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# Barriers to adopting climate change awareness and education in Zimbabwe: a hybrid structural equation modelling and extreme gradient boosting approach

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## Abstract

The study seeks to examine the barriers to climate change awareness and education in Zimbabwe, using a hybrid Structural Equation Modelling (SEM) and Extreme Gradient Boosting (XGBoost). The results revealed a positive link between media coverage, climate data accessibility, environmental education, stakeholder engagement, and technological advancement with the dissemination of information, except for public perception through SEM. The perception of the public had a negative beta value, highlighting the urgent need for education. Dissemination of information was identified as the principal barrier to climate awareness and education using the XGBoost model, whilst climate data accessibility was identified as the least important. Key contributions of the study include uncovering emerging trends, the development of a new theoretical framework, generation of effective and significant insights for policymakers and governments in their quest to improve climate awareness and education, and provision of guidelines for actions to reduce climate change.

**Keywords** Climate change · Climate awareness · Structural equation modelling (SEM) · Extreme gradient boosting (XGBoost) · Environmental education

**JEL Classification** Q54 · O13 · I25 · C38 · C45

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# 1 Introduction

Climate change represents a major threat to the global environment, as well as to economic and social structures. It is evident in rising sea levels, ozone layer depletion and extreme weather phenomena. Research by Tirkey et al. (2024) noted that climate change has been exacerbated by industrialisation, fossil fuel combustion and deforestation, which facilitate the emission of greenhouse gases. To manage this persistent problem, the international community recognises the importance of climate change education and awareness in promoting behavioural change, which will improve the lives of people and support adaptation strategies. Continentally, especially in Africa, climate change has adversely affected the environment, food security and the availability of water. Zimbabwe, like many developing countries, is susceptible to climate change, since it is primarily dependent on agriculture. Notwithstanding policies and frameworks to monitor climate change, education and awareness remain a problem within the general population. Addressing this gap through tailored education and awareness programmes targeting the country's citizens could help to address the current situation and contribute to sustainable development.

Climate change has given rise to erosion, deforestation, ozone layer depletion and soil oxidation, which could have irreversible consequences (Nayak et al. 2023). Education is therefore vital to promoting climate awareness, necessitating a collaborative effort on the part of all stakeholders. The study utilised a hybrid approach by integrating Structural Equation Modelling and XGBoost algorithm. Variable importance through the machine learning method will guide stakeholders and policymakers in determining which factors contribute more to climate change education (CCE) (Molthan-Hill et al. 2022). CCE is vital in that it makes it easier to understand the pressing need to solve climate change. Moreover, CCE provides people with the necessary tools to mitigate their carbon footprints, promote policy change and endorse community-based solutions. In essence, building a more sustainable and resilient future for everyone requires climate education that addresses the climate problem. The Zimbabwe 2030 Agenda and Sustainable Development Goal (SDG) 4 emphasise quality education for all. This ensures quality and accessible education for the citizens, which aligns with the study's goal in that it will contribute to climate resilience, awareness and action. Youth empowerment for climate action through education also enhances youth engagement, promoting a sustainable environment. The interaction of education, media and technology is vital in driving climate awareness and behavioural change. These elements interact to improve public understanding of, and collaboration in, climate-related issues, promoting sustainable practices. Education is important in encouraging the critical thinking necessary for people to make and implement informed decisions, and equipping people with the skills necessary to adapt to the impacts of climate change, promoting sustainable practices and innovation (Tripathy et al. 2024). The media raises awareness within the community about climate-related issues (Afroz et al. 2019). Radio and television could be used to disseminate information on climate change and improve public engagement. Technology, too, could bring innovative platforms such as podcasts and visual storytelling (Nyagadza 2022), improving climate literacy (Saini 2024). Although these strategies are essential, the challenge of climate change remains and requires the collaboration of all stakeholders.

Dissemination of information is seen as one of the challenges that impedes implementation of climate strategies. A framework on climate awareness should be consider understanding of barriers to climate change as the primary objective. The study by Oranga et al.

(2023), demonstrated the effect of having little knowledge on climate education which can lead to low engagement. Against this background, the current study will examine the factors that affect climate awareness and education (Fauzi, 2022; Hickman et al., 2021). Data is an essential part in promoting climate awareness and education since it enriches people through evidence-based approach. In most African countries, climate data is lacking and thereby restrict people from making sound decisions (Gross and Dinku 2022;Verhulst 2024). Some communities may have access to the data but unequal data,ribution may increase differences and thereby a few people may respond positively to climate change impacts. Moreover, stakeholder engagement is an important factor that determines the success of climate awareness and education and if essential information is accessed by stakeholders, certain challenges in the communities could be solved (Bridges et al. 2024; Manteaw et al. 2022).

Despite the urgent need to address climate change, mainstream curricula are still slowly and unevenly incorporating climate knowledge and instruction. Indeed, developing countries are lagging in implementing effective climate education because of limited resources and support (Acikalin et al., 2024). The ineffectiveness in promoting climate education will restrict community access to the vital skills necessary to reduce climate threats. Climate education remains important (Aryal et al., 2025), and if not taken seriously, communities will be vulnerable to climate-related problems. Developing countries have limited resources to finance climate-related issues, which impedes the successful implementation of climate education (Sohail et al. 2024). Additionally, social and political situations have contributed to the failure of climate education, especially if government fails to support the programmes (Oranga et al. 2023, Bhatti et al., 2022).

Moreover, public commitment may be impeded by psychological resistance from society, hampering climate education (Oranga et al. 2023). Such systematic resistance to climate education may delay its adoption despite the need for informed and proactive environmental action. Education continues to be an important tool to equip people with the knowledge and skills needed to take significant climate-related measures (Nyagadza, 2021). Climate education provides society with the necessary requirements it needs to strive for environmental conditions since it promotes critical thinking (Priatna and Khan 2024). The deterioration of climate education, however, continues to be a major problem despite its benefits to the community. Vital policies could be availed using a robust analytical framework that predicts the main barriers to the adoption of climate education using hybrid Structural Equation Modelling (SEM) and XGBoost technique. To ensure a more potent climate-resilient future for Zimbabwe and around the world, it is essential to explore the barriers to climate education.

This study deploys a hybrid SEM-XGBoost technique to assess the barriers to climate awareness and education in Zimbabwe. The merits of this approach are that it allows for a comprehensive understanding of complex causal and capturing non-linear relationships among variables for predictive purposes. Furthermore, it integrates theory- and data-driven insights, uncovering unexpected outcomes and or variables. It better handles data quality and structure, especially in critical contexts such as Zimbabwe, where data quality may be variable. In addition, SEM models help to pick unobservable variables and on the other hand, XGBoost provides important metrics, which identify the observed factors with the most significant influence. Moreover, the current hybrid methodology enhances relevance of policies, cross validation, improves model robustness and increases applicability in resource-constrained and multi-dimensional contexts.

Considering the foregoing, the objectives of this study are:

- To examine the interrelationships of the variables that affect climate education, taking into consideration the mediator variable.
- To develop a prediction model that would guide governments and policymakers as they take corrective action and rank the factors that affect climate education.

The following sections are organised as follows: in Sect. 2, the theoretical framework, literature review and hypothesis development are presented. In Sect. 3, the study's research methodology is presented. Thereafter, the model's results are thoroughly examined and discussed. Section 5 is devoted to the implications of the study, and the conclusion of the study is presented in Sect. 6.

## 2 Theoretical framework, literature review and hypotheses development

This section presents the Theory of Planned Behaviour (TPB) – Diffusion of Innovations (DOI) hybrid theoretical framework, which undergirds the study, highlighting the complex relationships of variables that impede climate awareness and education. Despite the global efforts on climate change, the problem of implementation remains a problem, particularly in developing countries, where climate change education is inadequate. This review will examine the barriers in detail and highlight strategies to enhance climate change awareness.

### 2.1 Theoretical framework

#### 2.1.1 Theory of planned behaviour

The present study is included in the Theory of Planned Behavior (TPB), which plays a significant role in understanding individuals' intentions toward climate change education. The theory consists of three components: subjective norms, perceived behavioural control, and attitude. In connection with climate change, an individual's attitude significantly influences their readiness to interact with climate-related topics (Monroe et al. 2019). Studies show that those who think climate change education is important and useful are more inclined to support and take part in it (Kolenatý et al. 2022). People's decisions are also strongly influenced by subjective norms, which are the social pressures they feel from friends, family, or important community leaders. In short, TPB not only explains why people might or might not want to learn about climate change, but it also points out things like attitudes, social influence, and control factors that can be changed to induce more people to change their behavior.

#### 2.1.2 Diffusion of innovations

The Diffusion of Innovations (DOI) theory allows for a comprehensive understanding of the adoption and dissemination of climate change education within a population or educational institution (Matabi 2017). The main components of DOI are the innovation characteristics that affect the rate of adoption (Park and Choi 2019). First, relative advantage determines whether climate education is viewed as better than the current curriculum. Second, com-

patibility considers whether it is in keeping with local beliefs, customs, and educational aims. Climate education that includes indigenous knowledge systems is more likely to be accepted. The third point highlights how complexity influences uptake: if the information is seen as excessively technical or abstract, especially in rural or under-resourced areas, it may deter people from using it. Lastly, two characteristics (trialability and observability) enable people to conduct small-scale experiments with climate education and observe tangible benefits, such as better environmental habits, before fully adopting it, making it less likely that people will resist it (Kulugomba et al. 2025). Innovators in climate education could include NGOs, progressive schools, or curriculum developers who are piloting new content (Okada and Gray 2023). Early adopters, such as passionate instructors or community leaders, have a significant impact on others, while the late majority and laggards, on the other hand, sometimes need more evidence or pressure from institutions to take up climate education. Finally, the broader social system, which includes government regulations, curricular frameworks, teacher training programmes, and community networks, can facilitate the diffusion process.

### 2.1.3 Theory of planned behaviour (TPB)—diffusion of innovations (DOI) hybrid perspective

A hybrid theoretical framework that combines the Theory of Planned Behaviour (TPB) and the Diffusion of Innovations (DOI) offers a strong, multi-dimensional approach for understanding and forecasting the uptake of climate change education (Anjum et al. 2024). DOI mainly looks at new ideas like climate education that are spread through social systems using innovation traits, communication channels, and adopter categories (García-Avilés 2020). On the other hand, TBP looks at personal decisions, subjective norms, and perceived behavioral control that affect people's intentions to act in a certain way (Abd Rahman et al. 2024). This combined TPB–DOI method, backed up by SEM and XGBoost, provides a whole explanatory and predictive framework for looking at how climate change education is spreading in different situations.

## 2.2 Environmental education

Environmental education is of the key factors that affect climate awareness and education and should be considered seriously to improve the current situation globally. Educating people about the environment is key to promoting skills and knowledge required to improve harness climate awareness and education. Education promotes the critical thinking abilities required to deal with climate concerns (Tripathy et al. 2024) since a structured and planned approach is vital, especially in developing nations, where resources are scarce. Sustainable practices are likely to be applied successfully by those who are exposed to environmental education, since they are aware of the dangers and benefits of using correct climate change practices (Bergman 2016). The study by Castillo and Nozaleda (2022), demonstrated that enhanced awareness through education potentially accelerates engagement in environmental protection. Even though environmental education can help people understand climate change, it is a challenge to make sure that everyone gets the same amount of climate change education. Considering this, there is a lot education in this regard. Consistent with the prior studies, the following hypothesis is formulated:

**Hypothesis 1 (H<sub>1</sub>)** Environmental education directly influences the dissemination of information.

### 2.3 Media coverage

The media plays a significant role in climate education as it shapes public perception and understanding of climate change. Many studies have highlighted the role of the media in enlightening and engaging viewers through its reporting of catastrophic weather events and focused educational campaigns. The study conducted by Zia et al. (2024) showed media as the primary source of information, and many respondents perceived it as augmenting their knowledge of climate change (Hartmann et al. 2024). Under catastrophic weather reporting, the media has increased coverage, as is seen in Germany, where 50% of participants indicated a change in their climate perceptions because of such media. Despite the limitations of media coverage in some developing countries, the media have contributed to addressing climate change issues. Public engagement could be improved through effective campaigns and targeted media segments, although lack of resources might impede such initiatives (Asimakopoulos et al. 2025). Moreover, studies demonstrate that media impact youth awareness more positively than formal education, highlighting the need for educational systems to successfully integrate media. On the other hand, although media coverage has significantly and positively affected climate education, it may also lead to desensitisation if not carefully managed. Consistent with prior studies, the following hypothesis is formulated:

**Hypothesis 2 (H<sub>2</sub>)** Media Coverage is positively associated with the dissemination of information.

### 2.4 Perceptions of public

People around the world have different perceptions about climate change, possibly owing to differences in cultures, lifestyles and beliefs. Different perceptions might affect climate education positively or negatively and, therefore, need attention. If the public is unresponsive to climate change, information dissemination might fail, reducing its effectiveness. In a study carried out by Al-Swidi et al. (2024), a positive correlation was noted between enhanced public awareness and proactive climate action, since informed communities are more inclined to embrace sustainable practices. Similarly, in Afghanistan, research by Sharma et al. (2024) demonstrates how awareness could empower individuals to participate in environmental initiatives at a larger scale. The link between public perception and educational levels has been observed to be positive, since people with higher education levels are associated with increased awareness about climate change impacts and issues (Cvetković and Grbić 2021). People's views on climate change education may differ based on demographic factors, including age and job status (Cvetković and Grbić 2021). The public has the tendency that climate related issues should be tailored to a specific group of people and yet it is a collective effort. In a study conducted by Ni et al. (2025), young people were observed as the dominant groups in climate related activities and hence the perception of public should be enforced.

Consistent with prior studies, the following hypothesis is proposed:

**Hypothesis 3 (H<sub>3</sub>)** The perception of the public positively influences the dissemination of information.

## 2.5 Climate data accessibility

Accessibility of data that is related to climate plays a significant role in promoting awareness and education and can lead to sound decisions. Although climate data cannot be readily available to all users, stakeholders can use tools like radio and television to improve information flow. Projects like Global Online Research on Agriculture (AGORA) have immensely improve the challenge and this seen Stakeholders such as communities and policymakers depending on this site to improve climate adaptation strategies (Bharathy et al. 2025). Notwithstanding the little resources some schools are facing, web portals such as klimafolgenonline-bildung.de, can be used to facilitate an understanding of complex climate linkages. To avoid imbalance across the globe, leaders from various parts of world can set a budget that is specifically tailored to promote climate awareness and education. The effort can promote data accessibility to people and thereby promote awareness. Services such as the IRI Data Library could be harnessed to improve accessibility of climate-related data, making it easier for non-experts to access information (Khan 2024). Even though this sector has made progress, there are still problems, such as the type of scientific data and the necessity for suitable standards in all locations (Montero et al. 2024). The following hypotheses are formulated:

**Hypothesis 4 (H<sub>4</sub>)** Climate data accessibility positively influences the dissemination of information.

## 2.6 Stakeholder engagement

Promoting climate education and awareness requires proper engagement with the important stakeholders. It is regarded as a critical element in the successful implementation of climate education and awareness. Climate change is seen as a global issue that requires teamwork and collaboration to control its effects. Considering this, stakeholder engagement plays a significant role in improving climate education throughout the world by promoting collaboration and co-production of knowledge across various groups. Stakeholders include educators, NGOs, the private sector, media and community leaders that successfully drive climate change initiatives (Angel 2025). To successfully implement climate education, each part plays a crucial role. According to Wilkins (2018), strong engagement results in the creation of knowledge and trust. Efforts from the NGOs have been noted, though they are short-term and consequently leading to poor results. The study by Nhamo et al. (2024) has shown that total commitment from the stakeholders in climate-related issues yields good results and is accepted. In Zimbabwe, despite national initiatives such as the Climate Policy (2017) and the National Climate Change Response strategy (2015), stakeholder engagement is still underutilized and requires collaboration from various sectors. Coordination from various ministries, such as the environment and education, requires proper planning and commitment. Through the engagement of stakeholders, concerns are considered, resulting in relevant climate solutions (Fejzić and Usher 2024). Moreover, customizing engagement efforts to social and cultural settings improves the effectiveness of climate education campaigns

(Kumar et al. 2025). Workshops can be planned where people interact and share ideas about climate change issues. The research conducted by Prajapati et al. (2025) postulates that participatory workshops have been instrumental in promoting effective dialogue among stakeholders, facilitating the exchange of knowledge and experiences. Despite the advantages of stakeholder engagement in climate change education, implementation remains a challenge, especially if it involves different states. Consistent with the prior studies, the following hypothesis is formulated:

**Hypothesis 5 (H<sub>5</sub>)** Stakeholder engagement positively influences the dissemination of information.

## 2.7 Technological advancements

Climate education is enhanced by technology, such as climate change chatbots that provide answers to students' questions. Technological advancements may be limited in some regions and hence, their applicability in the world may be hindered. Innovative technological approaches engage the public and facilitate the understanding of climate issues. In a study conducted by Khanal (2024), for example, the Virtual Reality (VR) Application was found to be a powerful learning tool. It can be simulated to happen and thus enable understanding of real-life situations in climate change. Despite the numerous advantages brought by advanced technology, developing countries may fail to access them due to limited resources and this hampers climate awareness and education efforts. Technological advancements can lead to community engagements, with Murphy and Obenaus-Emler (2024), noting that initiatives such as the one relating to hydrogen production raise public awareness, highlighting the need for community involvement. Moreover, curriculum development that incorporates climate change topics into curricula promotes critical thinking among students (Priatna and Khan 2024). The current study does not support Zimbabwe to prioritise high-cost technology such as Virtual Reality (VR) as the primary solution, but its results suggest that such initiatives should be implemented at a later stage, when the resources permit. Zimbabwe should prioritise expanding the use of low-cost, high-impact technologies, as other countries do. Mobile phones and radios should be used to improve climate change information and technology. In using these advanced tools, focus must be given to capacity building, with local leaders trained on how to use available tools. Despite the positive role of technological advancements in climate awareness and education, affordability remains the principal challenge, especially in developing countries, where resources are scarce. Consistent with prior studies, the following hypothesis is formulated:

**Hypothesis 6 (H<sub>6</sub>)** Technological advancements directly influence the dissemination of information.

## 2.8 Dissemination of information

Climate awareness and education, albeit essential to this study, may be unsuccessful because of poor dissemination of information, which serves as a mediator between the barriers to climate change and climate awareness. Information dissemination equips people with knowledge about climate change, its effects, causes and possible solutions (Damoah 2023).

Effectiveness of climate change education is impeded by a lack of organised structures (Elkhatat et al. 2024). Research by Debrah et al. (2021) has shown that a lack of knowledge among students is hampering efforts to promote climate change education, highlighting the need to improve current educational settings. Based on the discussion above, we set the following null and alternative hypotheses:

**Hypothesis 7 (H<sub>7</sub>)** Dissemination of information is associated with climate awareness.

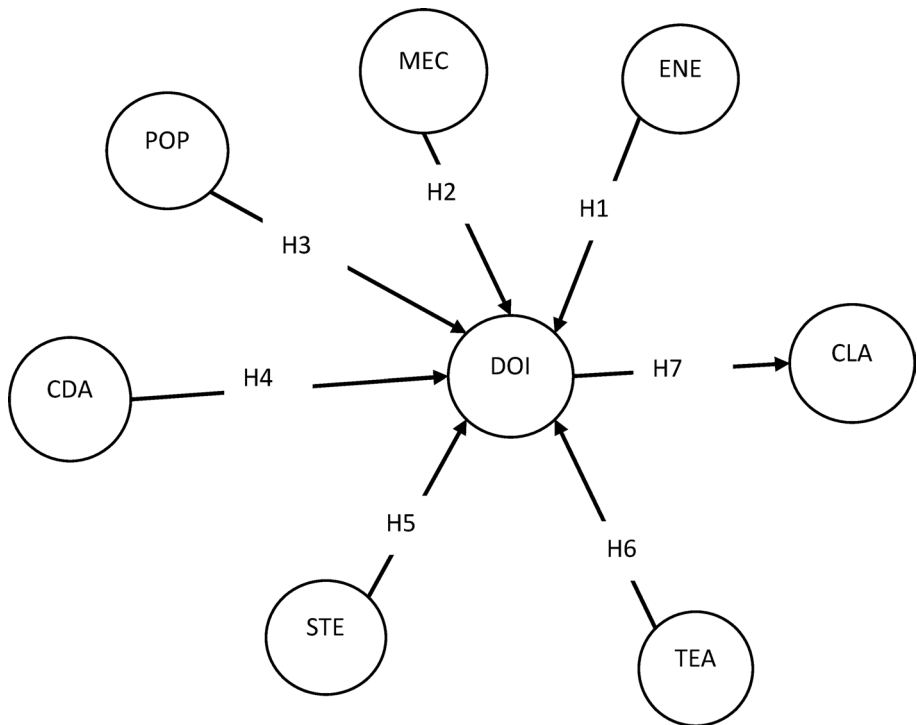
## 2.9 Climate awareness and education

Dealing with climate change is a complex issue that requires knowledge to deal with the problems. Climate awareness and education are a requirement that are composed of understanding and having the skill to tackle climate-related issues. Climate education requires collaboration from different stakeholders to manage its potential effects on the environment and people. The study by Ibrahim (2024), demonstrated that climate awareness can lead to cognitive overload, particularly in poor people, resulting in maladaptive behaviour such as eco-anxiety. Moreover, in another study by Sato and Park (2024), a positive association was found between climate awareness and education, highlighting the importance of educating people to improve awareness of climate related issues. This positive link emphasises how essential it is for communities to understand the importance of education in dealing with climate change. Climate change awareness varies with geographical variability and in a study carried out by Zammarchi and Maranzano (2024), people in Western countries showed a higher awareness than those in African and Asian countries (Fig. 1).

## 3 Research methodology

### 3.1 Questionnaire design and data collection

The research study was conducted in Marondera town in the Mashonaland East province of Zimbabwe. It used a cross-sectional design to examine the complex interaction of variables using a quantitative approach. A closed questionnaire was used to capture respondents' views on climate change education for public information. To fully capture the views of respondents, the study followed the recommendations made by Hair et al. (2017), that a sample of 200 would be suitable for a PLS-SEM methodology. The present study utilised a sample of 250 across the various respondent groups, which is above the number stipulated by Hair et al. (2017). Since the present study involved some knowledge of climate change, it utilised stratified sampling, where the population is divided into strata that would fully represent the views of the respondents. The strata were divided according to educational level (tertiary, secondary and primary) and occupation (educators, farmers and business owners). These variables were selected for consideration since educational background plays a key role in this kind of research. To avoid unnecessary expenses, participants (such as farmers and educators) were further selected randomly within each stratum. A five-point Likert scale was used (with responses ranging from strongly disagree to strongly agree) and respondents were given guidance if any questions were unclear. The questionnaire designed underwent pre-testing to address any errors made during the formulation phase. After pre-testing, the

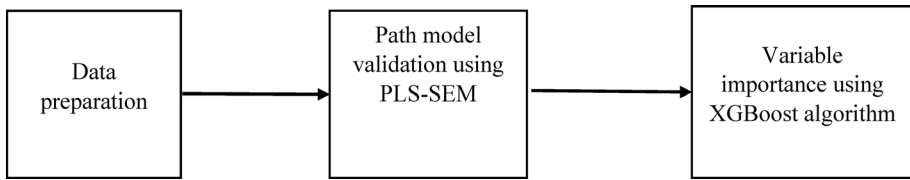


**Fig. 1** Conceptual model. *Key:* Environmental Education (ENE), Climate data accessibility (CDA), Stakeholder Engagement (STE), Technological Advancements (TEA), Perception of Public (POP), Media Coverage (MEC), Dissemination of information (DOI), Climate Awareness and education (CLA). Source: Authors' conception (2025)

questionnaire was distributed to respondents, and questionnaire responses were received within a month. Respondents were not forced to answer the questions, but the purpose and expected benefits of the study were explained to them, by way of motivation. Moreover, the questionnaire was designed in such a way that it was short and precise, adhering to the study objectives.

### 3.2 Data analysis

The study employed a hybrid system comprising Structural Equation Modelling (SEM), and the XGBoost method, unlike other studies that utilised the SEM alone. The application of the proposed hybrid approach validates the relationships amongst the constructs and provides a variable importance that would further improve the understanding of the variables. The first stage of the analysis involved testing variables using the PLS-SEM suggested by Hair et al. (2019). In the second phase, the XGBoost method was applied, through sensitivity analysis, to determine the importance of each factor. The PLS-SEM is shown in Sect. 4.2, whilst the XGBoost method is illustrated in Sect. 4.6. Figure 2 below shows the research framework for the proposed SEM-XGBoost hybrid method. The framework below shows the path of the two models from data preparation to model evaluation.



**Fig. 2** Research framework.  
Source: Authors' conception (2025)

### 3.2.1 Data preparation

Data modelling requires that data be cleaned before it is used so to ensure the validity and reliability of the results, since a questionnaire may have missing values, inconsistent responses and outliers. Removing unwanted data may also prevent biases, and removing misplaced responses may improve the overall data quality. Before they were used, the data sets were normalised to ensure that all the variables contributed proportionally when building the models. Under the Structural Equation Modelling, the reliability and validity of the data were checked using Cronbach's alpha test, average variance extracted (AVE) and composite reliability. During the XGBoost modelling, the data was split into 70% training and 30% testing sets, whilst hyperparameters were used to optimise the model.

### 3.2.2 Partial least squares structural equational modelling

SEM methods are widely used in various fields, including marketing and climate change, because of their ability to examine the relationship between the variables. The PLS-SEM method seeks to optimise the explained variance of the endogenous latent component (Yazdi et al. 2017). Although the covariance-based SEM approaches have limitations, in terms of huge sample size and multivariate normality, they are circumvented by employing PLS-SEM. The PLS-SEM model has two components, namely the measurement model and the structural model (Hair et al. 2019). The measurement model explains the association between the observed variables and the latent variables, whilst the structural model tests the theoretical hypothesis by looking at the casual relationships.

### 3.2.3 XGBoost

For both regression and classification tasks, the methodology of Chen and Guestrin (2016), XGBoost, is highly efficient. The algorithm uses the gradient boosting technique that repeatedly adds new trees to accurately predict values, taking into consideration the residual errors. The process of making repetitions consequently improves the efficacy of the algorithm. Friedman (2001) introduced the XGBoost technique using Taylor's expansion to approximate the loss function. Since the approach is centered on minimising errors, the algorithm results in a more advantageous balance between variance and bias. To fully explain the algorithm,  $m$  is taken as the features, whilst  $D$  denotes the set of samples. The formula for  $D$  can be expressed as:  $D = (p_i, q_i) (|D|) = n, p_i \in \mathbb{R}^m, q_i \in \mathbb{R}, p_i$  represents the eigenvalue whilst  $q_i$  is the true value. The final prediction is obtained by consolidating the results of  $k$  trees, and is expressed as:

$$\hat{q} = \sum_{k=1}^K f_k(p_i), f_k \in F \quad (1)$$

To obtain the final prediction  $\hat{q}$ ,  $k$  trees are incorporated for a specific set of input variables at data point  $i$ , represented as  $p_i$ . The final prediction is reached after a series of steps, resulting in the cumulative sum. The parameters include the number of trees  $K$ , the predictions made by each tree  $f_k$ , the input characteristics  $p_i$ , and the range of potential functions  $F$  that the individual trees can adopt.

The XGBoost technique comprises two primary elements, which include the loss functions for each data point and the regularisation term for each tree, as shown below.

$$l^t = \sum_{i=1}^n l(q_i; \hat{q}_i^t) + \Omega(f_k) \quad (2)$$

The symbol  $l^t$  represents the cumulative objective function value at iteration  $t$ , whilst  $n$  represents the total number of data points in the training set. The actual labels or target value of the  $i$ th data point in the training set is denoted by  $q_i$  whilst  $\hat{q}_i^t$  indicates the predicted value for the  $i^{\text{th}}$  data point derived from the ensemble at iteration  $t$ . The second part of the equation represents the regularisation term that is responsible for controlling the complexity of each tree to manage overfitting.

$$\Omega(f) = \gamma(T) + \frac{1}{2} \lambda \|w\|^2 \quad (3)$$

During the training process, overfitting is a problem, and the above equation is responsible for reducing overfitting. The symbol  $\gamma(T)$  caters to the complexity of the decision tree, whilst  $\lambda$  is the regularisation term. The process ensures the right balance between strong and general models whilst avoiding complex solutions. A new tree is included during the training stage, together with the residuals from the preceding iteration. For this reason, the model can be represented by the equation when it consists of  $t$  trees. The process continues until the final resilient model is obtained using hyperparameters. The data was partitioned into training (70%) and testing (30%) set and to examine the build the model.

### 3.2.4 Evaluation metrics

To examine the performance of the machine learning model, different evaluation metrics can be used and, in this section, the Root Mean Squared Logarithmic Error (RMSLE), Mean Squared Error (MSE), Mean Absolute Error (MAE) and Coefficient of Determination (R2) were used.

- (1) Mean absolute error (MAE)

The MAE is an evaluation metric utilized to measure the average magnitude of errors in a collection of prediction values and is used to assess the predictive power of the model. The MAE is illustrated in Eq. 4 as demonstrated by Willmott et al. (2005).

$$MAE = \frac{\sum \|(m_{obs} - m_{pred})\|}{n} \quad (4)$$

### (2) Mean square error (MSE)

Mean squared error (MSE) represents the values obtained by dividing the sum of the squares of errors by the total number of predicted values or average of the error's squares. The smaller the values of MSE the desirable it is. According to Willmott et al. (2005), the MSE is calculated using Eq. 5. From Eq. 5  $m_{obs}$  is the actual value, whilst  $m_{pred}$  represents the predicted value and  $n$  is the total number of samples used.

$$MSE = \frac{\sum (m_{obs} - m_{pred})^2}{N} \quad (5)$$

### (3) Root mean squared error (RMSE)

The RMSE is an evaluation metric which is obtained from the square root of the MSE, and it shows the difference between the actual and the predicted values. The calculation of the RMSE is shown in Eq. 6.

$$RMSE = \sqrt{\frac{\sum (m_{obs} - m_{pred})^2}{N}} \quad (6)$$

### (4) Coefficient of determination (R<sup>2</sup>)

The Coefficient of Determination is sometimes referred to as r squared error, and it determines the goodness of fit of the model. The R<sup>2</sup> explains the amount of variation in the endogenous variable being explained by the exogenous variables. The formula for the R<sup>2</sup> is indicated in Eq. 7, as shown by Menard (2000).

$$R^2 = 1 - \frac{\text{Explained variation}}{\text{Total variation}} \quad (7)$$

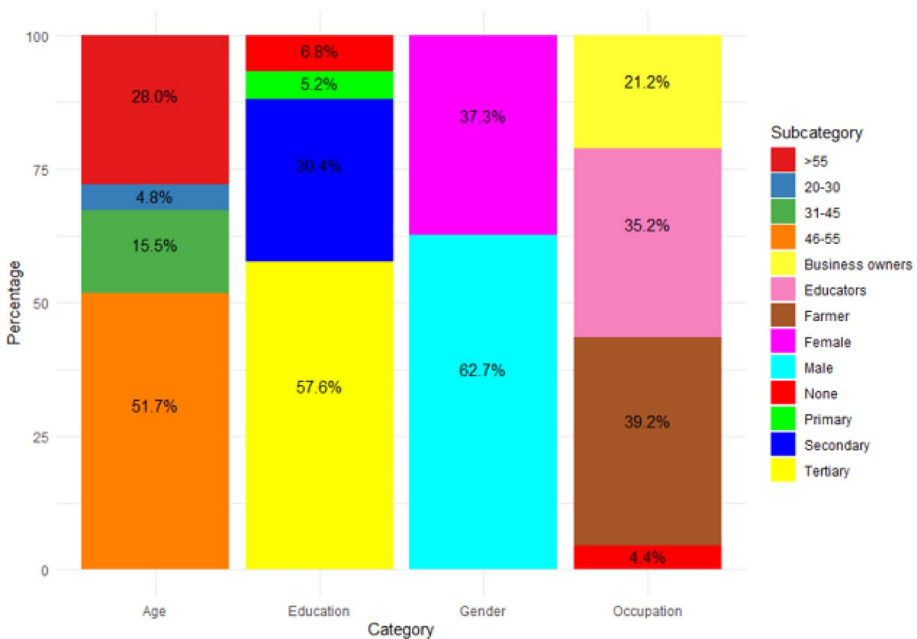
### 3.2.5 Justification of the hybrid technique

The study utilised a hybrid approach, where Structural Equation Modelling was used to test hypothesised relationships among variables. This technique allows for a clear view of both the direct and indirect effects and measurement validity. Since XGBoost struggles to deal with non-linearity, normality and complex data, it was applied to improve the predictive power and deal with non-linear relationships. The change from SEM to XGBoost ensures robust findings that will allow for decisions to be made based on strong methods. For this reason, the hybrid approach ensures that the findings are comprehensive in dealing with climate education and awareness.

## 4 Results

### 4.1 The demographic characteristics

The demographic characteristics shown in Fig. 3 reveal that males make up 62.5% while their female counterparts account for 37.5% of the respondents. The results indicate the dominance of males in this regard, and this could suggest disparities in educational and research opportunities. Most of the respondents (51.7%) were in the age range of 46–55 years. The age ranges 20–30, 31–45 and above 51 accounted for 4.8%, 15.5% and 28.8%, respectively. The prevalence of the 46–55 years age range might be attributable to the fact that these respondents may, unlike the younger ones, perceive climate education as having a direct impact on the community and have a full understanding of the benefits it brings. Moreover,



**Fig. 3** The demographic characteristics.  
Source: Authors' conception (2025)

the researcher had limited resources to reach everyone and hence resorted to people within the vicinity. The 20–30-year age group had few respondents, and this could be attributed to little knowledge of climate-related issues. The researcher also considered the occupational background of respondents and found that many (39.2%) were farmers. The educators and business owners accounted for 35.2% and 21.2% of the respondents, respectively. Only 4.4% did not want to disclose their occupation. The results displayed showed that the highest percentage of respondents were farmers and educators, which could be attributable to the nature of the research, which requires some knowledge on climate change. Furthermore, under the education category, tertiary and secondary level education dominated with a percentage of 57.6% and 30.4%, respectively.

## 4.2 PLS-SEM analysis

### 4.2.1 Measurement model

For the reliability check, Cronbach's alpha, which measures the reliability of the constructs as stated by Malhotra et al. (2012) was used. The results show that all the factors met the required value of 0.7, according to Tore et al. (2019). The consistency and validity of factors were assessed using the measurement model. A high correlation of multiple indicators in structural equation modeling can lead to poor results and this suggests that they assess the same fundamental concept. The present research employed the average variance extracted (AVE), composite reliability (CR) and the factor loadings to assess the convergent validity. The CR uses the standardized loadings of the items and the research by Hair et al. (2011), indicates that it is a better measure of internal consistency. CR values represent the thresholds at which manifest variables indicate the constructs of latent variables from the computation of the homogenous outer loadings associated with the constructs (Ali et al. 2016; Nyagadza 2022). The recommended outer loading value for the variable is greater than 0.7. From the results displayed in Table 1, the CR values were in the range of 0.764 and 0.902, suggesting that CR was met. The major principle under convergent validity is the AVE, which finds the meaning of the squared standardized pattern coefficients for variables depending on the same factor while being designated to measure no other factor (Kline 2016). The recommended value for the AVE is greater than 0.5, as propounded by Kline (2016). From the results displayed in Table 1, the AVE was given as 0.886 for environmental education, media coverage (0.842), perception of the public (0.883), climate data accessibility (0.790), stakeholder engagement (0.833), technological advancement (0.785), dissemination of information (0.782) and climate awareness (0.884), indicating that the convergent validity was met. Moreover, the normality test was also assessed through skewness and kurtosis, and the results were within the required range. After the convergent validity, discriminant validity, which indicates the degree to which a specific construct is unique from the other constructs, was examined as stated by Liu (2012). Various techniques like the cross-loading, Fornell-Lacker criterion and Heterotrait-Monotrait ratio (HTMT) can be used to examine the discriminant validity of variables. Our study employed HTMT and cross-loading. The HTMT is found to be the ratio of the average of the association between constructs of different indicators to the mean correlations among indicators of the same construct (Henseler 2015). The HTMT value must be lower than 0.9 for discriminant validity to be met (Henseler 2015) (Table 2). Table 3 gives the values of the HTMT, and all the

**Table 1** Constructs reliability

Construct	Items	VIF	Factor loading	Cronbach's alpha	CR	AVE
ENE	ENE1	1.14	0.905	0.837	0.867	0.886
	ENE2	1.25	0.823			
MEC	MEC1	2.13	0.824	0.843	0.860	0.842
	MEC2	1.73	0.806			
POP	POP1	1.68	0.783	0.876	0.874	0.883
	POP2	1.91	0.852			
CDA	CDA1	1.52	0.825	0.844	0.842	0.790
	CDA2	1.53	0.814			
STE	STE1	1.60	0.830	0.802	0.806	0.833
	STE2	1.41	0.775			
TEA	TEA1	1.23	0.833	0.784	0.798	0.785
	TEA2	1.42	0.755			
DOI	DOI1	1.21	0.772	0.764	0.784	0.782
	DOI2	1.24	0.847			
CLA	CLA1	2.27	0.902	0.902	0.903	0.884
	CLA2	1.85	0.848			

Source: Field Data (2025)

**Table 2** Cross loading

	ENE	MEC	POP	CDA	STE	TEA	DOI	CLA
ENE1	<b>0.804</b>	0.636	0.546	0.662	0.564	0.539	0.724	0.583
ENE2	<b>0.903</b>	0.701	0.602	0.508	0.552	0.488	0.652	0.651
MEC1	0.654	<b>0.832</b>	0.585	0.446	0.487	0.509	0.582	0.703
MEC2	0.457	<b>0.785</b>	0.660	0.663	0.650	0.632	0.675	0.623
POP1	0.734	0.453	<b>0.794</b>	0.638	0.704	0.447	0.654	0.503
POP2	0.642	0.564	<b>0.841</b>	0.585	0.673	0.672	0.572	0.645
CDA1	0.476	0.685	0.547	<b>0.779</b>	0.558	0.498	0.564	0.712
CDA2	0.558	0.704	0.658	<b>0.843</b>	0.447	0.535	0.606	0.536
STE1	0.743	0.34	0.661	0.549	<b>0.808</b>	0.607	0.623	0.487
STE2	0.458	0.653	0.559	0.608	<b>0.906</b>	0.655	0.607	0.561
TEA1	0.490	0.551	0.487	0.701	0.488	<b>0.785</b>	0.498	0.476
TEA2	0.664	0.645	0.543	0.563	0.496	<b>0.832</b>	0.571	0.664
DOI1	0.598	0.677	0.658	0.648	0.562	0.476	<b>0.903</b>	0.653
DOI2	0.587	0.583	0.509	0.543	0.694	0.654	<b>0.865</b>	0.456
CLA1	0.634	0.498	0.636	0.584	0.573	0.487	0.745	<b>0.822</b>
CLA2	0.546	0.652	0.641	0.603	0.476	0.563	0.456	<b>0.746</b>

Source: Field Data (2025)

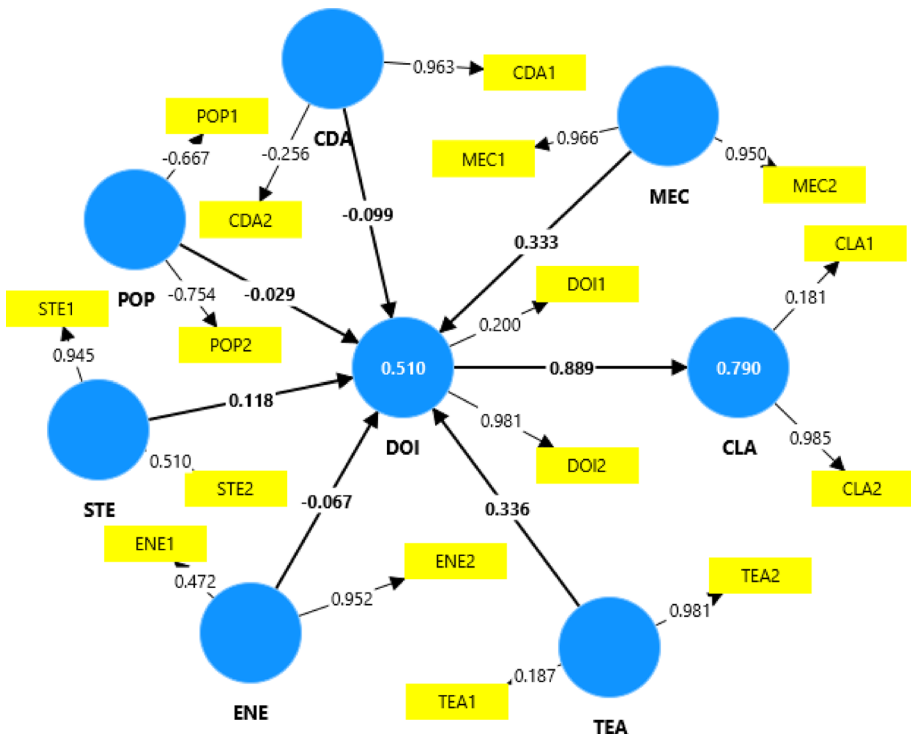
variables had values in the range 0.484 and 0.763, suggesting that the discriminant validity was met. Moreover, the study employed cross-loading criteria. Table 2 gives cross-loading results for discriminant validity, and the results satisfy the criterion.

**Table 3** Heterotrait-monotrait ratio (HTMT)

Constructs	ENE	MEC	POP	CDA	STE	TEA	DOI	CLA
ENE								
MEC	0.624							
POP	0.707	0.612						
CDA	0.538	0.621	0.631					
STE	0.701	0.714	0.664	0.631				
TEA	0.596	0.633	0.613	0.645	0.484			
DOI	0.635	0.660	0.721	0.642	0.640	0.609		
CLA	0.583	0.763	0.630	0.572	0.664	0.673	0.598	

Key: Environmental Education (ENE), Media Coverage (MEC), Perception of Public (POP), Climate data accessibility (CDA), Stakeholder Engagement (STE), Technological Advancements (TEA), Dissemination of information (DOI), Climate Awareness and education (CLA)

Source: Authors' conception (2025)



**Fig. 4** The path analysis.  
Source: Field Data (2025)

### 4.3 Structural model assessment

Model hypotheses were tested through SmartPLS v.4.1.0.9 to examine whether they were supported. Figure 4 shows the path analysis, where the bold lines show relationships. To evaluate the significance of the results, various indices such as confidence intervals, t-values,

beta and p-values were used. The study showed a significant new approach to understanding the complex factors that influence climate education and awareness. From the findings displayed in Table 4, many paths had significant relationships, and environmental education specifically had a positive relationship with the dissemination of information ( $H1: \beta=0.011, p<0.01, t=2.695$ ) and media coverage ( $H2: \beta=0.239, p<0.01, t=3.204$ ) with the dissemination of information. The positive association of media coverage with the dissemination of information could increase climate literacy and, most importantly, encourage governments and NGOs to work together with media houses. Moreover, climate data accessibility and technological advancement had a positive association with the dissemination of information ( $H4: \beta=0.291, p<0.01, t=4.230$ ;  $H6: \beta=0.140, p<0.01, t=2.716$ ), respectively. Furthermore, stakeholder engagement and dissemination of information showed a strong positive correlation with the dissemination of information and climate awareness and education ( $H5: \beta=0.333, p<0.01, t=6.14$  and  $H7: \beta=0.717, p<0.01, t=7.63$ ), respectively. The positive link between stakeholder engagement and the dissemination of information suggests that the active participation of society leaders and government entities is essential for effective promotion of climate education. Despite the strong correlation for many constructs, only the perception of the public exhibits a negative correlation ( $H3: \beta=-0.039, p<0.01, t=0.645$ ), introducing a new dimension, because poor public perception may weaken the dissemination of climate information. Even with good educational systems and strong media, public support remains vital in fostering awareness. The results indicated were also consistent with the confidence interval displayed.

**Table 4** Hypothesis testing of the research model

Hyp	Relationship	$\beta$	t-values	P-value	95% CI LL	95% CI UL	Comment
Direct effects							
H1	ENE → DOI	0.011	2.695**	0.007	0.004	0.102	Supported
H2	MEC → DOI	0.239	3.204**	0.000	0.098	0.374	Supported
H3	POP → DOI	-0.037	0.645	0.053	-0.015	-0.146	Unsupported
H4	CDA → DOI	0.291	4.230**	0.000	0.213	0.370	Supported
H5	STE → DOI	0.333	6.14**	0.000	0.162	0.408	Supported
H6	TEA → DOI	0.140	2.716**	0.004	0.076	0.209	Supported
H7	DOI → CLA	0.717	7.63**	0.000	0.308	0.804	Supported
Indirect effects							
H8	ENE → DOI → CLA	0.009	2.984**	0.008	0.002	0.118	Supported
H9	MEC → DOI → CLA	0.207	4.152**	0.000	0.122	0.372	Supported
H10	POP → DOI → CLA	-0.078	0.763**	0.087	-0.102	0.107	Unsupported
H11	CDA → DOI → CLA	0.274	4.743**	0.000	0.127	0.348	Supported
H12	STE → DOI → CLA	0.312	5.471**	0.000	0.254	0.509	Supported
H12	TEA → DOI → CLA	0.125	3.846**	0.005	0.103	0.326	Supported

Key: Environmental Education (ENE), Media Coverage (MEC), Perception of Public (POP), Climate data accessibility (CDA), Stakeholder Engagement (STE), Technological Advancements (TEA), Dissemination of information (DOI), Climate Awareness and education (CLA)

Source: Field Data (2025)

\*\* $p<0.01$ , \* $p<0.05$

#### 4.4 Mediation analysis

Mediation analysis enables the latent variables to link with the endogenous variables, thereby influencing the relationship. The present study proposed direct and indirect relationships according to Hair et al. (2019). The study employed information dissemination as the mediator variable. The mediation results are shown in Table 4, where the dissemination of information fully mediated environmental education, media coverage, perception of the public, climate data accessibility, stakeholder engagement and technological advancements. All the relationships were significant, except the perception of the public, as it is in a direct relationship. As to the weight of relationships, there were slight changes in terms of the significance of variables. The confidence interval confirms the results. The significance of variables excludes zero between the confidence lower limit (CILL) and confidence upper limit (CIUL) (Hayes and Rockwood 2020).

#### 4.5 Structural model assessment

After the model is developed, an assessment of the structure of the model is important to determine its dependability and usability. The study employed the coefficient of determination ( $R^2$ ), effect size ( $f^2$ ) and predictive relevance ( $Q^2$ ). The  $R^2$  entails the amount of variation explained by the exogenous variables in the endogenous variable and is therefore a good measure of how other factors excluded in the model also contribute. According to Hair et al (2011), the coefficients of determination ( $R^2$ ) of 0.75, 0.5 and 0.25 are categorised as strong, moderate and weak, in that order. The results shown in Table 5 show an  $R^2$  for climate awareness and education, which depicts a strong outcome. Moreover, dissemination of information had an  $R^2$  value of 0.510, contributed by the exogenous variables, and is classified as moderate. In conclusion, the contribution of the variable is generally classified as moderate to strong. On the other hand, predictive relevance ( $Q^2$ ) was also utilised to examine the structural relationship (Sharma et al. 2019).  $Q^2$  is classified as small (0.02), medium (0.15) and large (0.35) according to Fauzi et al. (2022). The results displayed in Table 5 show  $Q^2$  values of 0.373 and 0.381, which could be classified as medium to large, and the predictive relevance was sufficient for this model. Furthermore, the effect size was employed to assess the effect size in building the model. The effect size was classified as

**Table 5** Coefficient of determination ( $R^2$ ), predictive sample reuse technique ( $Q^2$ ) and effect size ( $f^2$ )

Endogenous Construct	$R^2$ (%)	$Q^2$	Relationship	$f^2$	Decision
DOI	51	0.373	ENE → DOI	0.301	Moderate
			MEC → DOI	0.318	Moderate
			POP → DOI	0.201	Weak
			CDA → DOI	0.414	Moderate
			STE → DOI	0.513	Strong
			TEA → DOI	0.309	Moderate
CLA	79	0.381	DOI → CLA	0.520	Strong

Key: Environmental Education (ENE), Media Coverage (MEC), Perception of Public (POP), Climate data accessibility (CDA), Stakeholder Engagement (STE), Technological Advancements (TEA), Dissemination of information (DOI), Climate Awareness and education (CLA)

Source: Field Data (2025)

$f^2 \leq 0.30$  (weak),  $0.3 < f^2 \leq 0.50$  (moderate) and  $f^2 > 0.50$  (strong effect) according to Ben-Shachar et al. (2024). As seen in Table 5 below, the effect size ranges from 0.201 to 0.520 and is therefore classified as moderate to strong.

#### 4.6 XGBoost results

The XGBoost model was constructed using training (70%) and testing (30%) using the selected hyperparameters. Using appropriate hyperparameters improves the accuracy of the model. To avoid overfitting, hyperparameter tuning was used and the tuning includes the model complexity, learning process, and regularization. Table 6 shows the hyperparameters and evaluation metrics results. The grid search method was employed with tenfold cross-validation. In this research, the model used a learning rate of 0.1, optimizing the equilibrium between convergence velocity and accuracy. Before selecting the final learning rate, values of 0.01, 0.05 and 0.1 were tested to ensure that the model learns well and produces good results. The model also employed a maximum depth of 6, maintaining equilibrium between model complexity and overfitting. A depth between 3 and 6 reduces the risks of overfitting, especially when using medium-sized datasets. To guarantee stable convergence and optimal efficacy, the model utilizes 100 boosting rounds. To improve generalization and randomness, the model uses a colsample and subsample of 0.8. Values of 1, 0.8 and 0.6 were tested before selecting 0.8 as the final. The selected hyperparameters ensure that the model performs well, which will provide insights into climate awareness and education. The selection of these hyperparameters will ensure a low RMSE value and maximize the  $R^2$  value. The built model managed to produce an  $R^2$  of 85%, indicating that it elucidates a considerable fraction of the variation in the data. The other evaluation metrics include the mean absolute error (MAE) of 0.172 and mean square error (MSE) of 0.173, showing a comparatively low overall prediction error. Moreover, the model employed the root mean square error (RMSE) and normalized RMSE and produced values of 0.416 and 0.19, respectively, which further confirms the model's accuracy and dependability. The use of evaluation metrics enables the assessment of the model's performance.

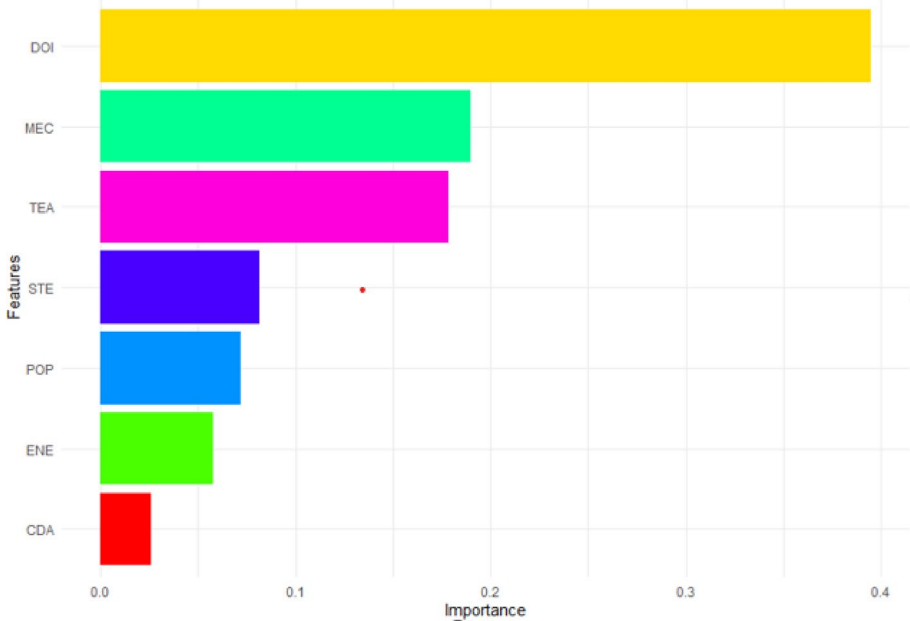
#### 4.7 Variable importance

The variable importance results from Fig. 5 showed the factors that impede climate awareness and education. Dissemination of information was ranked as the best variable that impedes climate awareness and education, while media coverage was ranked second. More-

**Table 6** XGBoost model results

Metrics	Value
MSE	0.173
MAE	0.172
RMSE	0.416
R2	0.85
Normalised RMSE	
Hyperparameters	
Learning rate	0.1
Maximum depth	6
Nrounds	100
Colsample and subsample	0.8

Source: Field Data (2025)



**Fig. 5** Variable importance.  
Source: Field Data (2025)

over, technological advancements and stakeholder engagement followed third and fourth, respectively. Environmental education was ranked fifth, whilst climate data accessibility had the least impact on barriers to climate awareness and education.

#### 4.8 Discussion

The study results were aimed at solving the complex relationship that impedes climate awareness and education in developing countries such as Zimbabwe. Despite climate awareness and education as the main variables of the study, dissemination of information acted as the mediator variable. The findings of the study are in congruence with Abubakar (2024), who found that the dissemination of information facilitates climate action and public involvement. To further boost the structural equation results, the XGBoost ranked dissemination of information as the most influential factor that impedes climate awareness and education.

Moreover, environmental education had a positive beta value with climate awareness and education, which further highlights the role of education in fostering understanding of climate awareness and education. The results showed that the accessibility of quality information can improve climate education. Related to the above, climate data accessibility had a strong association with climate awareness and education, which aligns with Knight's (2016) study. In addition, stakeholder engagement revealed the strongest effect sizes, necessitating the importance of interactive and communicative approaches in climate change initiatives aimed at improving the problem at hand. The SEM findings were reinforced by the XGBoost model results, by having high predictive accuracy and hence verified the impact of the variables on climate awareness. These observations do not verify the hypothesized

variables related to climate information but also reveal the complex interplay of complex roles of the public perception as a barrier that must be taken seriously in future campaigns. The ability of the XGBoost model to produce an  $R^2$  of 85% indicates the ability of the model to adapt to complex data sets and offers advancements in machine learning applications for environmental research.

The positive influence of environmental education and media coverage aligns with previous studies. The study by Abubakar (2024), argued that education encourages critical thinking and change of behaviour and consequently, this observation aligns well with the notion that climate change initiatives positively influence the dissemination of information. In another effort, Shetty et al. (2025), noted that mass media are crucial in enhancing public awareness and threats to the environment. These findings revealed that the driver of public engagement is via formal and informal communication on climate-related issues. Notwithstanding the similarities of these studies, there is one study that diverges from these observations. Many researchers observed public perception as a driver of climate change; the present study shows the opposite. The difference might be attributed to factors like distrust and misinformation, which may generate resistance.

In addition, a positive link between technological advancements and climate awareness was obtained, which further underscores the need for infrastructure that enhances cooperative initiatives (Balogun et al. 2020; Maziriri et al. 2024). Notwithstanding the strong positive associations between variables, public perception had a negative beta value with climate awareness and education, highlighting that misinformation may impede climate education initiatives. The negative relationship between public perception and the dissemination of climate information suggests that distrust and misinformation may impede the accurate flow of climate-related information. A positive link between public perception and dissemination of information usually exists in environments where the public perceives climate-related issues seriously and people have the appetite to have more knowledge and solutions. Taking, for example in countries like Germany and Sweden, where there is strong engagement with the campaign on climate change and policy programs (Ylä-Anttila et al. 2018). In the context where there is distrust and misinformation, as observed in Australia and the United States, a greater awareness of climate change may not necessarily result in constructive engagement. Thus, the negative link in the model could therefore show a situation where skepticism affects perception, hence weakening the connection to effective information dissemination. In developing countries like Zimbabwe, climate change may be considered less important, with minimal connection to the available realities. Poor understanding of the effects and causes of climate change can sometimes reduce the motivation to venture into scientific information related to climate change education. Moreover, distrust in institutions, especially in environments with weak governments, may be the cause for an inverse relationship between public perception and the dissemination of information. In addition, the existence of a negative link does not mean that public perception is not important, but rather, differing perceptions may be inappropriate with climate realities. The results indicate a shift that supports interventions aimed at treating public perception as an important factor in climate communication. The study results offer valuable insights to policymakers and stakeholders in enhancing climate awareness and education.

Upon comparing the present study with previous research, the study by Khatibi et al. (2021), demonstrated the importance of the dissemination of information to promote public engagement and sustainable practices. Similarly, studies by Meng et al. (2023) showed a

positive link between environmental education and media coverage with the dissemination of information, emphasizing the role of planned education and media in promoting climate education. In the study by Monroe et al. (2019), media access and education programs have been discussed as factors that can enhance public understanding of climate change. Moreover, the study presented by Hussain et al. (2024), showed the positive association of technological advancement and stakeholder engagement on climate awareness and education, indicating that digital tools and collaborative initiatives can markedly enhance climate-related communication. Despite the similarities with previous studies, the perception of studies showed a positive link with climate education in a survey by Boca and Saraçlı (2019), which contradicts the present study. A possible reason for this outcome could be attributed to a lack of trust in scientific data and climate skepticism, especially in areas where climate education is inadequate. In addition, previous studies have explored media and education as key factors of climate awareness. The current study identified technological advancements and stakeholders as important drivers, highlighting a change toward collaborative work and digitally oriented methods of climate communication. These changes highlight significant strategies that can improve climate change globally, given the different natures of the environment.

The study has significant practical and policy implications in improving climate awareness and education across various regions. Given the outstanding performance of variables like media coverage, dissemination of information, and technological advancements that emerged as key factors, policymakers and stakeholders must dwell on improving strategies in communication to improve climate data accessibility and engagement. Climate education can be introduced into school curricula as a mechanism to strengthen media coverage and engage the community, which will consequently encourage participation from many people. Partnerships between policymakers and governments must be prioritized to improve climate education and awareness. Moreover, public education should be done in the local language via channels such as radio and mobile platforms so that both the rural and urban communities are aware of climate change issues. Furthermore, the negative link between public perception and dissemination of information underscores a critical gap that needs to be addressed, taking into consideration climate skepticism and distrust in institutions. Theoretically, the integration of the SEM and XGBoost algorithm improves the predictive strength of variables that affect climate education and awareness. Consequently, considering all these factors that affect climate education and awareness using various techniques will result in a resilient framework leading to climate-informed decisions in Zimbabwe.

There were some similarities and differences between the results from structural equation modeling and XGBoost. Both methods demonstrated the importance of the dissemination of information as the best factor in climate awareness and education. Media coverage and stakeholder engagement were ranked second and fourth under the XGBoost algorithm, while the structural equation modeling showed strong positive beta values. The results showed the importance of these two factors in climate awareness and education. Environmental education and the perception of the public had almost the same magnitude in terms of strength for both methods. Notable minor differences were in climate data accessibility and public perception. Climate data accessibility had the least significance under the XGBoost algorithm, whilst on SEM, it shows some positive strength. The results might be attributed to the difference in the two methods when processing data. XGBoost can deal with complex and non-linear interactions.

## 5 Implications of the study

The following sections account for the academic, social, policy and practical implications of the findings of the current study.

### 5.1 Academic implications

The current study's findings advance knowledge on recognised behavioural and educational theories, especially the Theory of Planned Behaviour (TPB) and Diffusion of Innovations (DOI), to elucidate the adoption of climate change awareness and education in Zimbabwe. TPB holds that people are more likely to engage in pro-environmental behaviour when they think it is of importance, socially supported and within their control. The negative correlations between public perception and dissemination of information imply that poor attitudes and misinformation may impede climate education efforts, highlighting the need to address attitudes and normative beliefs. Likewise, DOI explicates the role of new ideas, such as climate education, disseminated within a population, as well as factors like media coverage, technological advancements, and stakeholder engagement, which are strongly related to innovation diffusion channels. The results emphasise the importance of a theoretical framework in understanding the gradual adoption of climate education in developing contexts, pinpointing certain variables that either promote or hinder this diffusion process. Moreover, the amalgamation of Structural Equation Modelling and XGBoost makes a novel theoretical contribution to environmental education by connecting causal explanation and predictive accuracy. While SEM examines the hypothesis in the model, XGBoost offers an advanced approach by ranking variables in terms of their predictive importance. This dual technique shows that some factors, such as the dissemination of information, albeit inadequately explored or underexplored in conventional theories, may play a central role in real implementation.

### 5.2 Social implications

In Zimbabwe, particularly in rural areas, people with a low level of climate change education are vulnerable, and this restricts the ability of both individuals and communities to adapt to environmental changes. Little knowledge on climate risks results in poor decision-making in agriculture, health practice and water use, which are already under strain because of poverty and a lack of infrastructure. Communities are more vulnerable to the effects of droughts, floods, and severe weather for lack of information about the climate, which exacerbates the situation. Empowerment of such communities could be achieved by improving awareness, especially through education and dissemination, encouraging people to adopt sustainable practices, push for legislative change, and strengthening local adaptation efforts. As a result, climate education plays a significant role in minimising exposure, enhancing preparedness, and building resilience, especially in groups already at risk. Social groups such as community leaders, peer groups, families and local institutions play an important role in either facilitating or obstructing climate education. Addressing these social differences is vital in promoting inclusive education on climate-related information across different societies.

### 5.3 Policy implications

The results from the SEM-XGBoost model revealed critical policy gaps in Zimbabwe as seen in the current climate education system, characterised by poor coordination in the sharing of information, limited access to climate data, and poor stakeholder engagement measures. Despite ongoing efforts by the stakeholders, climate change education remains inconsistent, poorly funded, or poorly integrated into formal and informal learning environments. The findings of this study could be utilised by the Ministry of Education, Environment and Information to improve the dissemination of information, which was found to be the greatest barrier to climate education, and this could be done through community outreach and accessible media. Moreover, climate change education could be included in the national curriculum, starting at lower levels, thereby ensuring early awareness and promoting enduring behavioural change. Targeted training could be done to ensure that climate content is accurate, age-appropriate and culturally relevant. The findings highlight the need for cross-sectoral collaboration, which involves government, NGOs and international partners to address knowledge and resource deficiencies. Policy tools such as information subsidies, school-based environmental programmes, and statewide campaigns could greatly improve climate change awareness if they are based on real-world data such as that obtained in this study. Consequently, the results of this study provide a data-driven map for making inclusive, equitable and resilient climate education policies specifically suited for Zimbabwe's socio-economic conditions.

### 5.4 Practical implications

The findings of this study have some practical implications. By way of example, to address the identified barriers, such as limited resources and misconceptions, educators and NGOs must tailor and simplify climate education materials to align with community realities. Utilising culturally suitable examples, indigenous knowledge systems and storytelling methods helps to close cognitive gaps and cultivate trust. Through the XGBoost algorithm, it was found that dissemination of information was the most influential factor in climate education, highlighting the need for more initiatives through radio programmes, mobile learning platforms, and workshops. In areas where resources are scarce, community radio and solar-powered devices could be used, since they are affordable. The training of educators should be tailored to include climate science content, interactive pedagogy, and problem-solving for social and environmental issues, enabling them to present accurate and engaging material effectively. This study directly supports United Nation's (UN) Sustainable Development Goal (SDG) 4 (Quality Education), especially Target 4.7, by showing how climate literacy could be better incorporated into both formal education systems (by developing curricula and training teachers) and informal channels (such as community outreach, media, and NGO programmes). Furthermore, the study findings also support SDG 13 (Climate Action) and SDG 10 (Reduced Inequalities), emphasising educating people on climate change and thereby enhancing community resilience.

## 6 Conclusion

This paper proposes the critical research problem of assessing the barriers to climate awareness and education using structural equation modelling (SEM) and XGBoost machine learning algorithms. The primary objective was to highlight the interrelationships of the variables that affect climate education and create a prediction model that guides governments and policymakers to take corrective actions and rank the factors that affect climate education. The findings of the study revealed that technological advancement, stakeholder engagement, access to climate data and media coverage had positive links with the dissemination of information and education. Despite the positive relationships of factors with information, public perception exhibits a negative link, underscoring the need for robust strategies aiming for engagement. Key findings indicate that dissemination of information emerged as the main variable that contributes more to barriers to climate awareness and education, while media coverage and technological advancements followed closely. It is noted that environmental education and climate data accessibility had the least contribution. The use of SEM enabled the researcher to understand the interaction of factors that impede climate awareness and education, while the XGBoost machine learning model aids the full understanding of the analysis by coming up with features that contribute more to awareness and education in order of importance. The high  $R^2$  value and predictive relevance from the XGBoost method show that the model has a strong predictive power, offering a good foundation for understanding the complex interaction of factors that affect climate education and awareness. The results showed important insights that will assist policymakers and stakeholders in improving climate change, especially in developing regions where resources are scarce.

## 7 Limitations

Although the present study offers some insights into climate awareness and education, it has some limitations. Overreliance on survey data may lead to self-reporting bias, as respondents may offer socially desirable responses instead of their true views. The use of SEM and XGBoost provided great insights, but the models produced might differ in terms of how they respond to sample size and data quality and consequently affect the dependability of results. The use of qualitative data might be incorporated in the future so as to capture hidden insights that would improve the results of the models.

## 8 Future studies

Future studies could deploy a more analytical approach to climate education, especially given how the dissemination of information impacts climate awareness and education in various regions. Further research could also examine the role of emerging technologies in climate education, since technological advancements played a crucial role in this study. Moreover, the detailed information required on the perception of the public on climate awareness and education could be obtained by carrying out various studies in different areas, since the study results depicted a negative correlation with climate education. Furthermore, future studies could examine the effect of climate data accessibility on climate awareness

and education, since this variable had the least effect on variable importance under the XGBoost model and allowing for more insights into ways of improving climate education.

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## Declarations

**Conflict of interest** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

**Ethical approval** The research received Ethical Approval from Ethics Committee of the Marondera University of Agricultural Sciences & Technology (MUASt), Zimbabwe, Research Board with Approval number MUASt 03/25.

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