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Climate Change Risks and Climate Adaptation in Agro-Processing Enterprises

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ABSTRACT

While climate change research has focused mainly on primary agriculture, evidence shows that Agro-processing enterprises also face climate risks affecting resource availability and use. Using Partial Least Squares-Structural Equation Modelling (PLS-SEM), this study analysed how socio-demographic factors (sex, age, marital status, education, and training) influence participation in agro-enterprises and climate adaptation strategies among 113 agro-processing enterprises in Gauteng, South Africa. Results show that direct participation in Agro-processing does not significantly predict adaptation ($\beta = 0.025$), indicating profit-driven rather than resilience-oriented engagement. Education significantly enhances participation in Agro-processing ($\beta = 0.325$, 95% CI = [0.196, 0.457]) and adaptation ($\beta = 0.325$, 95% CI = [0.168, 0.477]), with a positive indirect effect ($\beta = 0.106$, 95% CI = [0.049, 0.173]). Sex negatively predicts participation ($\beta = -0.181$), showing higher female involvement, while other variables were insignificant. Policy interventions should integrate climate education, targeted training, and capacity-building initiatives to strengthen resilience among Agro-processing enterprises.

1 | Introduction

Climate change presents significant challenges to global agricultural systems, including agro-processing enterprises, which play a crucial role in ensuring food security and economic sustainability (Tchonkouang et al. 2024). Agro-processing transforms raw agricultural products into consumable food, beverages, or industrial goods (Mthombeni et al. 2022). It adds value to farm produce, enhances food security, reduces post-harvest losses, and creates employment opportunities (Naicker et al. 2025).

Agro-processing plays a vital role in climate change adaptation by reducing post-harvest losses, diversifying agricultural production, and supporting livelihoods (Mohammed et al. 2023; Urugo et al. 2024). Processing perishable goods extends shelf life and ensures food security in climate-vulnerable regions (Michel et al. 2024). Additionally, agro-processing promotes economic stability and reduces reliance on climate-sensitive crops (Benitez-Alfonso et al. 2023; Godde et al. 2021). The integration of agro-processing and climate-smart agriculture provides a pathway to resilience by strengthening food systems, promoting resource efficiency, and enabling farmers and enterprises to adapt more effectively to climate shocks (Bhatnagar et al. 2024; Kurgat et al. 2020). Therefore, sustainable agro-processing is essential for building adaptive and resilient food systems in a changing climate.

Literature on global climate change adaptation highlights significant shortcomings, despite the growing policy and scholarly attention devoted to the topic. Although adaptation actions are being catalogued, much work still focuses on planning rather than implementation or measurable outcomes, especially in low-income, highly exposed regions, revealing an equity and justice gap (Sietsma et al. 2024; Abbass et al. 2022). Adaptation pathways offer promise as dynamic frameworks to manage deep uncertainty, yet their real-world implementation is hindered by limited legitimacy, coordination, and long-term monitoring (Haasnoot et al. 2024; Muccione et al. 2024). Coastal systems, notably in the Global South, including Africa, South America, and the Polar Regions, receive disproportionately little empirical research, despite acute vulnerability (Cabana et al. 2023).

Consequently, Institutional and capacity constraints at the local government level impede effective adaptation governance and adaptive capacity evaluation (Gadu et al. 2025; Malik and Ford 2024). Against these systemic constraints, household demographics and socio-economic endowments shape who enters agro-enterprises and the kinds of adaptation strategies they can sustain. (Zhou et al. 2025). Sex and marital status influence access to assets and networks; age correlates with risk preferences and planning horizons (Moore and Niles 2024). Education and training enhance the capacity to adopt new practices and technologies, while participation in agro-enterprises, especially those involved in climate-smart processing, storage, and value addition, reduces liquidity and information constraints that limit adaptation (Tilahun et al. 2025).

Literature on climate change adaptation in South Africa has mainly focused on primary agriculture, more consistently examining how farmers adapt to climate variability through strategies like crop diversification, agroforestry, conservation agriculture, and soil and water management (Kori et al. 2025; Zenda 2024; Zenda and Rudolph 2024). Moreover, smallholders and commercial farmers have responded to climate change risks by adopting drought-resistant crops, irrigation systems, and soil conservation techniques (Ogundeji 2022; Wilk et al. 2013).

Few studies have examined the adaptation strategies of agro-processing enterprises and how policies need to be adjusted to strengthen their coping mechanisms (Ahmed and Givens 2025; Grigorieva et al. 2023; Naicker et al. 2025). Given its far-reaching implications for resource use and environmental sustainability, understanding how agro-processing enterprises respond to climate change is essential for identifying strategies to reduce vulnerabilities in food supply chains, particularly for smallholder farmers.

The Sustainable livelihoods framework (SLF) provides a structured way to analyse how demographic and socio-economic characteristics (e.g., sex, age, marital status, education, training) shape households' access to and utilisation of livelihood assets (human capital, social capital, financial capital, physical capital, and natural capital) (Lund-Schlamovitz and Becker 2021). Agro-enterprise participation can be understood as a livelihood strategy undertaken to enhance income, resilience, and adaptive capacity. Climate change adaptation strategies then emerge as outcomes of how households combine and leverage these assets under conditions of climatic stress and institutional context (Urugo et al. 2024).

The paper utilised the Partial Least Squares-Structural Equation Modelling (PLS-SEM) to examine how demographic and socio-economic characteristics, namely, sex, age, marital status, education, and training, influence participation in agro-enterprises, and how these factors, together with agro-enterprise engagement, shape households' climate change adaptation strategies of 113 agro-enterprises practising Agro-processing in Gauteng, South Africa.

The findings aim to inform policies, enhance economic resilience, promote sustainability, and address inequalities, thereby ensuring that agro-processors can effectively adapt to the challenges posed by climate change.

2 | Materials and Methods

2.1 | Study Area

The study was conducted in Gauteng Province, South Africa's economic hub, covering an area of 18,178 km^2 with a population of approximately 15.1 million, representing 24% of the national total (Statistics South Africa 2021; Tshabalala and Rispel 2023). Gauteng contributes R2.2 trillion (33.1%) to South Africa's GDP, with major outputs in manufacturing and agriculture (Statistics South Africa 2023). The study map in Figure 1 shows the sampled Agro-processing enterprises in Gauteng municipalities.

Gauteng Province is centred around Johannesburg, Pretoria, Ekurhuleni, West Rand, and Sedibeng (Ebrahim and Everatt 2023). The agro-processing sector plays a key role by linking agricultural production with industrial manufacturing, transforming raw produce into value-added goods that strengthen the South African economy (Cele 2025).

2.2 | Data and Sample Description

The sample size was determined using the list of stakeholders provided by the Gauteng Department of Agriculture and Rural Development (GDARD) database. The systematic application of the Yamane formula has been validated across various studies in similar contexts, affirming its utility in research (Christianah and Adeniyi 2024; Ndateba et al. 2021). The systematic use of the formula was shown to yield adequate sample sizes while reducing potential sampling biases (Njeru et al. 2022). A sample of 113 agro-processing farmers was randomly selected from a population of 319, utilising Yamane's sampling formula.

Assuming a 95% confidence interval with a margin of error of ±5%, the calculated sample size was 113 Agro-processing enterprises.

Table 1 presents the sample distribution of agro-enterprises by district and the sex of the owners. The study covered five districts within the Gauteng Province, with a total of 113 agro-enterprises included in the sample.

Among the respondents, 56 were male and 57 were female, indicating an almost equal representation of both sexes. West Rand had the largest number of enterprises (51), reflecting a

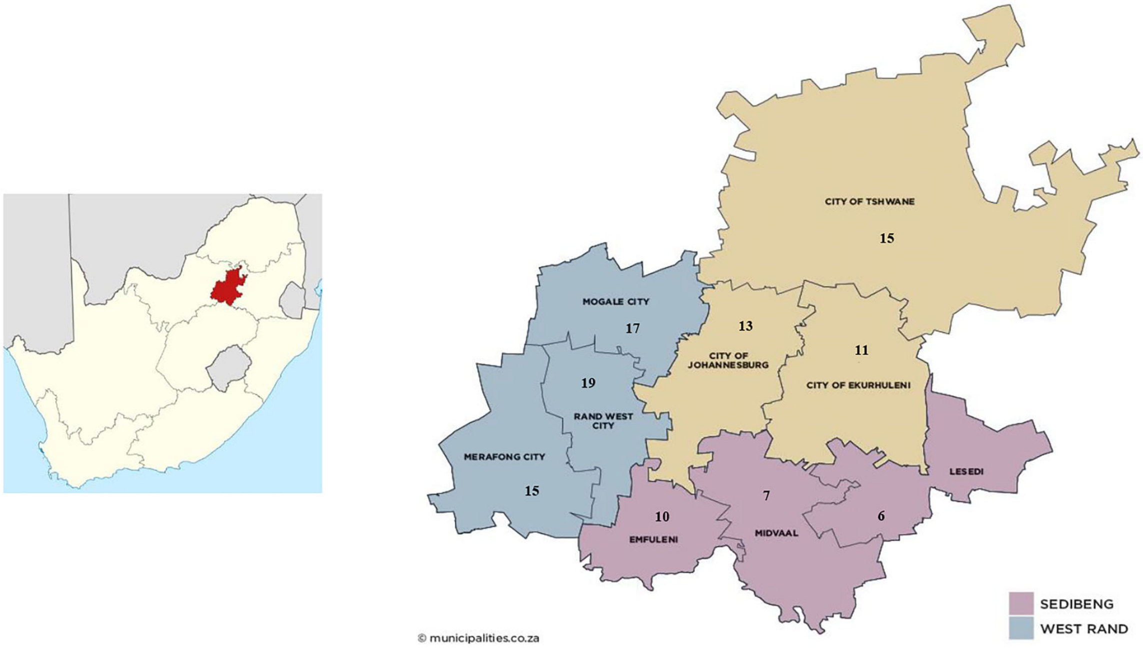

FIGURE 1 | Gauteng province map. *Source:* Municipalities of South Africa (2024).

TABLE 1 | Sample distribution.

District	Males	Females	Total
Tshwane	8	7	15
Johannesburg	7	6	13
Ekurhuleni	8	3	11
West Rand	23	28	51
Sedibeng	10	13	23
Total	56	57	113

Source: Authors.

relatively higher concentration of agro-enterprises in this district, while Ekurhuleni had the smallest sample (11), suggesting a lower enterprise density or participation in the study. Tshwane and Johannesburg contributed 15 and 13 enterprises, respectively, and Sedibeng accounted for 23 enterprises. This distribution provides insight into both the gender composition of agro-enterprise owners and the spatial spread of the enterprises across the study area, which is important for understanding local engagement in agro-processing activities.

Data for the study was collected using a structured questionnaire focused on quantitative information regarding agro-processing participation, climate change adaptation practices, and related training among respondents. This approach enabled systematic measurement and comparison across all surveyed Agro-processing-enterprises.

2.3 | Model Variable Classification

The study employed several variables to examine the relationships between Agro-processing enterprise engagement, training, and household adaptation strategies within the PLS-SEM framework. Table 2 shows the variables used in the PLS-SEM model.

The independent variable, Agroenterprise, is a single binary indicator representing engagement in Agro-processing, specifically whether an enterprise is involved in processing, manufacturing, or value addition of agricultural products. The mediating variable, Traingrain, is also a single indicator capturing whether the enterprise received training related to grain handling.

Initially, a latent variable (Training) was included, comprising five indicators: Training, Traingrain, Trainlvstk, Traincrop, and Trainfin. The sequential removal of Trainfin, Trainlvstk, and Traincrop was driven by their negative loadings, non-significant t-statistics, and contributions to poor reliability metrics. Demographic factors, namely, sex, education, marital status, and age, were included as mediating variables. The dependent latent variable, CCADAPTATION, represents a climate change adaptation variable comprising 13 indicators. The indicators contributing to the latent variable include insurance and credit, technology and breeds, water and soil management, rainwater harvesting, crop diversification, afforestation, herd management, government compensation, extension services, early warning, cultivation timing, investment in research and development, and social safety nets.

2.4 | Partial Least Squares-Structural Equation Modelling (PLS-SEM)

The PLS-SEM technique was applied to analyse how demographic and socio-economic characteristics (sex, age, marital status, education, training) influence Agro-processing participation, and how, in turn, these factors and Agro-processing affect households' climate change adaptation strategies.

TABLE 2 | Variable description.

Category	Variable name	Description
Independent variable	Agro-enterprise	Engagement in Agro-processing (1 = involved; 0 = not involved)
Mediating variables	Train-grain	Training related specifically to grain handling
	Sex	Sex of the respondent (1 = male; 0 = female)
	Education	Level of educational attainment (≤ 5; 6–10; 11–15; 16–20)
	Marital status	Marital status of the respondent (Single = 0; Married = 1)
	Age	Age of the respondent (≤ 30; 31–40; 41–50; 51–60; 61–70; ≥71)
Dependent variable	CCADAPTATION	Climate change adaptation composite latent variable.
	Insurance credit	Access to insurance or credit
	Technology breeds	Use of improved technology or livestock breeds
	Water soil mgmt.	Water and soil management practices
	Rainwater harvesting	Practice of harvesting rainwater
	Crop diversification	Engaging in multiple crop types
	Afforestation	Tree planting and forest regeneration
	Herd management	Strategies to manage livestock effectively
	Govt compensation	Access to government relief or compensation
	Extension services	Access to agricultural extension services
	Early warning	Use of climate early warning systems
	Cultivation timing	Adjustments in planting or harvesting times
	R&D investment	Investment in research and development
	Social safety nets	Access to safety net programmes (e.g., cash transfers)

Source: Authors.

PLS-SEM effectively evaluates cause-and-effect relationships among multidimensional constructs, providing consistent parameter estimates for linear equations (Hair et al. 2021). It enables the simultaneous estimation of indirect effects and offers a comprehensive assessment of model fit, distinguishing itself from traditional regression techniques (Furlan and Mariano 2025). PLS-SEM accommodates multiple dependent variables, requires fewer distributional assumptions, and is reliable with small samples and non-normal data, making it suitable for analysing formative and higher-order constructs in exploratory research (Hair and Sarstedt 2019).

In this paper, the application of PLS-SEM is methodologically sound and aligns with established guidelines by Furlan and Mariano (2025) and Hair et al. (2021). The analytical procedure followed four key steps:

Step 1: Factor Definition and Indicator Specification

Each construct was conceptually defined, and corresponding indicators were selected to capture their theoretical meaning, in line with Fan et al. (2016). This ensured that all latent variables were grounded in prior empirical and theoretical research.

Step 2: Study Design and Data Preparation

The characteristics of the study sample were described, and data screening procedures were conducted following Hair et al. (2021). The final dataset comprised 113 agro-processing enterprises. To retain the maximum number of valid responses for each construct, the pairwise exclusion method was employed to handle missing data.

Step 3: Measurement Model Assessment

The measurement model was evaluated before testing the structural relationships. Indicator loadings and their statistical significance were examined, followed by assessments of Composite Reliability and Average Variance Extracted (AVE) to establish internal consistency and convergent validity. Discriminant validity was assessed using the Heterotrait–Monotrait ratio (HTMT), while the Variance Inflation Factor (VIF) was calculated to detect potential multicollinearity among constructs (Hair et al. 2021).

Step 4: Structural Model Evaluation

The structural model was then assessed to estimate the hypothesised relationships among the latent constructs. This phase involved evaluating the direction, strength, and significance of path coefficients, thereby allowing for the empirical testing of the proposed research hypotheses (Hair et al. 2021).

The PLS-SEM models integrated socio-demographic and engagement factors as predictors of climate adaptation and is presented as follows;

$$\begin{aligned} \text{CCADAPTATION} = \beta_1 * \text{ Agroenterprise} + \beta_2 * \text{ Train} - \text{grain} \\ + \beta_3 * \text{ Sex} + \beta_4 * \text{ Education} \\ + \beta_5 * \text{ Marital Status} + \beta_6 * \text{ Age} + \zeta, \end{aligned}$$

where β_1 to β_6 is path coefficients and ζ is structural error term.

2.4.1 | Diagnostic Tests

2.4.1.1 | Multicollinearity Test. Multicollinearity in PLS-SEM arises when two or more predictor variables are highly correlated, making it difficult to isolate their individual effects on the dependent variable (Sarstedt et al. 2020). This can inflate standard errors, distort path coefficients, and reduce model reliability. The Variance Inflation Factor (VIF) was used to assess multicollinearity; a VIF value of 1.0 indicates no correlation, while values above 5 signal potential multicollinearity issues (Hair et al. 2021).

2.4.1.2 | Reliability and Validity. The reliability of the measurement model was assessed using Cronbach's alpha, composite reliability (ρC), rhoA, and average variance extracted (AVE). Cronbach's alpha, a classical test theory metric, measures internal consistency by determining how well items correlate to reflect the same underlying construct; very high values (>0.95) may indicate redundancy among items (Guenther et al. 2023). Composite reliability (ρC), widely used in covariance-based and PLS-SEM analyses, considers item loadings and error variances. Reliability values between 0.70 and 0.90 are regarded as satisfactory, whereas values exceeding 0.95 suggest item duplication (Hair et al. 2021). AVE assesses convergent validity, indicating the extent to which a latent construct explains the variance of its items. An AVE value of $\geq$ 0.50 demonstrates adequate construct validity (Hair et al. 2021).

2.4.1.3 | Hypothesis Testing. Hypotheses were tested by examining the estimated structural path coefficients and their corresponding levels of statistical significance (Hair and Sarstedt 2019). Statistical inference was conducted via nonparametric bootstrapping using the bootstrap_model() procedure with 1000 resamples. This yielded robust standard errors, confidence intervals, and reliability diagnostics for all latent constructs. The structural equation model was estimated in R using the SEMinR package, and the bootstrapped inferential framework facilitated rigorous testing of hypothesised relationships (Ray et al. 2024;).

3 | Results

3.1 | Descriptive Exploration of Variables

This section provides a descriptive overview of the socio-economic characteristics, agro-processing participation, and climate change adaptation strategies among 113 agro-processing enterprises. Table 3 summarises the descriptive statistics across these dimensions.

Female participants had a mean age of 47.2 years (SD = 11.3), slightly lower than males at 49.8 years (SD = 10.5). Education levels were comparable, with females averaging 13.5 years (SD = 3.4) and males 12.8 years (SD = 2.7). Notably, 56% of women were engaged in value-adding activities compared to 41% of men. Only crop training and marital status showed statistically significant sex differences. Climate adaptation strategies showed limited variation, though women reported slightly higher uptake of insurance and soil management practices.

3.2 | PLS-SEM Results

The various aspects of the model were assessed to explore its suitability. Reliability metrics were assessed to check the robustness of the measurement model. For single-indicator variables such as Agroenterprise, sex, education, marital status, age, and training, the reliability metrics Cronbach's alpha, composite reliability (rhoC), average variance extracted (AVE), and rhoA all equal 1.000. These perfect scores do not necessarily reflect true internal consistency, as they are an artefact of the variables being measured by a single indicator. For CCADAPTATION, the reliability indicators are strong but more realistic: alpha = 0.913, rhoC = 0.924, and rhoA = 0.924, all exceeding the recommended threshold of 0.7. However, the AVE for CCADAPTATION was 0.484, within the acceptable minimum of 0.5.

The variance inflation factor (VIF) analysis for the antecedents of the CCADAPTATION latent variable in the structural equation model reveals minimal collinearity, with VIF values all well below the threshold of 5. The values were as follows: Agroenterprise (1.201), sex (1.082), education (1.236), marital status (1.071), age (1.113), and training (1.079).

Figure 2 illustrates the original path coefficients among variables, showing varying strengths of their relationships. Notably, Participation in Agro-processing (Agroenterprise) shows a positive relationship with Education (β = 0.325) and also with CCADAPTATION (β = 0.325). Agroenterprise also has a positive relationship with Traingrain (β = 0.225) and also a positive and very weak effect on CCADAPTATION (β = 0.025). Marital status has a positive but weak relationship with Agroenterprise (β = 0.078) and a modest effect on CCADAPTATION (β = 0.141). Sex has negative relationships with both Agroenterprise (β = –0.181) and with CCADAPTATION (β = –0.019). Age also had negative relationships with Agroenterprise (β = –0.162) and with

TABLE 3 | Descriptive statistics.

Variable category	Variable	Label	Female	Male
Socio-economic factors	Sex		48% (59)	52% (63)
	Age categories (years)	Mean (SD)	47.2 (11.3)	49.8 (10.5)
		≤ 30	7% (4)	2% (1)
		31–40	25% (15)	30% (19)
		41–50	31% (18)	27% (17)
		51–60	24% (14)	27% (17)
		61–70	8% (5)	13% (8)
		>70	5% (3)	2% (1)
	Education (years)	Mean (SD)	13.5 (3.4)	12.8 (2.7)
		≤ 5	3% (2)	2% (1)
		6–10	10% (6)	8% (5)
		11–15	66% (39)	81% (51)
		16–20	20% (12)	10% (6)
	Marital status	Single	59% (34)	40% (24)
		Married	41% (24)	60% (36)
	District	Tshwane	13% (7)	14% (8)
		Johannesburg	13% (7)	10% (6)
		Ekurhuleni	15% (8)	5% (3)
		West Rand	42% (23)	48% (28)
		Sedibeng	18% (10)	22% (13)
	Training—grain	No	85% (50)	90% (57)
		Yes	15% (9)	10% (6)
	Training—livestock	No	71% (41)	68% (41)
		Yes	29% (17)	32% (19)
	Training—crop	No	76% (44)	90% (54)
		Yes	24% (14)	10% (6)
	Training—finance	No	88% (51)	78% (47)
		Yes	12% (7)	22% (13)
Agro-processing	Agribusiness enterprise	Vegetables	34% (20)	27% (16)
		Grains	14% (8)	8% (5)
		Livestock	9% (5)	15% (9)
		Poultry	16% (9)	20% (12)
		Fruits	2% (1)	2% (1)
		Other	26% (15)	28% (17)
	Value-adding currently	No	44% (26)	59% (37)
		Yes	56% (33)	41% (26)
	Enterprise in processing	No	59% (35)	76% (48)
		Yes	41% (24)	24% (15)
Climate change adaptation	Insurance/credit	No	67% (38)	81% (46)
		Yes	33% (19)	19% (11)
	Improved tech/seed/breed	No	62% (36)	70% (40)

(Continues)

TABLE 3 | (Continued)

Variable category	Variable	Label	Female	Male
		Yes	38% (22)	30% (17)
	Water/soil management	No	48% (28)	56% (31)
		Yes	52% (30)	44% (24)
	Rainwater harvesting	No	53% (31)	51% (29)
		Yes	47% (27)	49% (28)
	Crop diversification	No	49% (28)	46% (26)
		Yes	51% (29)	54% (30)
	Afforestation	No	81% (47)	73% (41)
		Yes	19% (11)	27% (15)
	Herd management	No	71% (36)	68% (36)
		Yes	29% (15)	32% (17)
	Govt. compensation	No	71% (41)	60% (33)
		Yes	29% (17)	40% (22)
	Education & consulting	No	50% (29)	46% (26)
		Yes	50% (29)	54% (31)
	Early warning	No	71% (41)	77% (43)
		Yes	29% (17)	23% (13)
	Change cultivation timing	No	72% (36)	64% (34)
		Yes	28% (14)	36% (19)
	Investment in R&D	No	79% (45)	75% (42)
		Yes	21% (12)	25% (14)
	Social safety net	No	71% (40)	74% (39)
		Yes	29% (16)	26% (14)

Source: Authors.

CCADAPTATION (β = −0.036). The direct relationship between Agroenterprise and CCADAPTATION, though positive, was weak (β = 0.025).

Bootstrapping evaluates the reliability of the path coefficients and other parameters by repeatedly resampling the data, allowing for a robust assessment of their significance. Table 4 presents the results of the bootstrapping analysis, which complements the PLS-SEM findings by providing additional insight into the stability and significance of the model estimates. The results include confidence intervals and significance levels, providing a more comprehensive understanding of the model's validity and the robustness of the observed relationships.

In bootstrapping, a path coefficient is considered non-significant if its 95% confidence interval (CI) includes zero, indicating that the effect is not reliably different from zero. The CCADAPTATION latent variable, representing climate change adaptation, is robustly measured by thirteen indicators, with original factor loadings ranging from 0.624 to 0.806. The bootstrapping results confirm the stability and significance of these loadings. The bootstrap means are closely aligned (0.600–0.803), and the 95% confidence intervals exclude zero, reinforcing the reliability of all indicators.

The bootstrapping results reveal significant relationships between Agroenterprise and mediators, as well as CCADAPTATION. Agro-processing and Education had a significant and positive relationship (β = 0.325, 95% CI = [0.196, 0.457]). Similarly, Agroenterprise and Traingrain also had a significant and positive relationship (β = 0.225, 95% CI = [0.038, 0.407]). Agro-processing and sex had a significant and negative relationship (β = −0.181, 95% CI = [−0.363, −0.016]), with sex coded as 1 (Male) and 0 (Female). The negative path coefficient indicates that engagement in Agro-processing activities was associated with a lower likelihood of being male. In essence, farmers participating in Agro-processing activities were more likely to be female. For CCADAPTATION, Education shows a significant positive effect (β = 0.325, 95% CI = [0.168, 0.477]), highlighting its strong influence on climate change adaptation behaviours. All the other paths were non-significant, with their CIs including zero, indicating these effects are not statistically reliable.

The indirect effect through Education is significant (β = 0.106, 95% CI = [0.049, 0.173]). This indicates that Agroenterprise positively influences CCADAPTATION indirectly through educational attainment, which in turn strongly supports climate change adaptation behaviours. The indirect effects through sex (β = 0.003, 95% CI = [−0.042, 0.052]), marital status (β = 0.011, 95%

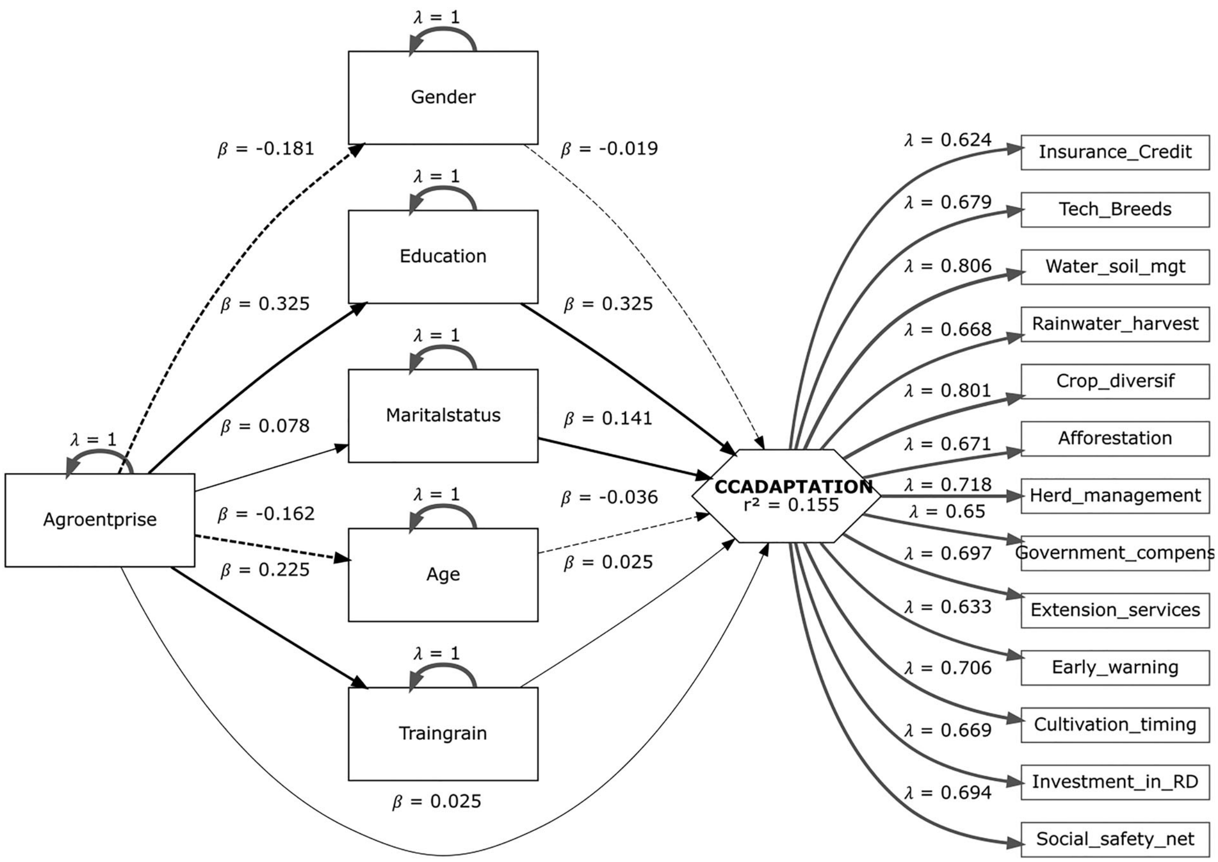

FIGURE 2 | The PLS-SEM results. *Source:* Authors.

CI = [−0.018, 0.058]), age (β = 0.006, 95% CI = [−0.026, 0.047]), and Traingrain (β = 0.006, 95% CI = [−0.039, 0.061]) are non-significant, with CIs including zero. These weak and unreliable effects suggest that sex, marital status, age, and training do not meaningfully mediate the relationship between Agroenterprise and CCADAPTATION. The significant indirect effect through Education highlights its pivotal role in mediating the influence of Agroenterprise on CCADAPTATION.

4 | Discussion

The paper utilised the PLS-SEM to examine how demographic and socio-economic characteristics, namely sex, age, marital status, education, and training, influence participation in agro-enterprises, and how these factors, together with agro-enterprise engagement, shape households' climate change adaptation strategies of 113 agro-enterprises practising Agro-processing in Gauteng, South Africa. The findings from the PLS-SEM path analysis reveal critical insights into the dynamics between agro-processing enterprise participation (Agroenterprise), demographic and socioeconomic factors, and CCADAPTATION. While direct associations between Agroenterprise and CCADAPTATION were weak and statistically insignificant, a more nuanced understanding emerges through the mediating pathways, particularly via education.

The weak direct relationship between agro-processing enterprise participation and climate change adaptation reinforces observations in the literature that engagement in agro-processing alone may not sufficiently motivate or influence climate adaptation behaviours. This is consistent with Cano and Campos (2024), who observed that adaptation is less about enterprise participation and more about exposure, income level, and social connectedness. Their study reported that older farmers, despite often having experience, were less likely to adapt due to fewer direct exposures to recent climate events. Instead, direct experience with climate disasters and peer influences within communities were more predictive of adaptive actions. Hence, merely engaging in agro-processing without concurrent exposure or support structures may not catalyse adaptation (Lund-Schlamovitz and Becker 2021). Agro-processing enterprises, if not embedded within broader systemic support mechanisms, may remain vulnerable to such external shocks.

Education was a significant positive mediator between participation in agro-processing enterprises and climate change adaptation. This highlights that while agro-processing itself does not directly encourage adaptation, it facilitates access to education, which in turn fosters adaptive behaviours. The strong direct effect between Education and climate change adaptation underscores the importance of educational attainment in building awareness, knowledge, and capacity for climate adaptation strategies (Budhathoki et al. 2025). These findings are echoed in several scholarly works. Mthombeni et al. (2022) assert that education enhances technical knowledge, critical thinking, and innovation capacity, skills necessary for agribusiness development and climate resilience. Thinda et al. (2020) similarly found

TABLE 4 | PLS-SEM bootstrapping results for direct and indirect effects.

Path/indirect effect	Original estimate	Bootstrap mean	Bootstrap SD	*T*-statistic	2.5% CI	97.5% CI
Agroenterprise → Sex	−0.181	−0.185	0.089	−2.037	−0.363	−0.016
Agroenterprise → Education	0.325	0.329	0.065	5.018	0.196	0.457
Agroenterprise → Marital status	0.078	0.077	0.093	0.838	−0.11	0.257
Agroenterprise → Age	−0.162	−0.165	0.089	−1.82	−0.336	0.006
Agroenterprise → Train grain	0.225	0.225	0.097	2.314	0.038	0.407
Agroenterprise → CCADAPTATION	0.025	0.015	0.125	0.199	−0.236	0.253
Sex → CCADAPTATION	−0.019	−0.017	0.102	−0.185	−0.218	0.18
Education → CCADAPTATION	0.325	0.33	0.079	4.117	0.168	0.477
Marital status → CCADAPTATION	0.141	0.152	0.099	1.431	−0.041	0.345
Age → CCADAPTATION	−0.036	−0.03	0.091	−0.392	−0.202	0.15
Train grain → CCADAPTATION	0.025	0.034	0.084	0.293	−0.14	0.202
Indirect effects						
Through sex	0.003	0.003	0.022	0.156	−0.042	0.052
Through education	0.106	0.108	0.032	3.308	0.049	0.173
Through marital status	0.011	0.012	0.019	0.578	−0.018	0.058
Through age	0.006	0.005	0.018	0.325	−0.026	0.047
Through g train grain	0.006	0.007	0.022	0.248	−0.039	0.061

Abbreviations: CI, confidence interval; SD, standard deviation.
Note. Bootstrapping with 5000 samples was used to assess path significance.
Source: Authors.

that higher levels of education positively influenced the intensity and quality of climate change adaptation strategies among smallholder farmers. Education equips farmers to understand climate forecasts, assess risks, adopt sustainable practices, and utilise new technologies effectively (Usman et al. 2023; Zeleke et al. 2024). Thus, in line with the National Development Plan (NDP) 2030 and the Agricultural Policy Action Plan (APAP), investment in rural education and training must be prioritised. Educational initiatives should be tailored to address both agro-processing and climate adaptation, ensuring that knowledge transfers translate into tangible resilience outcomes (Olerawaju et al. 2024).

While the relationship between Agro-processing and training in grain processing was significant, the indirect effect of Training in grain processing on climate change adaptation was weak and statistically non-significant. This mismatch suggests that while agro-processing enterprises are linked to training participation, the content or relevance of these trainings may not adequately support climate adaptation. As noted, the latent training variable included components related to grain, livestock, crops, and finance, but possibly lacked a specific focus on climate adaptation. Tchonkouang et al. (2024) argued that a lack of tailored training around climate change risks undermines adaptation, particularly in agri-food systems where knowledge gaps are critical.

Mungai (2024) further observed that while many agricultural training programs cover technical and business skills, few explicitly integrate climate change or environmental sustainability dimensions. Therefore, policy interventions must reorient training programs towards climate-smart agriculture, linking agro-processing with sustainability principles. The CSA implementation guidelines should be expanded to ensure that all agricultural training incorporates climate literacy, risk management, and adaptive capacity enhancement (Oladele and Ngidi 2025).

Embedding training within the SLF strengthens the key assets that support resilient agro-processing livelihoods (Mnukwa et al. 2025). Training enhances human capital by developing technical, managerial, and problem-solving skills and strengthens social capital by fostering networks, peer learning, and institutional connections. As participants gain the capacity to use and integrate their assets effectively, they are better equipped to sustain agro-processing activities, adapt to market and climate changes, and pursue more secure and resilient livelihood strategies (Lund-Schlamovitz and Becker 2021; Urugo et al. 2024).

The variables sex, marital status, and age did not significantly mediate the relationship between agro-processing enterprise participation and climate change adaptation, as indicated by confidence intervals that included zero. Despite this, the significant negative direct relationship between sex and agro-processing enterprise participation indicates that women are more likely than men to participate in agro-processing activities. This finding is critical, given the broader sex dynamics in agriculture. Studies like those by Godde et al. (2021) and Sahoo and Moharaj (2024) underscore that sexed inequalities often restrict women's access to adaptive resources, land, capital, and decision-making platforms. However, this study reveals a potential opportunity; women's overrepresentation in agro-processing could serve as a platform for scaling up adaptation, provided these activities are supported by tailored extension services and access to climate knowledge. According to the V&A framework, strengthening institutional and sex-sensitive support systems is necessary to buffer vulnerable groups, particularly women, from climate and market disruptions, thereby transforming vulnerability into adaptive capacity (Lund -Schlamovitz and Becker 2021).

Similarly, while age had a negative relationship with both agro-processing enterprise participation and climate change adaptation, these were not significant. Still, as Cano and Campos (2024) found, older farmers may have a lower likelihood of adaptation due to reduced exposure to recent climatic shifts or lower engagement with digital and informational channels. These insights should inform targeted policy interventions, particularly aimed at older farmers and their male counterparts who may be disengaged from adaptation processes. The V&A framework supports such targeted interventions by emphasising the differentiated vulnerabilities across population groups and advocating for tailored adaptation strategies that account for age, sex, and socio-economic disparities (Urugo et al. 2024).

5 | Limitations of the Study

The study acknowledges certain methodological boundaries that frame the interpretation of its findings. As the paper is based on cross-sectional data, the relationships identified reflect associations rather than causal directions. The sample of 113 agro-processing enterprises provides valuable insight into the Gauteng context, though results may vary in other settings with different environmental or institutional conditions. Self-reported data may also reflect respondents' perceptions at the time of the study. Furthermore, while the constructs and indicators were carefully selected, climate adaptation behaviours are multi-dimensional and may extend beyond the scope measured here. These considerations provide direction for future, broader comparative research.

6 | Conclusion

The paper provides critical insights into the relationship between agro-processing, climate adaptation, and socio-demographic factors, revealing both opportunities and limitations within existing policy and institutional frameworks. The findings showed that Agro-processing alone does not significantly enhance climate adaptation; instead, education plays a crucial mediating role, reinforcing both enterprise engagement and adaptive capacity. Female-led enterprises demonstrate higher participation in agro-processing, but structural barriers limit their contribution to climate resilience. Other socio-demographic variables, such as age, marital status, and general training, show weak or non-significant effects. Based on these findings, several recommendations emerge: First, strengthen education by expanding rural infrastructure, integrating climate science and agro-processing into curricula, and promoting adult learning. Second, redesign training programs to address real-world challenges, leveraging public-private partnerships for practical, accredited, and scalable modules. Third, address gender disparities through targeted, sex-responsive policies, financial inclusion, and mentorship for women entrepreneurs. Fourth, enhance institutional coherence for monitoring and evaluating the impacts of education and training on adaptation outcomes. Fifth, expand inclusive extension services to reach all demographic groups using diverse, participatory, and technology-supported approaches. Finally, the paper provides targeted incentives to stimulate climate-smart agro-enterprise development, including financial and technical support, risk-sharing facilities, and tailored loans for women and youth.

Author Contributions

Adrino Mazenda: conceptualization, methodology, investigation, data curation, formal analysis, writing – original draft, writing – review and editing, software. **Ajuruchukwu Obi**: conceptualization, supervision, investigation, writing – review and editing, project administration. **Maggie Kisaka-lwayo**: conceptualization, writing – review and editing, investigation, project administration. **Michael Antwi**: writing – review and editing, conceptualization, investigation, validation, visualization.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The experimental data and simulation results supporting this study's findings are available in Figshare with the identifier. https://doi.org/10.6084/m9.figshare.28644995.v1

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