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ORIGINAL ARTICLE

Water, sanitation, and energy as determinants of food security among rural women-led households

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Abstract
In South Africa, especially in rural areas, access to essential resources such as water, sanitation, and energy is limited. This issue disproportionately impacts female-headed households, which also face challenges related to poverty and gender inequality. This study examines how water and sanitation influence food security in these households, focusing on the role of energy access as a mediating factor in the rural provinces of Limpopo and the Eastern Cape. Data was collected from 2369 female-headed households through the 2022 South African General Household Survey, and the analysis was conducted using structural equation modelling. The study findings showed a positive effect of improved water sources and enhanced food security (estimate = 0.06, $p < 0.05$). Conversely, water interruptions reduce food security (estimate = − 0.09, $p < 0.001$), with a significant indirect effect (estimate = − 0.03, $p < 0.001$). Municipal water sources negatively affect food security (estimate = − 0.07, $p = 0.004$). Consequently, improved sanitation positively influenced food security (estimate = − 0.10, $p < 0.001$). The location of sanitation facilities positively affects food security (estimate = 0.20, $p = 0.001$). Finally, access to energy contributes to improved food security (estimate = 0.07, $p = 0.007$). The study highlights the need for targeted policies to address these households' unique challenges and strengthen their resilience against food insecurity.

Keywords Water-sanitation-energy nexus · Food security · Structural equation modelling · Rural provinces · South Africa

Introduction

Food security is a critical global issue influenced by various socioeconomic and environmental factors (Sani & Scholz, 2021). The World Health Organization (WHO) reports that 2.33 billion people worldwide experience food insecurity, with Africa particularly affected (WHO, 2024a). This issue is exacerbated by climate change, economic instability, and pandemics (WHO, 2024a). Gender equality in access to water, sanitation, energy, and food security is vital for the well-being of individuals and broader societal development. Addressing these disparities can help achieve sustainable development goals (SDGs), particularly those related to zero hunger and gender equality (Dickin et al., 2020). Gender disparities in water, sanitation, energy, and food security persist globally. Gender-specific differences in productive roles, resource perceptions, access to external actors, and decision-making significantly influence the management of components within the water-energy-food nexus (Villamor, 2023). Women-led households endure disproportionate burdens that impact their health, time, and opportunities (Njuki et al., 2022). Women household heads often bear unequal responsibilities for water and energy-related household tasks, exposing them to health risks, violence, and disempowerment (Sani & Scholz, 2021).

This study investigates how water and sanitation contribute to food security among rural women-led households, explicitly examining the role of energy access as a mediating factor in the South African rural provinces of Limpopo and the Eastern Cape.

The study assumes that access to water, sanitation, and energy directly enhances food security among rural women-led households by expanding their capabilities. Rooted in Sen's Human Capabilities framework, it highlights how these basic services enable essential functions such as food

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preparation, health, and time management. (Carrard et al., 2021; Sen, 1999). Understanding how water, sanitation, and energy interact to bolster community resilience and food security is vital (Ringler et al., 2022). Water is vital for food security, nutrition, and overall health, supporting agriculture, food processing, and safe drinking supplies (Chikozho et al., 2020). Access to water safeguards health and influences the labour force needed for agriculture, where the proximity and quality of water sources play critical roles (Cassivi et al., 2019). In South Africa, erratic rainfall patterns and inadequate infrastructure worsen water scarcity, particularly in rural areas where women-led households often shoulder the burden of water collection, further hindering productivity (Maluleke, 2024; Abrams et al., 2021). Poor sanitation practices, such as insufficient septic systems and the absence of sewer systems, lead to water contamination, soil pollution, and the transmission of waterborne diseases, which jeopardise food safety and human health (Zheng, 2022; McGuinness et al., 2020). Furthermore, water is integral to energy generation, notably hydroelectric power, which is crucial for food production and distribution (Zakari et al., 2021). Access to clean energy enhances food security and nutrition, as it diminishes household energy burdens and enables women-led households to engage in income-generating activities (Niyonshuti & Kwitonda, 2022). However, rural communities that rely on traditional fuels and face unreliable energy sources encounter difficulties adopting modern agricultural technologies, further exacerbating food insecurity (Berretta et al., 2023).

Although women-led households in rural South Africa are expected to be food secure due to land access and agricultural activities, they remain marginalised (Masuku et al., 2023). Insufficient government support, adverse climate conditions, and low water tables hinder agricultural viability, calling into question the sustainability of irrigation systems (Seruwagi, 2024; Ngarava et al., 2019). Moreover, diarrhoea, largely caused by contaminated water, remains a leading cause of child mortality, where poor sanitation restricts agricultural productivity and increases healthcare costs (WHO, 2024b; Murei et al., 2021). Finally, many rural communities depend on traditional energy sources like firewood or coal, which limit efficient food preparation and preservation, leading to increased post-harvest losses (Zakari et al., 2021). Load shedding and an unreliable energy supply further complicate this issue, hindering the adoption of modern agricultural technologies that could enhance productivity (Berretta et al., 2023).

Existing literature has predominantly focused on the relationship between water, sanitation, and food consumption (Prüss-Ustün et al., 2019; Winter et al., 2021) and water security's role in nutrition (Miller et al., 2021). Moreover, challenges such as an unreliable water supply in the Eastern Cape and Limpopo South African provinces highlight the urgent need for targeted interventions to bolster food security among women-led households (Mpongwana et al., 2022; Apraku et al., 2023). This study contributes to the literature by providing insights into women-led households' unique challenges in marginalised rural areas. It seeks to underscore the necessity for targeted policies that address these households' specific needs and enhance their resilience against food security challenges. Ultimately, this study informs stakeholders about the importance of integrated approaches considering the complex interplay between water, sanitation, energy, and food security, particularly for vulnerable populations. Data was solicited from 2369 women-led households collected in the 2022 South African General Household Survey and analysed using structural equation modelling.

The rest of the paper is structured as follows: introduction, materials and methods, results, discussion, and conclusions.

Materials and methods

Data and sampling

The data utilised in the study was obtained from the General Household Survey, 2021/22, a crucial resource that annually measures the living conditions of South African households. This comprehensive survey gathers information on social development, housing, health, education, access to facilities and services, and agricultural and food security. 2369 women-led rural households in marginalised provinces of the Eastern Cape and Limpopo provinces of South Africa were chosen for the study. The sample used for the General Household Survey is based on a stratified two-stage sampling design, wherein dwelling units are sampled using systematic sampling in the second stage and probability proportional to size sampling of primary sampling units in the first. Following sample allocation to provinces, the sample was further stratified using Census 2011 data for population traits and geography (primary and secondary stratification, respectively).

Water, sanitation and energy description

From the *water sources variable,* a binary variable was created for improved water sources, with 1 representing improved water sources and 0 representing unimproved water sources. The water sources were classified according as follows: improved sources (piped (tap) water in dwelling/house; piped (tap) water in yard; neighbour's tap; public/communal tap; borehole in yard; rain-water tank in yard; borehole outside yard) and unimproved sources (water-carrier/tanker; water vendor (charge involved); flowing water/stream/river; stagnant water/dam/pool; well; spring)

(Statistics South Africa, 2023; WHO, 2024). In addition to this criterion, an improved water source should be less than 200 metres to meet the criteria; however, in this analysis, distance to the water source was a specific variable included as one of the mediators.

A binary variable was created for *sanitation facilities*, whereby an improved sanitation facility variable was formulated, with 1 representing improved sanitation while 0 representing unimproved sanitation facilities. The classification in this analysis was as follows: improved sanitation facilities (flush toilet—public sewerage system; flush toilet—septic tank; pour bucket-flush toilet—septic tank; chemical toilet; pit latrine/toilet with ventilation pipe) and unimproved sanitation (pit latrine/toilet without ventilation pipe; bucket toilet; composting toilet; urine diversion dry toilet; portable flush toilet; open defecation) (Statistics South Africa, 2023; WHO, 2024b). In addition to this criterion, an improved sanitation facility should not be shared to meet the criteria. In this analysis, sanitation facilities were classified by type, and a shared binary variable was included as one of the mediators. The same was done for *energy access*, whereby households were asked if they had energy access. (Electricity in the household) .1 represents access to energy, while 0 represents non-access to energy.

Food security assessment

Food security can be measured by various measures such as the Food Consumption Score (FCS), Household Food Insecurity Access Scale (HFIAS), and Household Dietary Diversity Score (HDDS). Based on the variables available in the data, the HFIAS was deemed more appropriate. This analysis followed steps outlined in the Food and Nutrition Technical Assistance III Project (FANTA) guidance document (Coates et al., 2007). The HFIAS addresses three domains of food insecurity: anxiety and uncertainty regarding the household's food supply, inadequate quality in terms of variety and personal preferences, and insufficient food consumption along with its physical effects. The HFIAS module provides household-level data on food insecurity related to access. The food security variable was calculated as binary, food security (1 (food secure) and 0 (food insecure).

Structural equation modelling (SEM)

The study utilised data from the GHS (General Household Survey) dataset, which included a sample size of 2369 observations. A structural equation modelling (SEM) approach was employed to examine the relationships between water and sanitation variables and their relationship with hunger. The SEM was estimated using the maximum likelihood (ML) method with robust standard errors obtained through bootstrapping. The bootstrapping procedure involved 1,000 draws, providing robust standard errors. The SEM model included latent variables, direct effects, and covariances among key variables. To address missing data, the full information maximum likelihood (FIML) method was employed, which allows for the inclusion of all available data points, thereby maximising the sample size and reducing potential biases. The SEM model was specified as follows:

- Latent variables were defined to capture underlying constructs such as water interruption (interruption over the last 12 months; interruption longer than two days; interruption more than 15 days in total) and food security (1 (food secure) and 0 (food insecure).
- The mediators applied for the water component were water interruption latent variable, water distance, municipal source, and energy access. This included washing facilities, location, distance, sharing, and energy access for sanitation.
- Direct effects were modelled to assess the impact of independent variables (water source and sanitation facility type) on the dependent variable (food security).
- Covariances were specified between several variables to account for their interrelationships.

Data was handled and analysed in R statistical software (R Core Team, 2024, version 4.4.0). The haven package was used for importing and manipulating data (Wickham et al., 2023). A Mardia's multivariate normality test was conducted using the MVN package (Korkmaz et al., 2014). The SEM analysis used the lavaan package (Rosseel, 2012). The graphs were plotted by the semPlot (Epskamp, 2022).

Results and discussion

Descriptive statistics

Table 1 shows the descriptive statistics for water variables.

Table 1 shows that in the *Water variables*, 84% of the households had improved water sources, with over 57% having access to municipal water sources, mostly tap water. 75% of the households experienced water interruptions two days before the survey. 81% of the households had access to water within a 200 m radius. Due to water inadequacy, at least 41% of the households were practising agriculture activity.

Public or communal taps account for 19% of water access, while 10% of households rely on rainwater tanks. Boreholes, both on-site (6%) and outside the yard (2%), are used less frequently. A smaller percentage of households use alternative sources such as water vendors (5%), springs (3%), and flowing water from streams or rivers (4%). Minor sources include neighbours' taps (2%), water

Table 1 Water descriptive statistics

Variable Name	Code	Label	Frequency	Percentage	Stats/values
Main source of water	1	Piped (tap) water in dwelling	509	21	Mean (sd): 4.3 (3.4); min < med < max: 1 < 3 < 14
	2	Piped (tap) water on site or in yard	574	24	
	3	Borehole on site	135	6	
	4	Rain-water tank on site	247	10	
	5	Neighbour's tap	51	2	
	6	Public/communal tap	445	19	
	7	Water-carrier/tanker	14	1	
	8	Water vendor	120	5	
	9	Borehole outside yard	37	2	
	10	Flowing water/stream/river	87	4	
	11	Stagnant water/dam/pool	14	1	
	12	Well	8	0	
	13	Spring	77	3	
	14	Other source of drinking water	51	2	
Type of water source	0	Unimproved	371	16	Mean (sd): 0.8 (0.4); min < med < max: 0 < 1 < 1
	1	Improved	1998	84	
Water interruptions in the last 12 months	0	No	1355	57	Mean (sd): 0.4 (0.5); min < med < max: 0 < 0 < 1
	1	Yes	1014	43	
Water interruptions lasting more than 2 days	0	No	1613	68	Mean (sd): 0.3 (0.5); min < med < max: 0 < 0 < 1
	1	Yes	756	32	
Water interruptions lasting more than 15 days	0	No	1757	74	Mean (sd): 0.3 (0.4); min < med < max: 0 < 0 < 1
	1	Yes	612	26	
Distance to water source	1	Less than 200 metres	1923	81	Mean (sd): 1.2 (0.6); min < med < max: 1 < 1 < 4
	2	201–500 m	332	14	
	3	501 meters–one kilometer	78	3	
	4	More than one kilometer	31	1	
Municipal water source	0	No	1023	43	Mean (sd): 0.6 (0.5); min < med < max: 0 < 1 < 1
	1	Yes	1346	57	

Source General Household Survey (2022)

carriers/tankers (1%), and stagnant water bodies (1%). Notably, wells are reported as an unused water source in this data set.

Table 2. shows the descriptive statistics for sanitation and energy.

Table 2 shows that in the *sanitation variables*, approximately 67% of households use pit latrines, while about 37% utilise flush toilets. Additionally, 73% of households have a sanitation facility in their yard. However, 51% of these facilities do not include washing facilities. Other sanitation options, such as chemical toilets, portable flush toilets, composting toilets, and urine diversion dry toilets, are not commonly used. A small percentage (2%) of households still practice open defecation, indicating a lack of access to any form of sanitation. Overall, 77% of households have access to improved sanitation facilities, whereas 23% continue to use unimproved sanitation options. Finally, 97% of households had access to energy, primarily electricity obtained from the rural local municipalities.

Food security

The Household Food Insecurity Scale (HFIAS) was used as a method of analysis. In the analysis, the HFIAS Score was applied; however, the method used was not exactly the one stipulated by Coates et al. (2007) due to data constraints. A total of 14 variables from the General Household Survey (2022) data were used to compute the HFIAS score. These variables were converted to binary variables; in cases where there was the presence of food insecurity, this took a value of 1 (yes) and 0 (no) otherwise. The HFIAS score was then calculated by adding together the 14 variables, thus giving a maximum score of 14 in cases where the unit experienced all the forms of food insecurity. Based on the HFIAS score, a binary variable for household food security was calculated as follows: 1 (food secure) if the HFIAS score was 0 and 0 (food insecure) if the HFIAS score was greater or equal to 1. The HFIAS results are presented in Table 3.

Table 2 Sanitation and energy descriptive statistics

Variable name	Code	Label	Frequency	Percentage	Stats/values
Type of toilet facility	1	Flush toilet connected to a public sewerage system	627	26	Mean (sd): 4.1 (2.2); min < med < max: 1 < 5 < 12
	2	Flush toilet connected to a septic tank or conservancy tank	129	5	
	3	Pour bucket-flush toilet connected to a septic tank (or septic pit)	6	0	
	4	Chemical toilet	2	0	
	5	Pit latrine/toilet with a ventilation pipe	1060	45	
	6	Pit latrine/toilet without ventilation pipe	486	21	
	7	Bucket toilet	8	0	
	8	Portable flush toilet	1	0	
	9	Composting toilet	3	0	
	10	Urine diversion dry toilet	9	0	
	11	Open defecation (e.g. no facilities, field, bush)	39	2	
Type of sanitation facility	0	Unimproved	547	23	Mean (sd): 0.8 (0.4); min < med < max: 0 < 1 < 1
	1	Improved	1822	77	
Shared sanitation facility	0	No	2168	92	Mean (sd): 0.1 (0.3); min < med < max: 0 < 0 < 1
	1	Yes	162	7	
Location of sanitation facility	1	In dwelling	575	24	Mean (sd): 1.8 (0.5); min < med < max: 1 < 2 < 3
	2	In yard	1722	73	
	3	Outside yard	72	3	
Distance to sanitation facility	1	Less than 50 m	2352	99	Mean (sd): 1 (0.1); min < med < max: 1 < 1 < 4
	2	51–100 m	10	0	
	3	101–200 m	6	0	
	4	201–500 m	1	0	
Sanitation facility with handwashing	0	No	1204	51	Mean (sd): 0.5 (0.5); min < med < max: 0 < 0 < 1
	1	Yes	1125	47	
Access to energy	0	No	64	3	Mean (sd): 1 (0.2); min < med < max: 0 < 1 < 1
	1	Yes	2305	97	

Source General Household Survey (2022)

The findings indicate that 25% of households are classified as food insecure, according to the HFIAS. Several dimensions of food insecurity were assessed. Hunger was experienced in 12% of households, indicating any adult had gone hungry in the previous 12 months, while 7% had children having experienced hunger. Food shortage anxiety had about 14% of households worrying about food shortages, indicating uncertainty about their ability to maintain food supplies. Regarding food quality, 16% of households reported being unable to eat healthy and nutritious food because of a lack of money or other resources. About 17% indicated that there was a time when some members of the household ate only a few kinds of foods because of a lack of money or other resources, with 10% experiencing this limitation over 5 or more days in the previous 30 days. A concerning 6% of households reported skipping meals, with 3% experiencing this issue for multiple days. Additionally, 9% ate less than usual, and 4% had to eat less over several days. The survey showed that 8% of households ran out of food at some point, with 3% reporting this occurring over multiple days. Furthermore, 4% went hungry due to a lack of food, and 3% did not eat for an entire day.

Path analysis

The updated model fit analysis indicates a Chi-square test statistic of 343.556, with 39 degrees of freedom. The significance of the chi-square test ($p < 0.05$) suggests that the model may not fit the data perfectly, highlighting the need to review additional model fit indices. The Comparative Fit Index (CFI) of 0.969 and the Tucker-Lewis Index (TLI) of 0.939 indicate a better model fit than previous results. The

Table 3 Descriptive statistics: household food insecurity scale

Variable name	Code	Label	Frequency	Percentage	Stats/values
Worried about food shortage	0	No	2027	86	Mean (sd): 0.1 (0.4); min < med < max: 0 < 0 < 1
	1	Yes	342	14	
Did not have access to healthy food	0	No	2001	84	Mean (sd): 0.2 (0.4); min < med < max: 0 < 0 < 1
	1	Yes	368	16	
Had few kinds of foods	0	No	1976	83	Mean (sd): 0.2 (0.4); min < med < max: 0 < 0 < 1
	1	Yes	393	17	
Experienced few kinds of foods in 5 or more days in the past 30 days	0	No	2142	90	Mean (sd): 0.1 (0.3); min < med < max: 0 < 0 < 1
	1	Yes	227	10	
Skipped meals	0	No	2228	94	Mean (sd): 0.1 (0.2); min < med < max: 0 < 0 < 1
	1	Yes	141	6	
Skipped meals in 5 or more days in the past 30 days	0	No	2301	97	Mean (sd): 0 (0.2); min < med < max: 0 < 0 < 1
	1	Yes	68	3	
Ate less than usual	0	No	2145	91	Mean (sd): 0.1 (0.3); min < med < max: 0 < 0 < 1
	1	Yes	224	9	
Ate less in 5 or more days in the past 30 days	0	No	2263	96	Mean (sd): 0 (0.2); min < med < max: 0 < 0 < 1
	1	Yes	106	4	
Ran out of food	0	No	2172	92	Mean (sd): 0.1 (0.3); min < med < max: 0 < 0 < 1
	1	Yes	197	8	
Ran out of food in 5 or more days in the past 30 days	0	No	2304	97	Mean (sd): 0 (0.2); min < med < max: 0 < 0 < 1
	1	Yes	65	3	
Went hungry due to lack of food	0	No	2264	96	Mean (sd): 0 (0.2); min < med < max: 0 < 0 < 1
	1	Yes	105	4	
Did not eat for a whole day	0	No	2300	97	Mean (sd): 0 (0.2); min < med < max: 0 < 0 < 1
	1	Yes	69	3	
HFIAS food secure	0	Food insecure	586	25	Mean (sd): 0.8 (0.4); min < med < max: 0 < 1 < 1
	1	Food secure	1783	75	

Source General Household Survey (2022)

Root Mean Square Error of Approximation (RMSEA) of 0.057, with a 90% confidence interval ranging from 0.052 to 0.063. Additionally, the Standardized Root Mean Square Residual (SRMR) of 0.033, well below the 0.08 threshold, indicates a good fit overall. These indices collectively suggest an improved and adequate fit for the data. Parameter estimates were calculated using bootstrap standard errors, requesting 1,000 draws, of which 734 were successful. This bootstrapping method addresses potential non-normality in the data and provides robust standard errors. The path analysis showing the relationship between the study variables is shown in Fig. 1

Figure 1 's interpretation is made in conjunction with Table 4, which presents detailed standardised estimates, confidence intervals (CIs), and *p*-values, offering insights into these water variables' direct, indirect, and total effects on hunger.

The independent variable in this study is binary, representing the type of water source: 1 indicates improved water sources, while 0 indicates unimproved sources. The outcome variable is also binary, reflecting food security status, with 1 representing food-secure individuals and 0 representing those who are food insecure. The direct effect of the type of water source on food security (denoted as path c) was found to be statistically significant, with an estimate of 0.06 ($p < 0.05$). The standardised estimate for the path (a) from water source type to water interruption was positive and significant (estimate = 0.29, $p < 0.001$). The path (b) representing the direct effect of water interruption on food security was significant (estimate = − 0.09, $p < 0.001$), suggesting that water interruptions are directly associated with reduced food security. The indirect effect (a*b) through water interruption was significant (estimate = − 0.03, $p < 0.001$), indicating that water interruptions mediate the relationship between water source type and food security.

The relationship between water source type and distance to water sources (path a) shows a significant negative effect (estimate = − 0.50, $p < 0.001$), revealing that households accessing unimproved water sources are likely to have longer distances to those water sources. The path (b) on the relationship between water distance and food security is marginally significant (estimate = − 0.04, $p = 0.061$).

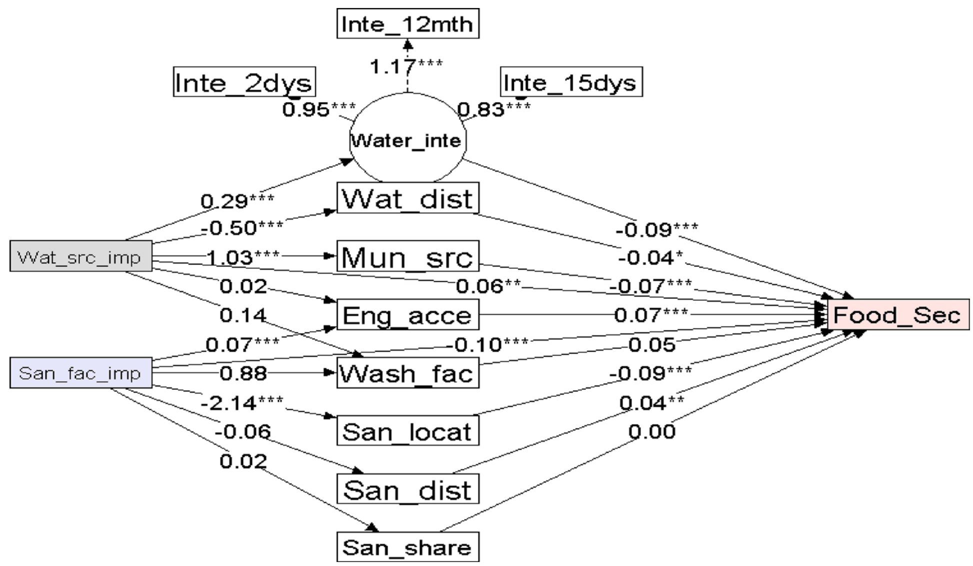

Fig. 1 Path analysis Source: General Household Survey (2022)

Table 4 Standardised estimates for water variables and energy access against food security

Effects	Mediators	Estimate	Lower CI	Upper CI	*p*-value
a	Water interruption	0.29	0.27	0.32	0.000***
	Water distance	– 0.50	– 0.55	– 0.46	0.000***
	Municipal source	1.03	0.90	1.17	0.000***
	Energy access	0.02	– 0.03	0.07	0.398
b	Water interruption	– 0.09	– 0.13	– 0.06	0.000***
	Water distance	– 0.04	– 0.09	0.00	0.061*
	Municipal source	– 0.07	– 0.11	– 0.02	0.004***
	Energy access	0.07	0.02	0.11	0.007***
c (Direct effect)		0.06	0.01	0.10	0.013**
a*b (Indirect effect)	Water interruption	– 0.03	– 0.04	– 0.02	0.000***
	Water distance	0.02	0.00	0.05	0.062*
	Municipal source	– 0.07	– 0.11	– 0.02	0.004***
	Energy access	0.00	0.00	0.00	0.397
Total indirect		– 0.07	– 0.12	– 0.02	0.006***
Total effect		– 0.01	– 0.06	0.04	0.635

Significance levels: ***1%, **5%, * 10%

Source General household survey (2022)

The indirect effect (a*b) through water distance is marginally significant (estimate = 0.02, p = 0.062). The path (a) relationship between water source type and municipal source was positive and significant (estimate = 1.03, $p < 0.001$), suggesting that municipalities provide the most improved water sources. The path (b) relationship between municipal sources and food security is negative and significant (estimate = – 0.07, p = 0.004). The indirect effect (a*b) through municipal water sources is negative and significant (estimate = – 0.07, p = 0.004), indicating that municipal water sources mediate the relationship between water source type and food security.

The path (a) relationship between water source type and energy access shows a non-significant effect (estimate = 0.02, p = 0.398). However, the path (b) relationship between energy access and food security was positive and significant (estimate = 0.07, p = 0.007), reinforcing the importance of energy access in ensuring food security. The indirect effect (a*b) through energy access is insignificant (estimate = 0.00, p = 0.397).

The independent variable is sanitation facility type (1 being improved and 0 being unimproved), and the outcome variable is food security. The mediation results are shown in Table 5.

Table 5 Standardised estimates for sanitation variables and energy access against food security

Effects	Mediators	Estimate	Lower CI	Upper CI	*p*-value
a	Sanitation shared	0.02	– 0.02	0.06	0.236
	Sanitation location	– 2.14	– 2.73	– 1.55	0.000***
	Sanitation distance	– 0.06	– 0.24	0.13	0.538
	Wash facility	0.88	– 7.81	9.58	0.842
	Energy access	0.07	0.03	0.12	0.003***
b	Sanitation shared	0.00	– 0.04	0.04	0.950
	Sanitation location	– 0.09	– 0.15	– 0.04	0.001***
	Sanitation distance	0.04	0.01	0.08	0.016**
	Wash facility	0.05	– 0.54	0.63	0.877
	Energy access	0.07	0.02	0.11	0.007***
c (Direct effect)		– 0.10	– 0.14	– 0.06	0.000***
a*b (Indirect effect)	Sanitation shared	0.00	0.00	0.00	0.950
	Sanitation location	0.20	0.08	0.32	0.001***
	Sanitation distance	0.00	– 0.01	0.01	0.524
	Wash facility	0.04	– 0.10	0.18	0.577
	Energy access	0.01	0.00	0.01	0.048**
Total indirect		0.24	0.07	0.42	0.007***
Total effect		0.14	– 0.03	0.32	0.108

Significance levels: ***1%, **5%, *10%

Source General Household Survey (2022)

The direct effect (path c) of sanitation facilities and food security was statistically significant (estimate = – 0.10, $p < 0.001$). (*This is also presented in Figure 1*) The relationship between the various mediators and the independent and outcome variables is presented below. The path (a) relationship between sanitation facility type and sanitation shared was statistically insignificant (estimate = 0.02, $p = 0.236$). The path (b) relationship between sanitation shared and food security is also statistically insignificant (estimate = 0.00, $p = 0.95$). The indirect effect (a*b) through sanitation shared was insignificant. The path (a) relationship between sanitation facility type and location of sanitation facilities is negative and significant (estimate = – 2.14, $p < 0.001$), indicating that improved sanitation facilities tend to be closer to the dwelling. The path (b) relationship between sanitation location and food security was positive and significant (estimate = – 0.09, $p = 0.001$), suggesting that closer sanitation facilities are associated with better food security. The indirect effect (a*b) through sanitation location was positive and significant (estimate = 0.20, $p = 0.001$).

The path (a) relationship between sanitation facility type and sanitation distance was statistically insignificant (estimate = – 0.06, $p = 0.538$). However, the path (b) relationship between sanitation distance and food security was significant (estimate = 0.04, $p = 0.016$). The indirect effect (a*b) through sanitation distance is insignificant.

The path (a) relationship between sanitation facility type and washing facility was statistically insignificant (estimate = 0.88, $p = 0.842$). The path (b) relationship between washing facilities and food security is also insignificant (estimate = 0.05, $p = 0.877$). The indirect effect (a*b) through washing facilities is insignificant.

The path (a) relationship between sanitation facility type and energy access was positive and significant (estimate = 0.07, $p = 0.003$). The path (b) relationship between energy access and food security is also significant (estimate = 0.07, $p = 0.007$), suggesting that better energy access is associated with improved food security. The indirect effect (a*b) through energy access was significant but marginal.

Discussion

The study findings indicate that households with adults experiencing food insecurity were most common in the study area. This could be due to limited and unsuccessful farming activities and a lack of income or financial resources to buy food (Tambe et al., 2023). This aligns with a study conducted in Limpopo by Abrams et al. (2021), which pointed out that residents were poor, with a high unemployment rate and low agricultural production due to unfavourable rainfall patterns. Furthermore, the type of primary water sources households use reflects their wealth status, as reported by Mbhenyane and Tambe (2024). They argued that having no access to water in a dwelling or house indicates poverty.

The relationship between distance to water and food security was marginally significant. The distance from the nearest water source, where water can be obtained, can be time-consuming, negatively affecting household activities and limiting the time that could have been used for other household tasks, earning extra income, and preparing food (Mbhenyane & Tambe, 2024). Households with a shorter distance to the water source, such as those using piped water and boreholes, are likelier to use water for personal hygiene and production (Winter et al., 2021). Access to piped water nearby is more likely to increase usage for hygiene and productivity purposes (Mshida et al., 2020; Mpongwana et al., 2022).

The standardised estimate for path (a) from water source type to water interruption was positive and significant. Path (b), representing the direct effect of water interruption on food security, is also significant, suggesting that water interruptions are directly associated with reduced food security. The indirect effect through water interruption is significant, indicating that water interruptions mediate the relationship between water source type and food security**.**

Water supply interruptions can impact food availability, accessibility, and utilisation. Water plays a crucial role in food production. Therefore, households with better water accessibility experience improved nourishment daily (Ringler et al., 2022). These findings align with the research of Chikozho et al. (2019), who emphasised that limited access to improved water sources is linked to decreased food security. Additionally, Mshida et al. (2020) stress the importance of understanding how water demand, sources of pollution, and the reuse and contamination of food through water impact food safety. Water is also crucial for food utilisation, including food preparation, which is not only an ingredient. "The agricultural sector is the largest consumer of water, requiring 100 times more water than personal needs" (Bhagwat, 2018). According to Prüss-Ustün et al. (2019), the water used in food production should be suitable for drinking. Water quality depends on its source, and proper water treatment is essential to ensure it meets safe drinking water standards for food production, i.e., safe for human consumption (Miller et al., 2021). Water is an essential resource in the production and preparation of food. Consistent access to water is a critical component of good nutrition (Miller et al., 2021; Gaffan et al., 2022). The relationship between municipal resources and food security was negative and significant. This is because many rural households rely on traditional water catchment methods, while in some cases, boreholes are constructed by the municipality or non-governmental organisations (Lantagne et al., 2021). Rural municipalities provide boreholes as the main water source for household consumption. There are non-borehole facilities for irrigation or agricultural production. Previous studies have emphasised the importance of safe water, sanitation, and hygiene (Prüss-Ustün et al., 2019; Winter et al., 2021). Household access to improved sanitation and water services significantly contributes to food utilisation, a key aspect of food security. Moreover, having access to an adequate water supply enables households to produce food and reduces their vulnerability to unforeseen challenges (Woodhill et al., 2022).

The relationship between the proximity of sanitation facilities and food security was significant. This suggests that having sanitation facilities closer is associated with better food security. Having to travel longer distances to reach sanitation facilities may discourage individuals from using them, leading to the adoption of inadequate hygiene practices. This could increase the risk of waterborne diseases, impacting food production and nutritional status (Tseole et al., 2022). According to Young et al. (2021), travelling to remote sanitation facilities can reduce the time available for agricultural activities and food preparation within households, potentially leading to decreased food availability. Similarly, Ingrao et al. (2023) argued that if sanitation facilities are far away, the risk of illness increases, potentially reducing agricultural output and food security. Poorly located sanitation facilities can pollute nearby water sources, affecting crop irrigation and livestock drinking water, thus impacting food security (Bazaanah & Mothapo, 2023).

The path (a) relationship between sanitation facility type and energy access was positive and significant. Communities prioritising sanitation often recognise the importance of energy access for overall quality of life. This can lead to joint initiatives and investments that enhance both sectors. (Casati et al., 2023). Access to clean cooking fuels and sanitation facilities is significantly lower worldwide than access to improved water and electricity. This lack of access is more prevalent in poorer countries and among impoverished individuals in middle-income countries. Additionally, it is associated with health risks that disproportionately affect women. (Narasimha & Pachauri, 2017).

The relationship between energy access and food security was positive and significant, highlighting the importance of energy availability in ensuring food security. Higher energy costs can lead to increased production expenses in the agricultural sector, which may result in reduced food processing and production (Ma et al., 2021; Li et al., 2024). This effect is particularly noticeable with clean energy, associated with improved food security, in contrast to some renewable energy sources. For instance, specific renewable energy projects, such as solar farms, may compete with agricultural activities for land and resources. If land previously used for food production is repurposed for biofuel crops, it could diminish the area available for growing food. Moreover, competition for water resources between energy production—such as fossil fuel extraction and large-scale biofuel farming—and agricultural needs could create irrigation and crop growth challenges, further impacting food security (Li et al., 2024).

Conclusion

This study used structural equation modelling to explore the mediating effects of various water, sanitation, and energy on food security of 2369 women-led households in the South African marginalised rural provinces of Limpopo and Eastern Cape, drawn through a stratified two-stage sampling design with data from the General Household Survey based on a stratified two-stage sampling design. Data was from the South African 2021/2022 General Household Survey. Analyses of water-related variables reveal that water interruption and municipal sources significantly mediate the relationship between water source type and food security. The overall effect of improved water sources on food security is complex and mediated by several factors. The findings emphasise the need for comprehensive strategies to improve water sources and address related infrastructure to reduce food insecurity in affected populations. The analysis of sanitation-related variables shows that factors like the location of sanitation facilities and access to energy significantly influence the relationship between improved sanitation and food security. The impact of enhanced sanitation facilities on food security is complex and shaped by various factors. This highlights the need to consider multiple dimensions of sanitation and infrastructure when tackling food insecurity in vulnerable populations.

Based on the study findings, several policy recommendations are suggested:

First, interventions and programs to enhance food security should consider women-led households' unique challenges and the community's access to sufficient and quality water and sanitation. Access to water sources is crucial, so food security policies must address factors such as the distance households must travel to obtain water, the impact of interruptions in water supply on household sanitation, and the role of municipalities in providing water to households and communities. To ensure consistent access to clean water in rural areas, it is recommended that boreholes be constructed, communal taps be installed, and water purification systems be implemented.

Second, sanitation facilities should be improved. This entails upgrading existing facilities, promoting safe hygiene practices, and eradicating open defecation through community-led initiatives in partnership with local authorities.

Third, water and sanitation interventions should be integrated with agricultural programs to enhance water management, soil conservation, and crop diversification, thereby boosting farm productivity and resilience to climate change. Fourth, empowering rural communities by providing education and training on water and sanitation, sustainable agricultural techniques, and food processing and storage methods is important. Encouraging community ownership and involvement in decision-making processes related to these initiatives is vital.

Finally, collaboration among government agencies, NGOs, academic institutions, and private sector stakeholders should be encouraged to mobilise resources, share expertise, and coordinate efforts toward achieving sustainable water, sanitation, and food security outcomes.

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Declarations

Competing interest The authors declare that they have no competing interests

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