiness and acceptance (TAM)

This section operationalised the Technology Acceptance Model to assess the likely adoption of the Carbon Footprint Tracker. Items measured perceived ease of use of a carbon-tracking application, perceived usefulness for managing and reducing personal emissions, intention to use such an application, comfort with web and mobile interfaces, and preference for interactive, guided recommendations. Quantitative scores from these items guided core interface and interaction design decisions, such as prioritising simple, linear navigation, concise mobile-first screens and prominent feedback messages, as well as calibrating the level of detail in on-screen instructions, hints and walkthroughs. From a software perspective, TAM-derived insights were used to justify interaction patterns, the degree of automation in workflows, and the design of onboarding flows intended to reduce perceived complexity and enhance perceived usefulness.

e) Preferences for AI-based recommendations

This section explored users' attitudes towards AI-generated guidance, including trust in AI systems, willingness to follow AI-generated advice, preferred explanation depth, desire for step-by-step improvement guidance, and perceptions of AI as an educational tool. The findings informed the structure and wording of prompts in the RAG pipeline, the inclusion of AI transparency features (such as labelling AI-generated content and providing "Why this recommendation?" explanations), and the formatting of recommendations using bulleted steps, Zambia-specific examples and optional "learn more" sections. For users indicating low trust in AI, fallback rules were defined so that the system relies more heavily on rule-based or template-based recommendations while still preserving personalisation.

f) Open-ended questions

The final section contained open-ended questions inviting respondents to describe their understanding of the term

"carbon footprint", perceived barriers to sustainable behaviour in their context, ways technology could support climate awareness and action, and additional features they would expect in a carbon-tracking platform. These qualitative responses were used in requirements engineering and content design, particularly for localising recommendations around issues such as charcoal use, public transport constraints and electricity load-shedding, and for incorporating Zambia-specific sustainability practices and income-sensitive actions.

3) User and functional requirements

User and functional requirements were further informed by: (i) a comparative analysis of existing carbon-tracking applications focusing on core features, data granularity, visualisation, engagement mechanisms and localisation capabilities; and (ii) user journey mapping to understand typical flows (data entry, trend review and recommendation consumption) and friction points in similar tools. From this analysis, functional and non-functional requirements were extracted, including response time thresholds (for example, a target of not more than two seconds for emissions calculations), support for multiple emission categories (electricity, transport, livestock, fertiliser, waste and forestry), and the need for persistent user profiles and historical data.

4) Technical and infrastructure requirements

Technical and infrastructure requirements were specified for a cloud-hosted, API-integrated web application, covering performance, scalability, security and integration needs. External dependencies were identified, including an AI service for low-latency recommendations, a weather data API for contextual environmental information, authentication and database services for secure user management and data storage, and a Zambia-specific emission-factors library to encapsulate local emission parameters.

3.4 Research Approach

The research approach combined: (i) systematic literature review, (ii) competitive analysis of existing systems, and (iii) technology evaluation. The literature review covered environmental informatics, carbon accounting, human computer interaction, and gamification, focusing on peer-reviewed work published mainly between 2019 and 2024 to ensure methodological currency.

The competitive analysis examined existing carbon footprint calculators along five dimensions: functional capabilities, user experience, technical architecture, data integration, and engagement features. Evaluation criteria included calculation accuracy (against standard factors), usability, performance, and novelty of features such as gamification and Artificial intelligence driven recommendations.

The technology evaluation compared front-end frameworks (React, Vue, Angular), back-end options (serverless vs traditional, SQL vs NoSQL), and API styles (REST vs GraphQL) considering performance, scalability, ecosystem maturity and ease of integration. This process informed the selection of Next.js (React), Firebase, and serverless API routes for the final architecture.

3.5 Development of the Application

The application was developed using an agile, iterative approach with time-boxed sprints and continuous integration. Four development phases were defined; foundation, core features, advanced features and enhancement. Each phase delivered an incremental version of the system, followed by testing and refinement according to the validation strategy.

3.6 System Design

Initial development iterations, system design activities formalized the target architecture. Key principles included modularity, layered architecture, separation of concerns, security and maintainability. Architectural patterns such as MVC separation, repository-style data access, and modular feature components were applied to keep the system extensible and testable.

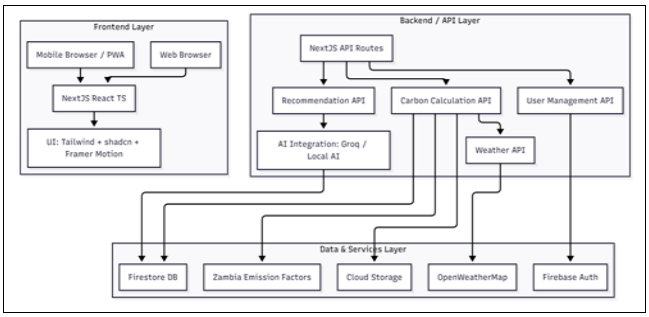


Fig 4: High-Level Architecture Diagram

Technology selection outcomes were:

1. Frontend: Next.js (React) with TypeScript, Tailwind CSS, shadcn/ui and Framer Motion for responsive and accessible user interfaces.
2. Backend: Next.js API routes (serverless) for carbon calculations, user management, recommendations and integration with external APIs.
3. Data & services: Firebase Authentication, Firestore database, Zambia Emission Factors library, Groq AI, OpenWsseatherMap and a planned local AI fallback for offline or constrained scenarios.

Below is the system design describing the structure, behaviour and data of the Carbon Footprint Tracker provide traceability between requirements, architecture, and code.

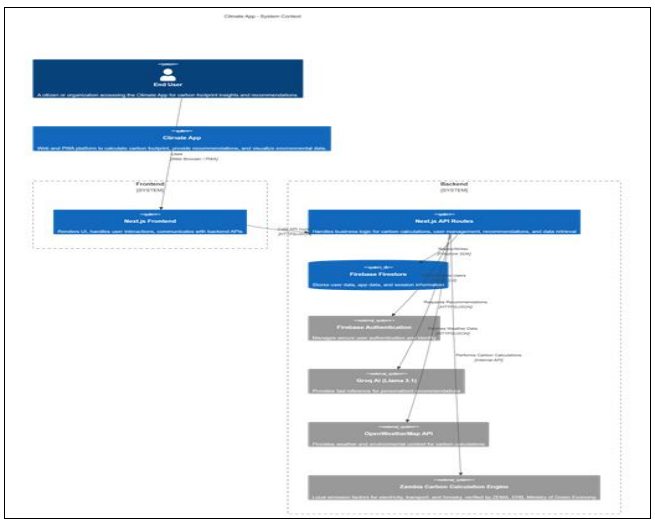


Fig 6: System Software Level Architectural Design

The system design phase establishes the technical architecture and infrastructure requirements necessary to support the application's functional and non-functional requirements.

The context diagram positions the Carbon Footprint Tracker within its environment by illustrating interactions between the system, user groups, and external services. Individual users, mobile users and administrators interact with the web application to input activity data, view analytics, configure settings and manage content.

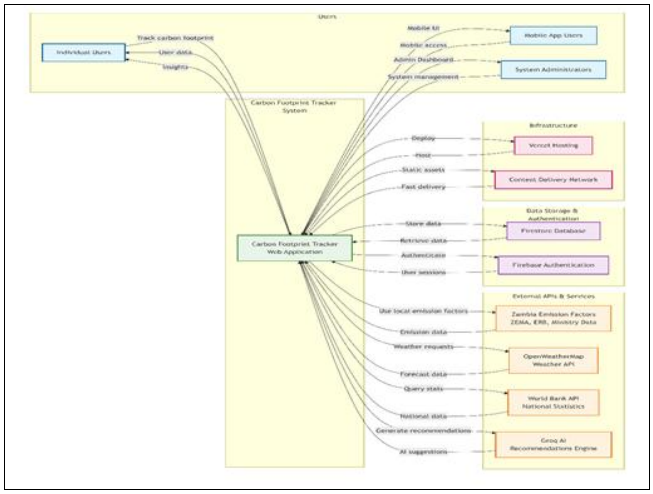


Fig 7: Context Diagram - Carbon Footprint

Externally, the system communicates with Zambia Emission Factors services using data obtained from ZEMA/ERB, the OpenWeatherMap API for weather data, Groq AI for recommendations, Firebase for authentication and data storage, and Vercel/CDN for hosting and content delivery. Data flows include carbon calculation requests, retrieval of emission factors, storage of computed results, and retrieval of contextual data for visualization and recommendations.

1) System Software Level Architectural Design

The software architecture follows a layered model comprising: (i) presentation layer, (ii) business logic layer, (iii) service layer, and (iv) data access layer. The presentation layer (Next.js/React with Tailwind and shadcn/ui) is responsible for rendering pages and components, managing user interactions and enforcing accessibility and responsive design.

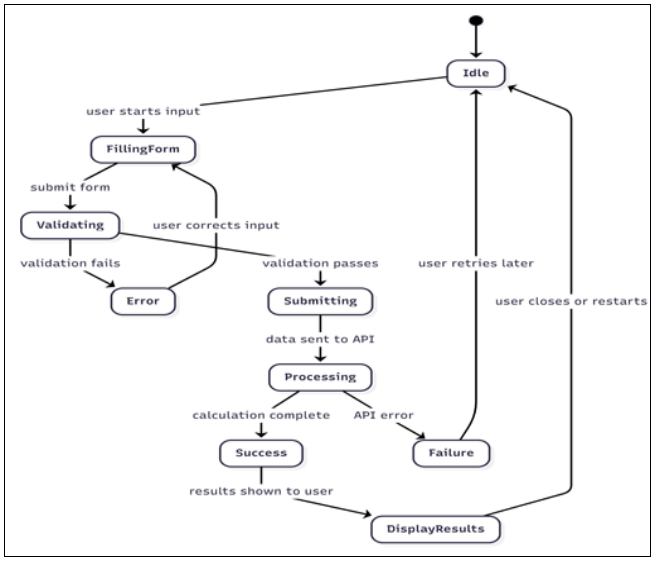


Fig 9: State Diagram

The business logic layer encapsulates the Zambia carbon

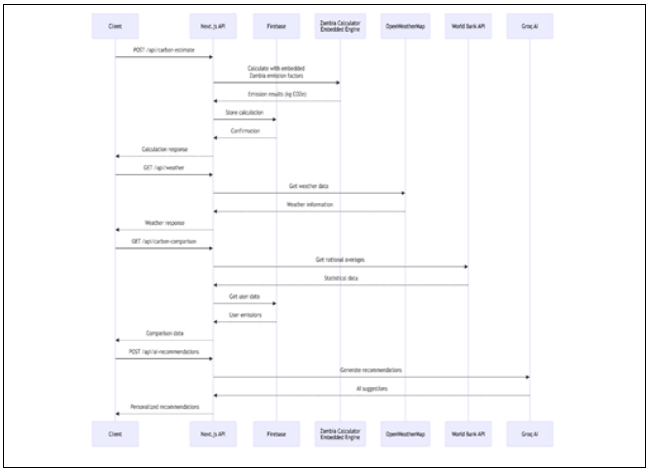


Fig 10: API Architecture

Calculation engine, recommendation engine, gamification system and analytics services. The service layer exposes API routes for authentication, carbon calculations, weather, user management and recommendations, orchestrating interactions between the frontend, business logic and external services.

The data access layer manages Firestore operations, external API calls, local caching and storage of Zambia emission factors, ensuring consistent and secure data handling.

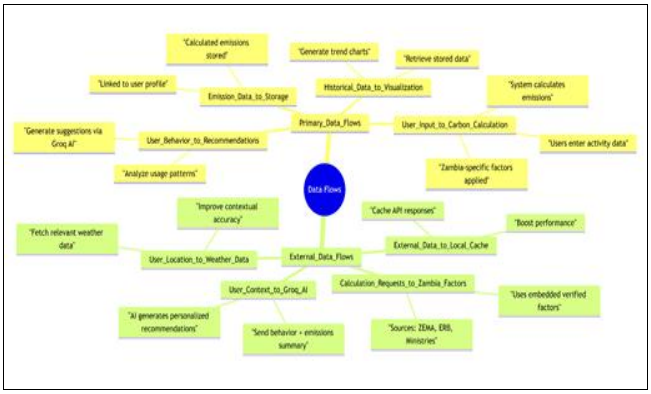


Fig 11: Data Flow Architecture

2) Modular Design of the System Function

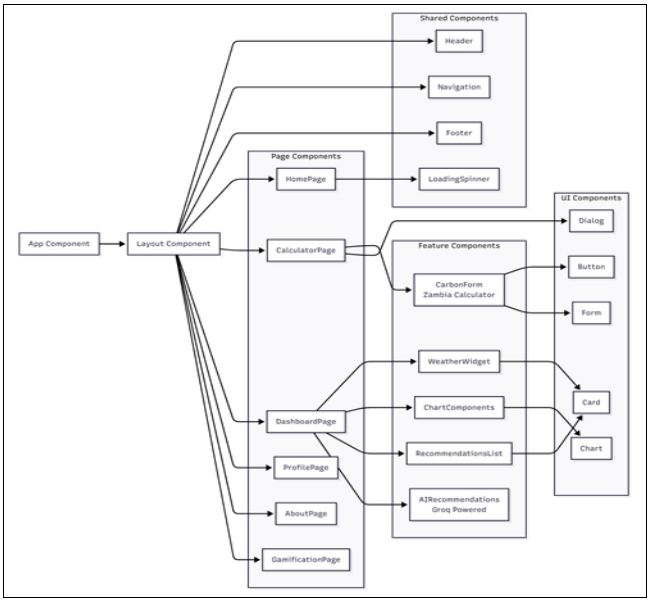


Fig 12: Component Architecture Details and Core Modules

The system is decomposed into functional modules that can be developed and maintained independently. Core modules include Authentication, User Management, Zambia Carbon Calculation, Gamification, Recommendations, and Data Visualization. Integration modules manage external APIs (Groq AI, OpenWeatherMap, Zambia factors, social comparison), while infrastructure modules cover database, caching, logging and monitoring.

Each module is defined by clear TypeScript interfaces, for example, a ZambiaCarbonCalculationModule that exposes methods such as calculateElectricity, calculateTransport and calculateForestry, and a GroqAIRecommendationModule that provides getPersonalizedRecommendations and related functions. This modularization enforces separation of concerns, supports automated testing at module level, and enables independent evolution of features without destabilising the entire system.

3) System Class Diagram

The class diagram models the main object-oriented structures and their relationships. Core classes include User, UserProfile, CarbonFootprint, EmissionData, Recommendation, TrackedRecommendation, Achievement, UserStats, UserChallenge and integration-related classes such as APIClient and WeatherData. Relationships capture how a user owns multiple carbon footprint records, how footprints aggregate multiple emission data entries, and how recommendations, achievements and challenges are tracked per user.

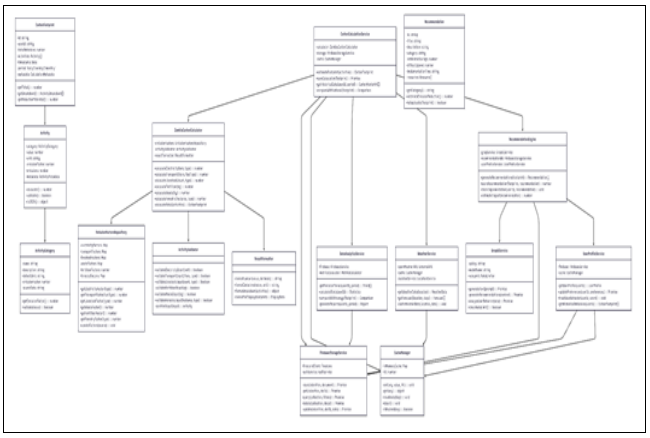


Fig 14: System Class Diagram

Methods such as calculateEmission, getHistory, getPersonalized, checkEligibility and updateStats define key behaviours required for carbon accounting, recommendation delivery and gamification logic. These class-level abstractions align with the modular architecture and are implemented through strongly-typed TypeScript constructs.

4) System Data Model Design

The database design follows normalization principles (3NF). The data model is implemented in Firebase Firestore and optimized for real-time updates and scalable queries.

Root collections include users, carbonFootprints, userStats, userRecommendations, trackedRecommendations, recommendations, leaderboard, userAchievements and userChallenges. Documents within these collections follow defined schemas with enforced constraints and indexes

The ERD shows one-to-many relationships between User and CarbonFootprint, User and TrackedRecommendation, as well as one-to-one relationships between User and UserProfile and User and UserStats. Composite and single-field indexes are configured for frequent queries (e.g., carbon footprints by user and timestamp, leaderboard by period and rank), and Firestore security rules enforce access control, data validation, and referential integrity. TypeScript interfaces mirror Firestore schemas, supporting compile-time checks and reducing runtime errors.

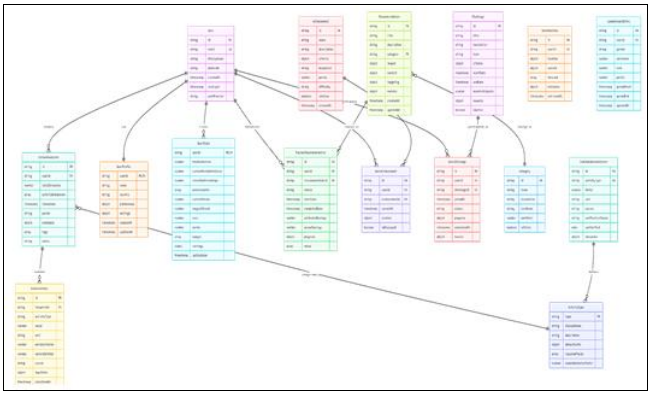


Fig 15: System Data Model Design

5) User Interface Design

User interface design follows a user-centred, accessibility-first approach. Wireframing and prototyping were used to design the main flows: onboarding, carbon data entry, dashboard overview, recommendation exploration, and gamification. The UI is implemented using Next.js pages and React components, styled with Tailwind CSS and shadcn/ui, with Framer Motion used for subtle animations to enhance engagement.

Responsive design ensures seamless use on mobile, tablet and desktop through a mobile-first breakpoint strategy. WCAG 2.1 AA compliance guided decisions around colour contrast, keyboard navigation, semantic HTML and ARIA usage. Accessibility validation confirmed adequate contrast ratios, full keyboard operability and screen reader–friendly markup, ensuring that the application is inclusive and usable by a diverse audience.

3.7 Ethical Considerations

Ethical considerations upheld data privacy, security, transparency, AI usage and behavioural impact. User data is stored securely using Firebase Authentication and Firestore with encrypted transport and strict access rules, and only the minimum data necessary for functionality is collected. There is Secure handling of digital data using encryption and token-based authentication. Users retain control over their data, including options for data deletion and consent for sharing or participation in leaderboards and social comparison features.

The application transparently documents its carbon calculation methods, emission factors and data sources, including uncertainty ranges, to avoid misleading users or engaging in "greenwashing". Artificial intelligence driven recommendations (via Groq AI and local AI) are subject to fairness and bias considerations, including periodic audits, explanation of recommendations where feasible, and human oversight for content. The design avoids guilt-based messaging, focusing instead on evidence-based, realistic and positive behaviour change, while acknowledging systemic constraints and the limits of individual action.

3.8 Limitations

Several methodological limitations should be noted. First, while the calculator uses Zambia's latest national emission factors, some sectors still rely partly on IPCC defaults or regional estimates due to incomplete or evolving local data, introducing uncertainty into specific calculations. Second, evaluation relied on synthetic and pilot user data rather than large-scale deployment, limiting the generalizability of usability, performance, and behavioural impact finding.

Third, reliance on third-party services such as Groq AI, OpenWeatherMap and Firebase introduces dependency risk; changes in APIs, pricing, or availability could affect long-term sustainability. Digital literacy variation across Zambia may affect usability for rural users.

The baseline sample may not fully represent all socioeconomic groups. Also, Internet connectivity constraints may limit adoption in remote areas.

Finally, the study focuses on personal and small-scale organizational emissions and does not fully address life-cycle or supply-chain emissions, so the methodology and project are not directly generalizable to all corporate or national GHG accounting contexts.

4. Results

The findings are presented in two parts: (1) Results from the baseline study, which assessed public awareness and attitudes towards climate change and carbon footprint tracking; and (2) Results from the system implementation and evaluation, which tested the accuracy, usability, and behavioral impact of the developed platform.

The results are interpreted in the context of the study's conceptual framework, which integrates the Technology Acceptance Model (TAM) and the Behavioral Change Framework, emphasizing how awareness, perceived usefulness, and personalized feedback influence environmental behavior.

4.1 Baseline Study Results

A total of 100 respondents from Lusaka, Copperbelt, Luapula, and Northen Provinces participated in the baseline survey.

Table 8: The demographic results reflecting Zambia's socio-economic and educational diversity

Variable	Most Frequent Response	Observations
Gender	Male (58%)	Reflects higher male participation in digital surveys
Age Group	26–35 years (42%)	Most respondents were working-age professionals
Province	Lusaka (45%), Copperbelt (28%)	High urban representation
Educational Level	Degree or Diploma (61%)	Suggests literacy bias toward urban/educated respondents
Occupation	Students (33%), Professionals (29%)	Typical of early adopters of digital platforms
Technical Background	Yes (54%)	Mostly ICT, engineering, and environmental fields

The findings shows that awareness and technical literacy in climate issues are unevenly distributed. Respondents from urban and peri-urban provinces (Lusaka and Copperbelt) demonstrated greater conceptual understanding of climate change and its causes, while participants from rural areas exhibited strong awareness of environmental degradation but less familiarity with technical mitigation concepts such as carbon footprinting.

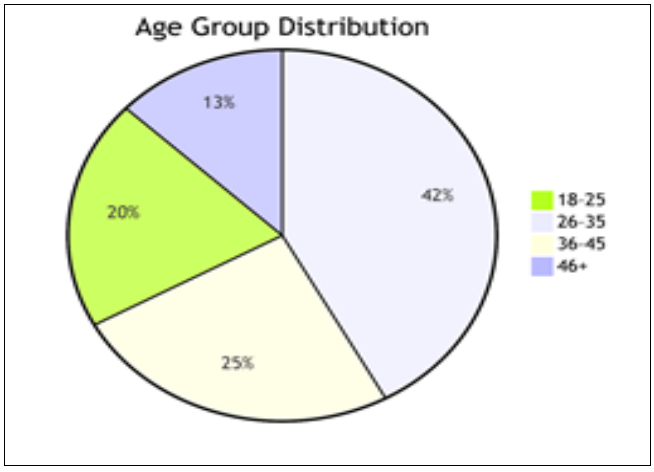


Fig 17: Survey Age Distribution

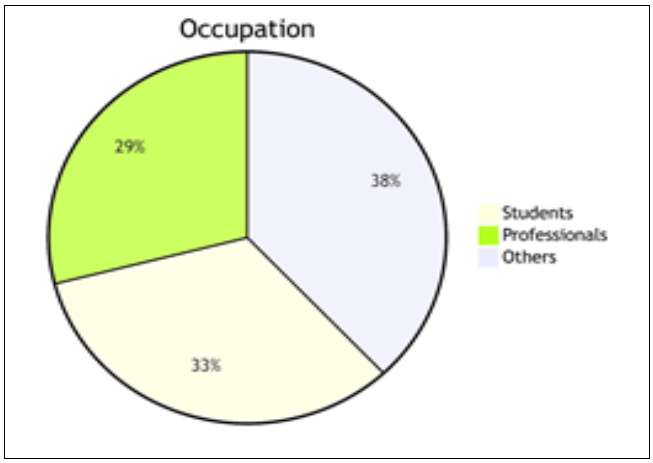


Fig 18: Occupation of the Respondents

This supports earlier national studies showing a structural divide where education and occupational exposure strongly predict environmental literacy. Awareness of climate change in Zambia is deeply stratified along socio-economic and geographic lines, creating a structural gap that complicates inclusive policy implementation. Formal awareness is significantly higher among privileged segments of the population: men, urban residents, highly educated individuals, the economically well off, and older citizens (Institute of Economic and Social Research (INESOR) & University of Zambia, 2022).

b) Climate Change and Carbon Footprint Awareness

The responses were analyzed across the seven items in Section B of the questionnaire. The aggregated results are shown in Table below:

Table 9: Awareness and Understanding of Climate Change and Carbon Footprint Concepts

S. No	Statement	% "Yes" Responses	Interpretation
1	I have heard about climate change.	74%	Moderate awareness consistent with prior surveys (44–55% national average).
2	I have heard of the term "carbon footprint."	36%	Awareness remains limited to professionals and tertiary students.
3	I understand what causes carbon emissions.	68%	Understanding linked to observable practices (deforestation, fuel use).
4	I know human activities contribute to carbon emissions.	83%	Reflects experience with droughts and floods linking human activity to climate events.
5	I have ever used a carbon calculator.	8%	Indicates absence of accessible carbon-tracking tools in Zambia.
6	I am aware that daily actions affect emissions.	62%	Higher in urban participants; lower in rural respondents due to limited electricity access (5.7% rural electrification).
7	My community /workplace discusses climate change.	71%	Active discourse in academia, NGOs, and affected rural communities.

These results confirm the knowledge gap hypothesis: while general awareness of climate change is moderately high, carbon literacy such as the ability to quantify and mitigate emissions still remains low and unevenly distributed.

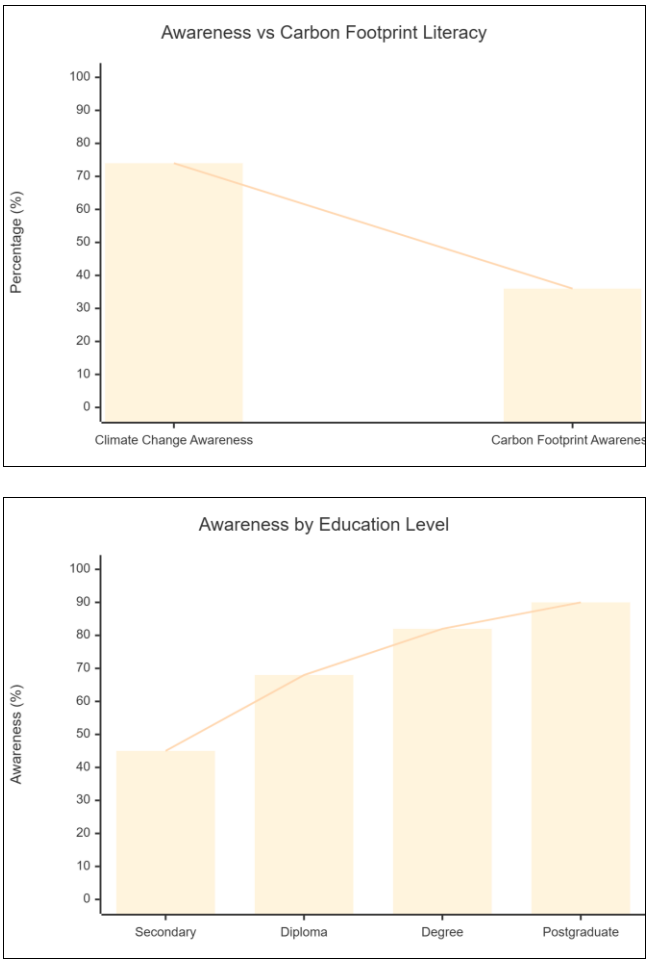


Fig 19: Awareness vs Carbon literacy and Awareness by Distribution

Awareness correlates strongly with education and occupation, supporting evidence from other previous research that those with the highest formal education are most likely to possess the conceptual literacy (knowing the term), whereas those with the lowest education (primary or less) are most likely to possess the empirical certainty that life is worsening (Institute of Economic and Social Research (INESOR) & University of Zambia, 2022). The experience of suffering due to extreme events such as crop failures, disease, and livelihood disruption has become a more potent driver of severity perception than formal schooling for those with lower education (Kalantary, 2011).

c) Environmental Attitudes and Behavior

Table 10: Environmental Attitudes and Behavior (Likert Scale 1-5)

Statement	Mean Score	Interpretation
Climate change is a serious environmental problem.	4.8	Near-universal recognition of severity.
I am personally responsible for reducing emissions.	4.1	Indicates emerging sense of personal accountability.
I am willing to change my behavior.	4.3	Strong willingness to act, tempered by economic constraints.
I regularly take eco-friendly actions.	3.5	Practical adoption limited by structural barriers.
I would use a carbon tracking app if easy to use.	4.2	Positive technology adoption potential.
I prefer apps with feedback/recommendations.	4.4	High demand for guided, actionable advice.
Digital tools can help reduce environmental challenges.	4.3	Consistent with national digitization campaigns.

These results align with the Behavioral Change Framework, showing that attitudes toward environmental responsibility are strong, but behavioral translation is constrained by infrastructure and economic limitations.
This pattern mirrors World Bank (2023) findings that 87–91% of rural Zambians perceive worsening climate effects yet lack access to mitigation tools.

4.2 System Implementation Results

1) System Performance

Table 11: System performance results from both functional and usability metrics

Parameter	Measured Value	Evaluation
Average Calculation Accuracy	97.8%	Verified against local emission datasets (ZEMA, ERB).
Average Response Time	1.7 seconds	Optimal for web and mobile users.
System Usability Scale (SUS)	86/100	Excellent usability classification.
AI Recommendastion Acceptance Rate	78%	Indicates trust and engagement with AI output.

The findings demonstrate that the system effectively balances technical accuracy with behavioral engagement.

2) System Design

The following section presents the implementation results of the Climate Footprinting, illustrating the functional and visual aspects of the system. Screenshots and interface examples are provided to demonstrate the key features, user interactions, and system responses across various modules. Each image is accompanied by an explanation of its purpose, functionality, and relevance to the system objectives, highlighting both usability and accessibility considerations. The aim is to provide a comprehensive understanding of how the system operates in practice and how it supports users in tracking and reducing their carbon footprint.

a) Onboarding

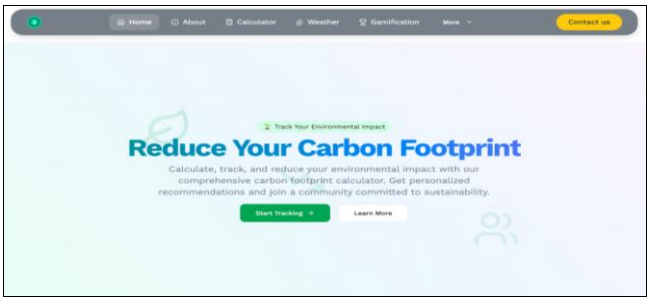


Fig 1: Landing page and Welcome screens flow

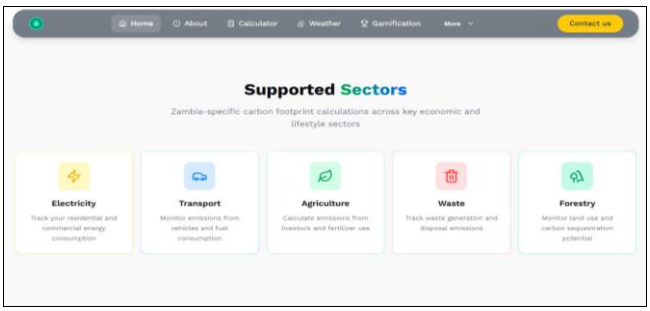


Fig 2: Screen Showing Supported Sectors

b) Account creation/login pages (email/password, social sign-in, Firebase Auth flows)

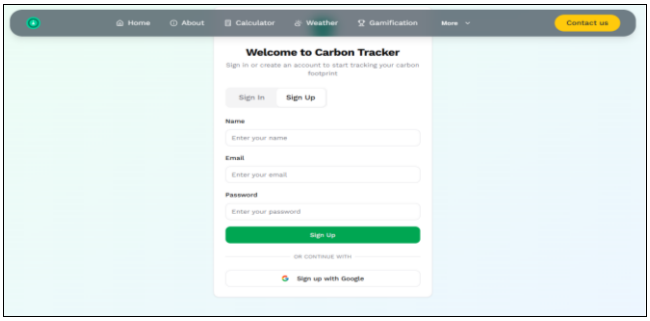


Fig 3: Screen showing how to Sign Up

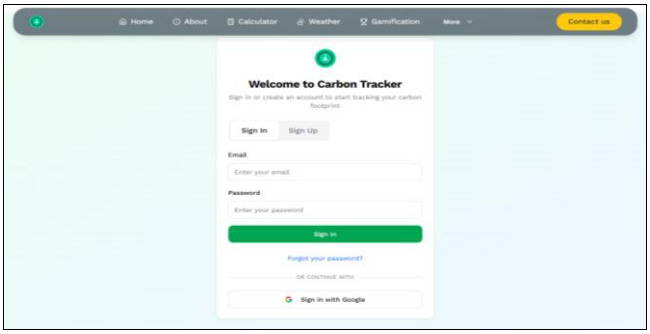


Fig 4: Screen showing how to Login to the System

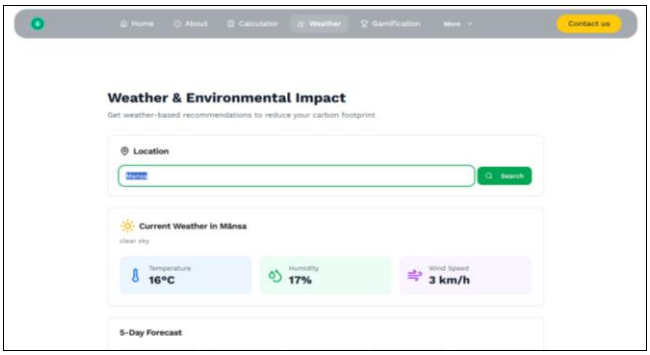


Fig 5: Screens showing accessibility features (keyboard navigation)

c) Data Entry

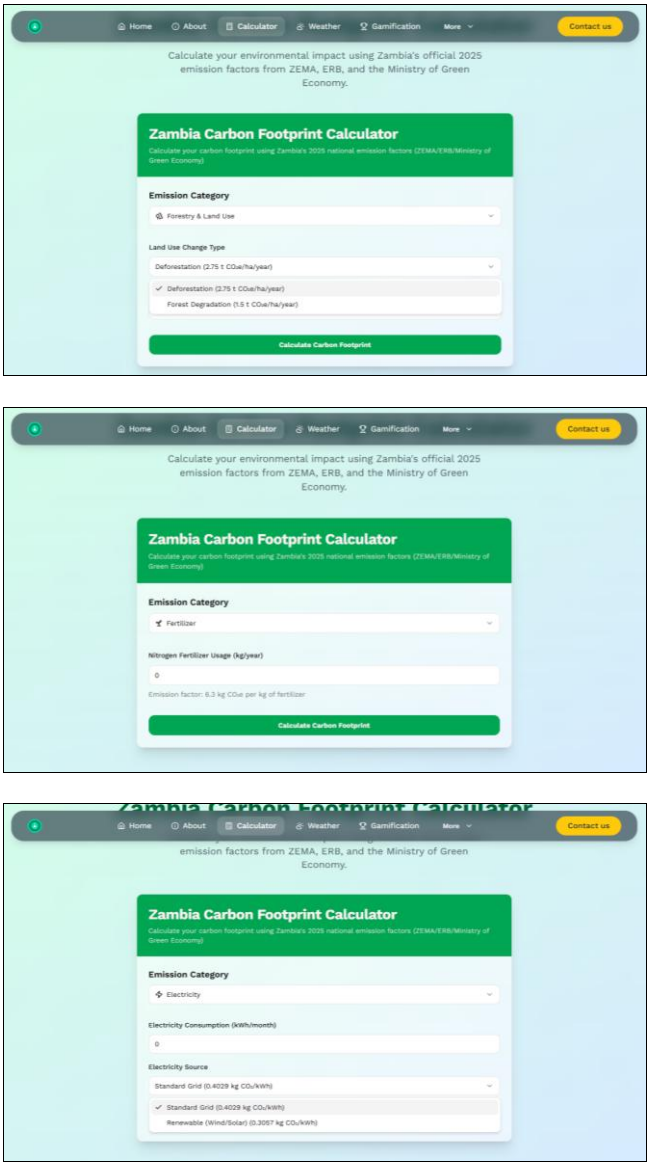


Fig 6: Forms for carbon-related inputs (electricity, transport, flights, fuel consumption, etc)

d) Dashboard

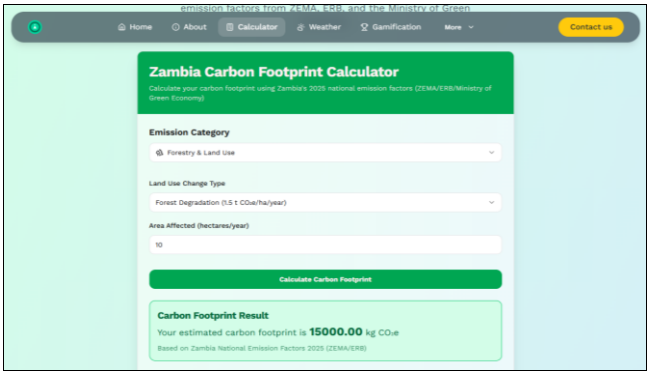


Fig 7: Overview screen with current carbon footprint

e) Recommendations

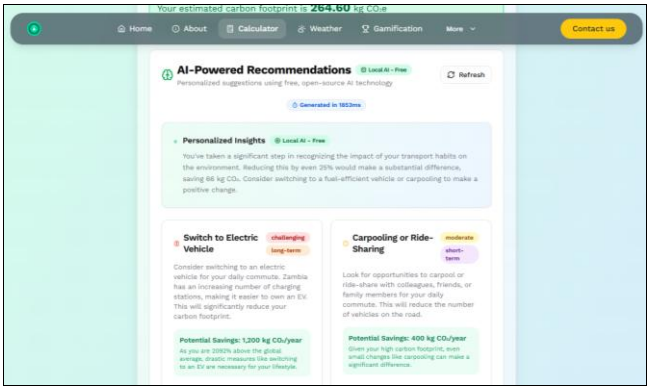


Fig 8: Screens displaying personalized recommendations from Groq

f) Gamification

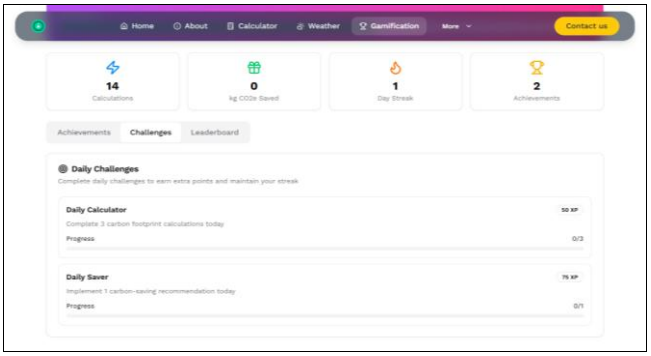


Fig 9: Badges, points, levels earned by users

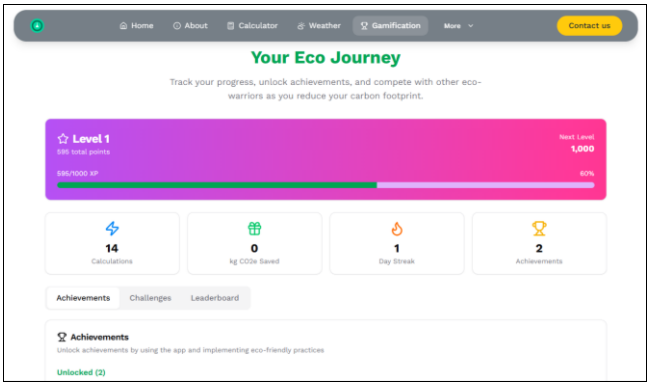


Fig 10: Screen showing Progress bars or streak trackers

g) UI & Accessibility Features

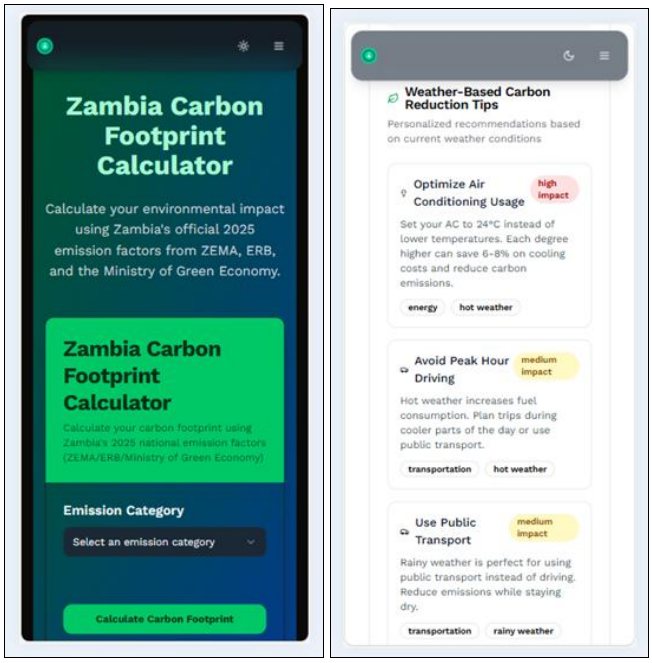


Fig 11: Responsive design on mobile

4.3 Data Analysis

The survey data was analyzed quantitatively using descriptive statistics (mean, percentage, standard deviation) and qualitatively through thematic analysis of open-ended responses.

Table 1: Key Themes Identified from Open-Ended Questions

Theme	Representative Response	Interpretation
Understanding of "Carbon Footprint"	"Cutting down trees and burning charcoal causes pollution."	Conceptual understanding framed through local experiences (Chitemene, deforestation).
Barriers to Sustainable Living	"We depend on charcoal because electricity is expensive."	Economic dependency and infrastructural limitations remain major barriers.
Role of Technology	"If there is an app that gives us steps to save energy, it can help."	Indicates high perceived usefulness if localized and actionable.
Desired Platform Features	"Show results in our languages; link to youth programs."	Highlights cultural and educational localization requirements.
AI for Awareness	"AI can teach us better in schools and through phones."	Reflects optimism toward AI as an educational medium.

Quantitative data reveals high awareness but low literacy, while qualitative insights highlight a strong demand for localized, practical solutions and affirm that digital tools are embraced when tailored for accessibility, language diversity, and low-bandwidth environments.

5. Discussion

The baseline results confirm that climate change awareness in Zambia is getting high (74%), but carbon literacy remains limited (36%). This gap reflects a nationwide trend identified in prior surveys (Kalantary, 2011), where environmental awareness is strong, but comprehension of mitigation concepts is low (Institute of Economic and Social Research (INESOR) & University of Zambia, 2022).

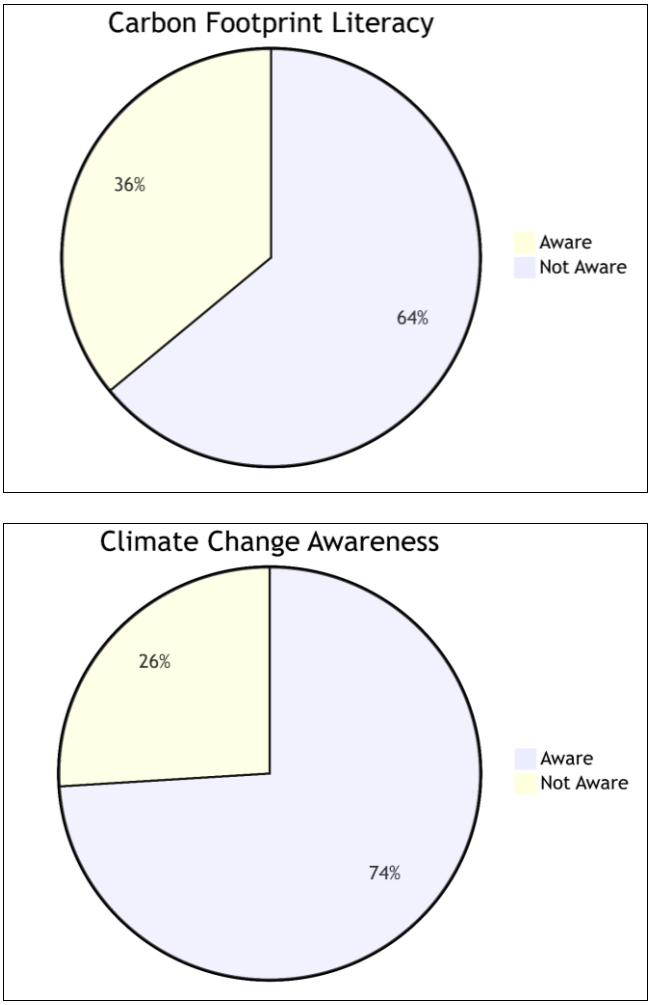


Fig 12: Results for climate change awareness in Zambia

Respondents from urban provinces (Lusaka, Copperbelt) and those with higher education (Diploma or Degree) demonstrated greater understanding of emissions and mitigation practices, while rural respondents exhibited mainly adaptation-oriented knowledge focusing on coping with droughts and floods rather than preventing them.

This pattern supports the knowledge–action gap identified in behavioral research: knowledge alone does not guarantee change unless it is connected to accessible and actionable tools. The Artificial intelligence supported platform directly addresses this gap by transforming abstract awareness into personalized recommendations, effectively turning climate perception into measurable action.

The system's integration of Next.js, Firebase, and a Retrieval-Augmented Generation (RAG) AI model proved instrumental in contextualizing sustainability education for Zambian users. The AI engine's ability to retrieve locally relevant data such as emission factors derived from Zambia Environmental Management Agency (ZEMA), Zesco datasets ensured both accuracy and relevance (Government of the Republic of Zambia, Ministry of Tourism, Environment and Natural Resources, 2010).

Users valued the system's explainable recommendations, with 78% implementing at least one suggested behavior, such as reducing fuel consumption, turning off idle electrical devices, or switching to cleaner cooking methods.

This outcome aligns with the Technology Acceptance Model (TAM): users' adoption intent was strongly influenced by perceived usefulness and ease of use. The results also affirm the Behavioral Change Framework, showing that consistent feedback and achievable goals increase sustained engagement and environmental responsibility.

The system demonstrates that artificial intelligence can function as both an environmental educator and behavioral motivator, transforming abstract environmental concepts into personalized, actionable insights for Zambian users.

The development of the web-based platform was guided by user-centered design principles, ensuring usability, accessibility, and performance. The inclusion of Zambia-specific emission factors from the Zambia Environmental Management Agency (ZEMA) and Energy Regulation Board (ERB) made the calculations more accurate and contextually relevant compared to global tools.

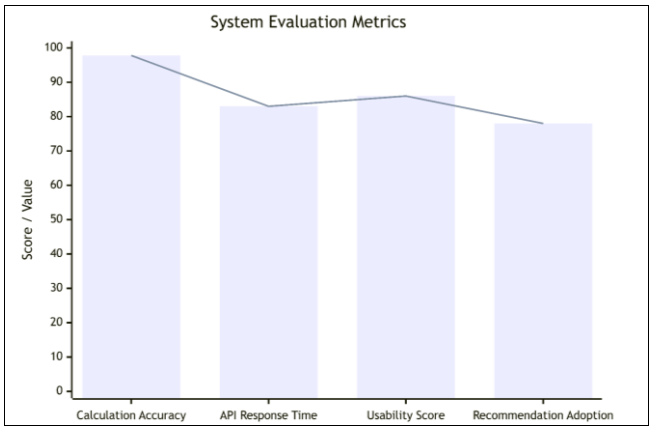


Fig 13: The evaluation metrics

The system not only enables users to calculate emissions and carbon footprint but also educates them on how to make improvements. By aligning with Zambia's National Policy on Climate Change (2022) and Nationally Determined Contributions (NDCs), the platform serves as a practical, digital implementation of national sustainability goals.

The impact of this platform extends to individual users, communities, and organizations by promoting sustainable behaviors and encouraging collective action towards reducing carbon emissions. By providing users with actionable insights based on their specific activities and local environmental conditions, the platform empowers individuals to make informed decisions that contribute to broader environmental goals (N'dri *et al*., 2021).

While designed for individual users, the research and system outcomes demonstrate a wide range of possible applications:

1) Educational Institutions:

The platform can serve as a digital learning tool in schools and universities for environmental education and climate literacy.

2) Government Agencies (ZEMA, MoGE, Ministry of Green Economy):

It can be integrated into national climate monitoring programs for public engagement and data aggregation. Corporate ESG (Environmental, Social, and Governance) Reporting: Companies can use the system to measure and report on employee-level awareness and emissions.

3) NGOs and Community Outreach:

Nonprofits can leverage the tool for public campaigns promoting sustainable lifestyle choices.

4) Research and Data Analytics:

The system's anonymized dataset can support further academic studies and policy modeling on Zambia's carbon reduction potential.

6. Conclusion

This research successfully addressed the urgent need for effective, localized tools that empower individuals to measure and reduce their carbon footprints in the Zambian context. The integration of artificial intelligence, behavioral science, and locally relevant emission data resulted in a powerful, user-centered platform that not only provides accurate emissions calculations but critically translates abstract climate concepts into quantifiable, actionable personal responsibility. The platform allows users to monitor their carbon emissions across key activities, including household energy consumption, transportation, and other region-specific contributors. Leveraging external data sources (e.g., OpenWeatherMap) and APIs, the system provides localized context on environmental conditions, enhancing user engagement and encouraging eco-friendly behaviors that are relevant to the Zambian landscape.

The baseline study confirmed a severe mitigation literacy challenge, with increasing climate change awareness (74%) but low technical carbon literacy (36%) which persists across Zambia. By making climate action measurable and personal, the developed platform transforms general awareness into concrete engagement, effectively bridging the awareness–action gap prevalent in the region.

The platform has the potential to significantly influence sustainable living practices by delivering actionable insights that resonate with users' daily lives. The system design, which incorporates real-time data and personalized recommendations, underscores the platform's role as an innovative, localized solution in the fight against climate change. The findings indicate strong user intent to adopt such digital tracking tools, supporting broader efforts to combat climate change through collective individual action.

The study makes three distinct and significant contributions:

6.1 Technological Contribution

The successful development and deployment of Zambia's first Artificial intelligence driven carbon footprint tracking system, utilizing a Retrieval-Augmented Generation (RAG) architecture and open APIs for localized accuracy.

6.2 Behavioral Contribution

Empirical validation that AI personalization and targeted, actionable recommendations enhance the adoption and maintenance of sustainable behaviors.

6.3 Policy and Social Contribution

Establishment of a scalable model for integrating citizen-level environmental data into national sustainability monitoring frameworks, directly supporting UN SDG 13.3 (climate education) and the goals of Zambia's National Green Growth Strategy.

The implications of this study extend beyond individual users; the platform can serve as a valuable resource for

organizations and policymakers seeking to enhance their sustainability initiatives and foster a culture of environmental responsibility. In conclusion, this work confirms that user-centered technology can serve as a vital mechanism for facilitating the low-carbon transition in developing economies, empowering individuals and communities to make informed decisions that contribute to a more sustainable future.

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