scientific reports

OPEN

Adoption of nature based solutions for energy transition in rural households of Northern Nigeria

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Transition to clean energy is crucial to reducing deforestation, improving health and the socio-economic development of developing countries. Little is known about energy transition decision making processes in the poorest areas of the developing world. The present study focuses on the Hadejia Valley in northern Nigeria, which has been affected by the invasion of the *Typha spp*. plant. The primary aim is to investigate the acceptance and the willingness to adopt and pay for nature-based clean cooking technologies based on *Typha spp.* spp. biomass, considering socioeconomic and cultural dimensions, while considering gender differences, within the household. The findings indicate that a considerable proportion of individuals are willing to adopt and pay for biogas, particularly women. Hence, our findings indicate that gender (female), concerns about the extensive time employed in cooking, technology concerns and decision-making power, among other factors, significantly influence adoption rates, with notable differences when considering preferences of men and women separately. These results highlight the importance of raising men's awareness of the benefits of biogas and policies that empower women in decision-making to ensure effective and equitable adoption of the technology in these rural communities. This study may provide guidance to successfully link energy transition with nature-based solution in other contexts.

Keywords Technology adoption, Nature-based solution, Gender, Culture

Access to clean energy sources is a pressing need, with climate change posing a growing threat to the health and livelihoods of people worldwide, as well as to ecosystems health and biodiversity[1]. Despite this, there are persistent gaps in access to clean, modern energy, holding back the most vulnerable. Tackling these problems is part of the 2030 Sustainable Development Goals, the well-known United Nations initiative to eradicate poverty, protect the planet, and promote prosperity.

Energy is essential for carrying out multiple activities in households and most economic sectors. One of the key indicators for measuring the economic development of a country is energy consumption per capita[2–4]. Access to clean and affordable energy is crucial to socioeconomic development and improved quality of life[5]. Using inefficient stoves with solid fuels causes domestic air pollution and is a significant health risk, mainly for women and children, since they are more exposed to the smoke. According to the World Health Organization (2023)[6], domestic air pollution caused by the use of harmful cooking fuels and technologies is responsible for 3.2 million deaths, including 240,000 pneumonia-related deaths in children under the age of five. The use of firewood is also associated with negative effects in terms of deforestation, soil degradation and climate change[7,8], as well as emissions of black carbon (a component of soot) due to the inefficient burning of biomass[9].

Between 2010 and 2020, the proportion of people worldwide with access to clean fuels and technologies for cooking increased by 12%, reaching 69%. However, in 2021, an estimated 2.3 billion people were still used polluting fuels and technologies for most of their cooking, mainly in sub-Saharan Africa and Asia[10]. If current trends continue, only 76% of the world's population will have access to clean cooking fuels and technologies by 2030[11]. Biofuels may be an energy supply option for developing countries that allows an improvement in their economy and preservation of the environment[5]. Nature-based technologies can play a key role in the energy transition by offering locally adapted solutions aimed at protecting, sustainably managing and restoring natural ecosystems. This approach effectively addresses social and environmental challenges and enhances well-being at the community level[12,13].

This study focuses on the Hadejia Valley Irrigation District in northern Nigeria, which has been colonised by an invasive aquatic plant, *Typha spp.* spp. The invasion extends over approximately 200 km^2, from the Kano River

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Irrigation Project to the Nguru wetland, primarily affecting the Hadejia Valley. *Typha spp.* spp. blocks irrigation canals, rivers and navigation channels, colonises agricultural and grazing land, and provides a suitable habitat for snakes and malaria-transmitting mosquitoes[14]. The rapid growth of *Typha spp.* spp. is a significant problem in the Hadejia Valley as it impedes water flow, reduces rice productivity, and hinders navigation and fishing activities. In addition, the biodiversity of these ecosystems is negatively affected, facilitating the persistence of water-borne diseases and an increased incidence of malaria[15].

Efforts to control the invasion of *Typha spp.* spp. include the identification of different environmental and economic benefits from the harvest of this plant; for example, biomass for livestock bedding, compost[16], silage feed[17] and bioenergy[18,19]. By employing invasive plants like *Typha spp.* spp. for second-generation biofuels, local communities in extreme poverty can use a threat to their advantage, improving their access to energy while helping to reduce the spread of the plant.

Previous studies have demonstrated the potential of *Typha spp.* spp. for biogas production[20–23], showing that its energy values Typha spp.are comparable to wood pellets at 20 MJ/kg[16]. However, it is important to be cautious about the timing of harvesting, as the potential for biogas production decreases as the plant matures[20,22]. Nkemka et al. (2015)[24] show that the characteristics of *Typha spp.* spp. make it a viable raw material for biogas production, with yields comparable to maize silage. However, unlike maize, *Typha spp. spp*. does not present the ethical dilemmas associated with food use, making it a more sustainable and ethically acceptable alternative, as this is not edible. In a recent study, Sale et al. (2022)[25] examined different parts of the *Typha spp*. plant to determine their effectiveness in producing biogas. They discovered that each part of the plant has unique characteristics that influence the ability of microorganisms to decompose it. In particular, the spike proved to be the most efficient in gas production, while the root proved to be the least efficient. This suggests that selecting specific parts of *Typha spp.* can optimize energy production.

The present study addresses bioenergy production for cooking, aiming to understand the adoption process as well as users 'preferences. Hence, it is important to achieve a successful uptake of the technology, considering the adopters' social, economic, and cultural aspects to ensure they obtain the expected benefits.

In the transition to clean energy consumption, it is essential to examine the factors driving adoption and the target public's willingness to pay (WTP) to plan the implementation of new technologies. As a new and locally adapted technology, biogas made from *Typha spp*. biomass has no market value; therefore, it is necessary to determine the WTP for this type of energy.

Our work contributes to the literature assessing the adoption process of a nature-based solution that can promote energy transition to clean cooking in local communities while helping to reduce *Typha spp.* invasion in nearby critical areas. The main objective of this work is to examine the barriers and facilitators associated with the adoption of *Typha spp.* biogas cooking technology and assess the WTP among local communities. In particular, our objective is to gain insights into the pivotal role of gender and other socio-cultural factors related to issues in the adoption process. This analysis provides an understanding of the challenges and opportunities for the successful implementation of this technology in rural communities. One of the contributions of this study is that, through a careful approach to data collection, it presents a comprehensive view of the experiences and perceptions of both household heads and women in rural households. This allows for a more complete understanding of how gender influences technology adoption and household dynamics related to cooking and household energy.

The study uses the Heckman sample selection model[26] to investigate the factors influencing WTP, avoiding selection bias by addressing the potential non-random nature of survey responses. This model is applied to correct for the fact that WTP is observed only for those who have expressed an initial interest in biogas adoption, which could lead to biased estimates if not accounted for. To understand the influence of gender on the adoption process, we estimate three Heckman regressions to check the robustness of our results. The first 'pooled model' corresponds to adoption and willingness to pay at the household level. The second model is conducted to assess the factors influencing women only, while the third model includes only men's responses.

In the next sections we provide information about the energy transition dilemma in Nigeria, and we continue with the description of the data collection procedure, and main results and conclusions derived from this research.

Energy consumption. Clean cooking technologies and fuels in Nigeria

The predominant source of energy in Nigeria is fossil fuels, but more commonly biomass. Biofuels and waste represent 54% of the total primary energy supply[27]. Over half of the population is multidimensionally poor and deprived of access to cooking fuel[28].

According to World Bank (2020)[29] data, 44.6% of the population has no access to electricity. In this respect, the rural population is above the national average, with 75.4% having no access. The Northeast of Nigeria, where the study area is located, has the highest proportion of households without electricity at 79.1%[30]. Only 15% of the Nigerian population has access to clean cooking technologies and fuels, with this figure dropping to 4.2% in rural areas[31].

According to the Living Standards Measurement Study (LSMS)[30], 43% of households use a three-stone open fire. Firewood is used by 66% of households, while kerosene is used by 21.3%. The average expenditure on firewood is 1212 Nigerian naira (NGN) per month (approximately USD 2.82).

Energy poverty is related to other problems, such as deforestation, gender inequality and health issues. In 2020, Nigeria's forest area was 216269.5 km^2, corresponding to 23.7% of the territory[29]. In 2015, Nigeria ranked ninth globally in timber extraction with 87% of the resources used as wood fuel, and during the 2010–2015 period it registered a 5% net loss of forest area[32]. In Nigeria, firewood is a significant energy source that supplies roughly 60% of the country's overall energy needs; moreover, its use is significantly higher in the northern states of Nigeria due to the lack of modern cooking fuel there[7].

Regarding health, cooking smoke is known as "the silent killer". The primary sources of energy are wood and charcoal. In Nigeria, smoke causes more than 95,000 deaths each year, primarily affecting women and children[33] due to their higher exposure. In addition, they often also have the task of collecting or buying firewood, which is a great physical and time burden.

Nevertheless, women are frequently excluded from decision-making processes regarding investments in general, and in particular, in clean and efficient energy sources, while they typically have limited access to financial resources[34,35]. In relation to gender issues, the 2023 OECD[36] Development Centre's Gender and Social Institutions Index (SIGI) for Nigeria is 42.4 (where 0 is NO discrimination, 100 is ABSOLUTE discrimination). Nigeria exhibits a higher score than the average for Africa (39.9) and the world (29.1). The country's cultural heritage is characterised by patriarchal traditions and women are traditionally responsible for cooking, cleaning, childcare, water and wood collection. Food preparation is considered "feminine"; women decide what and how food is cooked.

Data sources and methodology
Study area and data sample
A survey was conducted in seven communities of the Hadejia Valley Irrigation District: Marina, Furawa, Akubushin, Auyakayi, Auyo, Getafe, and Yamidi. These communities, located along the Hadejia river, are within the Auyo Local Government Area (LGA) of Jigawa State. Their locations are illustrated in Fig. 1. The state, which is in the northern part of the country, covers an area of about 22,210 km^2 or about 2.2 million hectares and lies between latitudes 10°57' N and 13°' 03' N and longitudes 8°08' E and 10°37' East. The communities were purposely selected based on their location in the Hadejia Valley Irrigation Scheme, where the uncontrolled

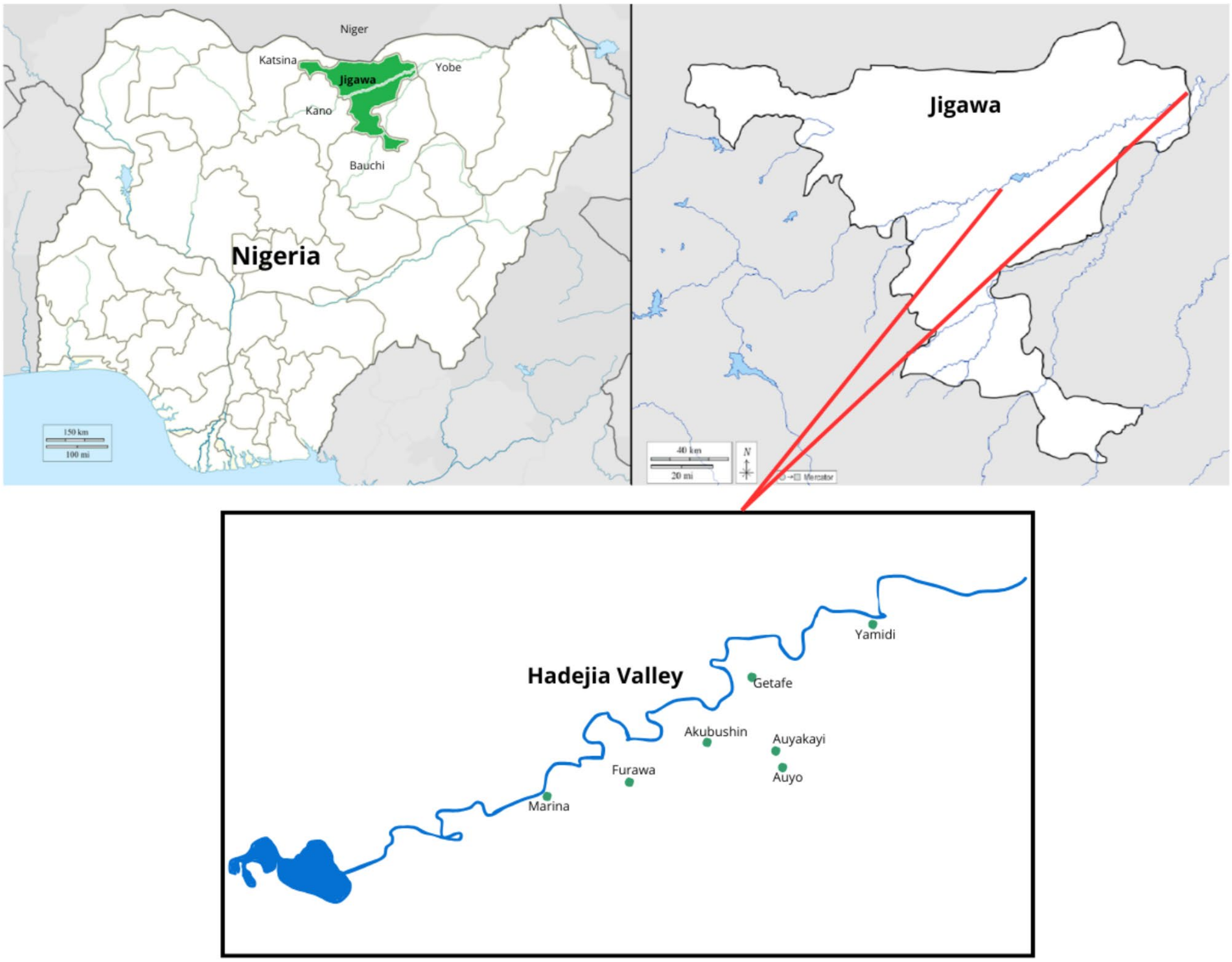

Fig. 1. Location of the Hadejia Valley Irrigation District within Jigawa State, Nigeria. The top-left panel shows Nigeria with Jigawa State highlighted (base map from D-Maps, © 2007–2025: https://d-maps.com/carte.php?num_car=112862&lang=en). The top-right panel provides a zoomed-in view of Jigawa State (D-Maps, © 2007–2025). The bottom panel illustrates the Hadejia Valley and surveyed communities, redrawn and adapted from Elufioye[37], Modifications include redrawing the map to highlight the surveyed communities and improving visual clarity."

growth of *Typha spp*. poses a major threat by blocking water infrastructure and canals, thereby increasing flood risk. The population is mainly made up of Hausa and Fulani ethnic groups.

In the Hadejia Valley, as in other parts of Nigeria, polygamy is a culturally accepted and widely practised custom; the ability to maintain several wives is seen as a symbol of status and wealth. Thus, a household usually includes the husband, his wife or wives, children and any other people who live and share food with them. On average, households are made up of between 10 and 11 persons. Household size determines the available labour force to be employed in carrying out production activities. The primary source of labour supply for the typical peasant household, which is labour-intensive, is family labour.

Some activities are practically reserved for men, such as caring for the cows or cleaning *Typha spp*. in the water canals and farming areas. Women's work is concentrated in household activities such as cleaning, childcare, and food preparation. These roles are shaped by cultural practices such as purdah, which involves the segregation of women from public life, limiting their mobility and interactions outside the home[38]. Furthermore, women frequently have restricted property rights. Hausa society maintains a clear delineation between the roles of men and women, which generates distinct social dynamics for each gender. Despite these limitations, women actively participate in economic activities and create networks among themselves, including generating financial independence and a deep awareness of their environment[39,40].

The data collection process was conducted in two phases and was designed and implemented in collaboration with the National Agricultural Extension and Research Liaison Services (NAERLS). This institution has had extensive experience with the local communities of the study area for decades and are familiar with the irrigation project, the invasion problems posed by T*ypha spp*. and, as partners in this World Bank project (PHA Project-*Developing economic uses of Typha spp*., is an action research component of TRIMING (Transforming Irrigation Management in Nigeria), funded by the World Bank, 2017–2020. PI: Eva Iglesias.), were also involved in developing and testing the proposed *Typha spp*.-based technology. In recognition of the importance of participant comprehension of the novel technology, during the questionnaire, visual support material was presented to the respondents to facilitate information and understanding. The entire process, from the design of the questionnaire to the administration of the survey, was meticulously overseen by a team trained in collaboration with NAERLS.

In the first step, focus group discussions were conducted to support the design of the field survey, engage stakeholders in project implementation and ensure that bottom-up ideas were considered in the project's development and technology adaptation phases. A workshop was organised to provide local communities with information about the use and advantages of biogas for cooking purposes. After the workshop, focus group discussions were conducted aimed at identifying household perceptions, assessing the potential demand for *Typha spp*.-based biogas technology and defining strategies and incentives to promote the adoption of new uses of *Typha spp*. A deliberate effort was made to involve women actively, giving them a voice in these discussions and recognizing their role as primary users of this technology. Five focus groups were formed from the 54 attendees, including community leaders and potential beneficiaries. Men and women were divided into separate groups for cultural reasons: 12 men comprised one group, while 42 women formed four groups with 9 to 13 members[40]. Different perceptions and concerns between women and men were identified during the focus group discussions the regarding the current energy sources in the home and the community.

The approach was to capture the perspectives of women, the primary users of the biogas technology. The information obtained in this way served as the basis for designing the questionnaire, which is structured into five sections: Personal and family data, perceptions on *Typha spp*. invasion and impact, decision-making and collective action, energy sources, and adoption of *Typha spp*.-based biogas technology. The sample size was calculated using G*Power software[41]. A power analysis was set up considering an Odds ratio of 2.5, a significance level (α err prob) of 0.05 and a desired power (Power (1-β err prob)) of 0.80. This resulted in a minimum required sample size of 59 observations. We made an effort on persuading households to participate, being able to interview 150 different randomly selected households within a list of 2000 households registered in the water users association.

The survey itself was conducted at the household level, with the head of the household—typically a man—and his wife or wives being interviewed separately. This approach was intended to capture both, male and female perspectives without mutual influences in their responses. The surveys were administered in two periods. The first was in June and July 2019. Due to the emergency arising from COVID-19, the completion of the surveys had to be postponed. Therefore, in May 2020, the rest of the surveys were administered. A total of 365 interviews were conducted, face-to-face and computer-assisted, 217 for women and 148 for men, corresponding to 150 different households.

The model specification can be found in the Supplementary material.

Results and discussions

Several problems regarding the current energy sources at the home and the community have been identified during the focus group discussions. Women consulted about this issue mentioned smoke and its effects on health as the most critical problem, followed by the problematic use of wet firewood during the rainy season. In contrast, men consider the high cost of energy to be the most significant problem[40]. Our model results provide deeper insights on the role of women and the key factors driving adoption.

The variables used in our empirical models are described in Table 1, while Table 2 presents the descriptive statistics of these variables. For ease of comprehension, we have grouped the independent variables into four distinct categories: demographic, cooking sources and practices, perception of *Typha spp*. invasion and culture. Given that a significant aspect of the study involves identifying disparities between men and women concerning the factors influencing biogas adoption, gender-based distinctions are systematically accounted for across all categories.

Variable	Description
Adoption	Biogas adoption (1 if yes, 0 otherwise)
WTP	Willingness to pay for cooking (NGN/day)
Gender	Gender (1 = female, 0 = male)
Age	Respondent age
Household size	No of members in the household
Income	1 if high income, 0 otherwise
Cooking time	Time spent cooking (hours/day)
Biomass	Cooking with biomass (1 if yes, 0 otherwise
Cooking concerns	Concern about change in the way of cooking, 1if yes, 0 otherwise
Typha abundant	Typha abundance near household, 1 if yes, 0 otherwise.
Workshop	Attendance at inception workshop (1 if attended, 0 otherwise)
Decision power	1 if yes, 0 otherwise
Togetherness	Considers the community to be united 1 if yes, 0 otherwise
After lunch	1 if the interview took place after lunch, 0 = before lunch (control variable)
Same gender	1 if the gender of the respondent is the same as the gender of the interviewer, otherwise 0 (control variable).

Table 1. Variables.

	Total			Female			Male		
Variable	Obs.	Mean	Std. Dev.	Obs.	Mean	Std. Dev.	Obs.	Mean	Std. Dev.
Adoption	365	0.72	0.45	217	0.74	0.44	148	0.70	0.46
WTP	365	144.93	127.45	217	145.16	130.66	148	144.59	123.05
Age	365	0.59	0.49	217	42.38	10.24	148	46.41	10.33
Household size	365	44.01	10.45	217	10.80	6.17	148	10.96	4.18
Income	365	10.86	5.45	217	0.33	0.47	148	0.46	0.50
Cooking time	365	0.06	0.243	217	5.63	7.26	148	3.85	4.30
Biomass	365	6.29	4.08	217	0.74	0.57	148	0.44	0.50
Cooking concerns	365	0.67	0.469	217	0.75	0.43	148	0.68	0.47
Typha abundant	364	0.72	0.45	217	0.25	0.44	148	0.32	0.47
Workshop	364	0.28	0.451	217	0.29	0.45	148	0.41	0.49
Decision power	365	0.34	0.473	217	0.73	0.44	148	0.81	0.39
Togetherness	365	0.28	0.45	217	0.89	0.31	148	0.82	0.39
After lunch	365	0.45	0.50	217	0.48	0.50	148	0.41	0.49
Same gender	365	0.76	0.43	217	0.88	0.32	148	0.58	0.49

Table 2. Descriptive statistics.

The estimation of households' WTP for Typha spp. biogas is divided into two stages: the first stage ascertains whether or not participants are willing to adopt the biogas (asked individually); while the second stage determines the value households would be willing to pay. For the first stage, the dependent variable is a binary variable obtained through the question: "*Would you consider using biogas for cooking in your household?*". We found that 72% of the respondents are WTAd biogas for cooking (Table 2). Per gender, 73% of women (70% of men) are WTAd biogas. For the second stage, a payment card-type question is asked to elicit their WTP. In particular, the question states, "*How much would you be willing to pay to get enough biogas for cooking your everyday meals*?" The mean WTP of women who are willing to adopt (WTAd) is NGN 196.87 per day, representing 73% of the total sample. Of the 70% of men who indicated a WTAd, the mean daily payment amount was slightly higher, NGN 209.

Demographics

The questionnaire contained a section about the sociodemographic situation of the respondent's household. First, the man and the woman/ women of the same household were interviewed. Since these are polygamous households, 59% of the participants are women. In terms of household size, the average number of household members is 10. The question about participants' monthly income were presented in categories to prevent non-response (< NGN50,000; NGN50,000 - NGN150,000; NGN151,000 - NGN200,000; NGN201,000 - NGN250,000). To make the variable more operational, income was coded as 0 or 1, with 1 indicating monthly household income in the highest income range and 0 otherwise. Binary coding was selected as the method of analysis to facilitate the comparison between higher-income households and the remainder of the sample, thereby allowing for a more straightforward interpretation of the impact of income level on WTP. Since women often do not have complete information on household income, this type of payment-card coding allows women's perceptions of household income to be gathered. The final variable in this category was age: the average age of the participants was 42 for women and 46 for men.

Cooking sources and practices

Wood (67%) and charcoal (36%) are the primary energy sources, with 75% of the population having no access to electricity. To better understand households' WTP for biogas to cook their daily meals, it is essential to understand the household's cooking practices. On average, women—the primary cooks—spend six and a half hours a day preparing food. Biomass, the region's primary energy source, is used for cooking by 67% of households. Previous studies[42,43] have found that the low level of adoption of clean cooking technologies is related to the fact that they are not adapted to people's needs and habits. Therefore, participants were asked "*Are you concerned that the adoption of Typha spp.-based biogas could change your current way of cooking*?" (*Cooking concerns*); 72% of those surveyed responded that one of the concerns about biogas is that it changes the way people cook with firewood. This could prove to be a major impediment to the adoption of the technology.

Perceptions of the *Typha spp*. Invasion

Since the biogas being offered is based on *Typha spp*. biomass, the analysis accounts for whether participants live near the *Typha spp*. invasion problem (Typha Abundant). We hypothesise that those households close to the areas colonised by *Typha spp*. will be more willing to adopt biogas. Hence, scaling up this technology and enabling the use of Typha spp. biomass to produce biogas for their daily cooking could introduce an economic incentive to clear *Typha spp*. from invaded areas. In this respect, 28.2% of the people interviewed consider that there is an abundant amount of *Typha spp*. near their home.

Culture and gender

Culture, understood as a set of shared values and informal norms that guide interactions and practices within a community, plays a crucial role in social cohesion and the adoption of new technologies. Uzuegbunam and Geringer (2021)[44]highlight the notion that culture functions as a set of unwritten rules that not only shape individual behaviour, but also affects economic success and innovativeness within communities. In the context of the Hadejia Valley, cultural influence is particularly evident in family structure and gender divisions. The traditional roles assigned to men and women largely determine social and economic dynamics. We used *Togetherness/closeness* as an indicator of the cultural component, reflecting these shared values and social cohesion within the communities. Respondents were asked, "*Do you consider that you are close to your village?*" *(Togetherness)*; 86% responded affirmatively, reflecting the important bonds among community members.

The decision to adopt technology is related not only to the potential economic benefits but also to various factors that influence household dynamics. Households go through a complex process to make the decision whether to adopt, given that they are made up of multiple individuals with heterogeneous preferences and degrees of empowerment[45]. A common factor mentioned in previous studies is women's limited access to resources. Since men are the providers of economic resources, they generally dominate decision-making in the household[46–48]. Furthermore, the deeply entrenched cultural norms prevalent in numerous rural communities serve to reinforce traditional gender roles, thereby further constraining the participation of women in pivotal decision-making processes concerning the adoption of novel technologies. Since women may have limited decision-making capacity and little access to financial resources, the following question was formulated, "*Do you feel that you have the power to make important decisions that affect the household (i.e. investments or purchases of goods?"* (*Decision power*). An affirmative answer was given by 76.5% of respondents (corresponding to 73% of women and 81% of men). This is a proxy of how feasible it is for women to participate in the decision-making process of adopting a technology that they are much more likely to use. While the majority of womenresponded affirmatively, still the proportion is 8 points below men's.

Prior to administering the questionnaire, an informative and participatory demonstration workshop was held to provide an understanding of how the technology works. This served as a means to disseminate knowledge about the technology; therefore, respondents were asked about their attendance at this event.

Additional control variables

Additional control variables were included to account for potential biases and confounding factors that could affect the results. Specifically, we controlled for the time of the day when the interview took place (*AfterLunch*) and the gender match between respondent and interviewer (*SameInterviewer*). These variables help to isolate the effects of the primary independent variables by reducing the impact of external factors such as interview fatigue or gender bias during the data collection process, thereby increasing the robustness and validity of the results.

The Heckman two-step model was employed to assess the factors influencing biogas adoption and WTP, using STATA software (version 17, StataCorp). To ensure robustness, we applied bootstrap resampling for standard errors. Given that the pooled and female only models involved more than one individual per household, we clustered standard errors by household to account for potential within-household correlation.

To further validate the robustness of the results, a logistic regression (Table S1) and an interval regression model (Table S2) are included in the *Supplementary Material*. These analyses complement the Heckman model and ensure consistency across different methodological approaches.

The results of the Heckman model are presented in Table 3. The pooled model results, where both men and women are included, are reported in the first column. The female only and male only results are provided in the second and third columns, respectively. This approach enables us to evaluate the factors influencing the willingness to adopt and pay for biogas while also identifying trends that differ between males and females. The inverse Mills ratio (IMR) coefficient is significant and positive for the women's model, meaning that a positive

		Total	Female	Male
Adoption (selection equation)	Gender (1 = female, 0 = male)	0.337** (0.176)		
	Age	0.009 (0.010)	0.14 (0.009)	0.007 (0.015)
	Household size	0.024 (0.016)	0.029 (0.031)	−0.014 (0.037)
	Income	−0.127 (0.242)	0.404 (0.562)	−0.558 (0.425)
	Cooking concerns	−0.349* (0.204)	−0.422* (0.225)	−0.186 (0.323)
	Cooking time	0.077*** (0.022)	0.097*** (0.036)	0.068 (0.041)
	Typha abundant	0.635*** (0.239)	0.209 (0.327)	0.891* (0.499)
	PowerImportant decison	0.600*** (0.166)	0.794*** (0.256)	0.547* (0.298)
	Togetherness	0.489* (0.259)	0.122 (0.406)	0.679* (0.359)
	AfterLunch	0.068 (0.159)	−0.433 (0.273)	0.795* (0.417)
	Same gender	−0.279 (0.230)	-0.372 (0.249)	−0.142 (0.393)
	Constant	−1.261** (0.622)	-0.677 (0.697)	−1.265 (0.908)
WTP (output equation)	Gender (1 = female, 0 = male)	−8.949 (16.121)		
	Household size	2.948*** (0.941)	2.159 (1.765)	5.869*** (2.313)
	Income	13.434 (16.671)	16.991 (24.31)	61.739** (29.998)
	Cooking time	3.538** (1.693)	6.467** (2.822)	1.715 (2.191)
	Biomass	24.007* (12.94)	18.592 (15.83)	16.576 (23.226)
	Typha abundant	−36.67*** (14.155)	−52.73*** (19.837)	−61.117** (30.775)
	Workshop	56.886*** (18.188)	77.11*** (23.067)	15.858 (24.636)
	AfterLunch time	−21.498 (14.671)	−52.64** (20.971)	−33.532 (26.085)
	Same gender	−14.938 (14.033)	−16.547 (20.71)	−0.142 (0.393)
	Constant	138.245*** (31.635)	114.22** (45.302)	−1.266 (0.908)
	Lambda	38.33 (28.438)	113.77*** (44.022)	−61.175 (48.183)
	Rho	0.383	0.938	−0.659
	Number of observations	365	217	148

Table 3. Heckman selection model – two-step estimated models. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

selection bias exists, i.e., without the bias selection correction, the coefficient α from the WTP equation would have been upward-biased. In the case of men and the pooled sample model, the selection bias is not significant. There is a significant correlation between first adoption decision and women's WTP, indicating that this is conditional on their willingness-to-adopt.

Gender-differentiated analysis reveal that selection bias in women may be related to their internalisation of questions about technology adoption due to its potential impact on their daily lives. However, it is possible to calculate men's adoption and willingness-to-pay equations independently, as they may not fully recognise the benefits of technology in their context.

Selection equation

The selection equation evaluates whether the respondents are willing to adopt biogas for cooking their daily meals. The characteristics influencing the willingness to use biogas produced with *Typha spp*. are captured. It can be observed that *Gender*, *Decision Power (DP)*, *Typha*, *Cooking time*, *Cooking concerns*, and *Togetherness* are significant variables in the selection equation for the pooled model while *Decision Power*, *Cooking time* and *Cooking concern*s are significant in the women's model. In contrast, for men, *Typha spp. abundant*, *Decision Power*, *Togetherness* and the control variable *AfterLunch* are significant.

The G*ender* of the respondent in the pooled model is significant at $p < 0.05$, indicating that women are more likely to be willing to adopt biogas than men. Studies such as those by Agurto Adrianzen (2009)[49] and Kelebe et al. (2017)[50] have found that female-headed households tend to adopt more biogas technology. The latter authors contend that since women and children are involved in firewood collection and strenuous domestic work, it makes sense that females would be more interested in adopting biogas. Conversely, Kabyanga et al. (2018)[51] and Jan and Akram (2018)[2] report that households with female heads are less likely to adopt the technology. A common factor mentioned in the studies is women's limited access to resources; since men are the providers of economic resources, they generally dominate decision-making in the household[46–48].

Our results reveal that cultural variables are important determinants of adoption but show significant differences among models. *Decision power* and *Togetherness* are significant and positive in the pooled model. *Decision power* is positive and significant in all three models. This is especially important in the women's model as it implies that those women who feel they have the power to make important decisions within their household are more likely to adopt biogas, while women who feel they do not have a say in their household decisions show less interest in adoption. In this rural context, men usually make the important decisions within the household. The decision-making power dynamic can affect the adoption of biogas, as the person with more decision-making power may not prioritise its purchase. Several studies show that women in communities where men traditionally assume a dominant role tend to have limited decision-making power in important matters, whereas it is more common for them to participate in small, everyday decisions[45,52,53]. According to Yasmin and Grundmann (2020)[45], only 10% of women in their study stated that they played an important role in the decision-making about adopting biogas, while 23% of women reported that they were not consulted in the process. The power to make decisions is closely related to financial resources, where males typically have more decision-making power[48]. Recent studies[54,55] find that households where women participate in decision-making are likelier to adopt the technology than households where a man is the sole decision-maker. In most African traditions, the relationship between men and women significantly impacts the adoption and use of the type of technology and the WTP for it[51]. Consequently, facilitating access to finance or subsidies for women could increase the adoption of *Typha spp*.-based biogas for household cooking[44].

The perception of *Togetherness* among community members is positive and significant at $p < 0.10$ in the pooled and male model. This may be related to the fact that in many rural cultures, community cohesion is a core value that drives members to act collectively, especially in risky contexts such as the adoption of new technologies. Trust or *Togetherness* is necessary for cooperative behaviours[56–58]. High connectivity can act as a catalyst in the diffusion of new ideas and technologies, facilitating adoption when early adopters have a positive experience.

Typha abundance is positive and significant at $p < 0.01$ in the pooled model. This indicates that people living in places with a lot of Typha spp. are more likely to respond positively to adoption. This makes sense since this abundance facilitates the collection of the feedstock needed to generate the biogas. In addition, adopting the technology can provide an economic benefit and may help to alleviate the problems caused by the invasion of Typha in nearby areas. In models differentiated by gender, this factor is significant only for men. This can be explained by the fact they are the ones who do the work of cleaning *Typha spp.* from the irrigation canals, their lands and other common areas.

Regarding the main activity for which biogas would be used, cooking, the variables *Cooking time* and *Cooking Concerns* are statistically significant in the joint and women model. The more time spent cooking (*Cooking time*), the more likely people are to be WTAd biogas technology. Cooking is one of the most time-consuming tasks, spanning the process from collecting firewood to getting and cooking the food. Compared to firewood, less time and effort is required to cook with biogas technology[59]. The adoption of biogas can thus give users freedom, especially women, freeing up time to spend on other types of activities.

However, a common concern about changes in cooking technology is whether this will allow for the same taste and way of cooking. Both in the joint and women´s model, it can be observed that the more importance respondents assign to this aspect (*Cooking concerns*), the less willing they are to adopt. The use of firewood is not only associated with difficulty accessing clean cooking technologies; it is sometimes related to cultural traditions. For example, Troncoso et al. (2019)[43] find that people in Chiapas, Mexico, prefer to continue cooking with firewood even if they have an LPG stove, since they say that the food tastes different.

In regard to the control variables, the results indicated that the variable *After Lunch* was statistically significant for the male model, indicating that the timing of the interview may have an influence on responses. In this case, interviews conducted after lunch appeared to elicit a greater WTAd biogas among male respondents.

Outcome equation

The outcome equation for biogas analyses the factors influencing the differences in WTP. Six predicted variables and two control variables are considered.

The positive relationship between Household s*ize* and WTP is significant for the pooled and male models. When households are made up of more members and a lot of time is spent cooking, individuals declare a higher WTP for biogas. In the case of improved cookstoves in Nigeria, Onyekuru et al. (2021)[60] find the same positive relationship between household size and WTP; as more people need to be fed in the households, they are looking for effective and efficient means of cooking. In our study, when it comes to time spent cooking (*Cooking time)*, men do not seem to perceive the same burden as women, as this variable is not a significant factor for men's WTP.

The male model showed a significant and positive correlation with high-income (*Income)* households ($p < 0.05$). This indicates that males from households with higher incomes are more likely to pay for biogas, probably due to their greater financial capacity and lower risk aversion, which allows them to invest in new technologies. This finding confirms a broad consensus that income is one of the determinants of adoption in developing countries[61–64].

Cooking with *Biomass* is significant and positive for the pooled model, with those who use firewood to cook reporting a higher WTP. If households use a large amount of biomass, they may perceive biogas as a cheaper alternative. Lindgren (2020)[65] reports that more than 30% of a household's monthly income is spent on buying firewood and charcoal. Perceptions of biomass use differ by gender; women may prefer biogas for health benefits and reduced workload, while men may view it as a way to save fuel. The World Bank (2019)[66] emphasizes showcasing the agricultural and financial benefits of biodigesters in areas where firewood is predominant to attract men's interest. The presence of *Typha spp*. near homes could make biogas a more accessible alternative, especially since men, who usually clear invaded lands, might be motivated by the potential benefits of biogas production. In relation to this, the variable *Typha spp*. is statistically significant in a negative sense in all three models. This implies that WTP declines in response to a perceived abundance of the raw material *Typha spp*. This perception may lead to the expectation that Typha spp.-based technology should be more economically accessible, given that the feedstock is readily available.

Attending the Inception *Workshop* carries a significant and positive effect in the pooled model and female model. Attending the demonstration of biogas use helps make people willing to pay more; this may be because they have received information on the operation and use of biogas. Other studies also find that information is a determinant of increased WTP; for example, Soon and Ahmad (2015)[67] report that residents of urban households have higher WTP for renewables, as they have more information, awareness and exposure to these technologies. As various studies demonstrate, information and experience in the use of the technology are important factors in the decision to adopt; they should be a central pillar in technology implementation and scaling plan for both men and women.

In relation to the designated control variables, the only variable that has been found to be of significance is AfterLunch in the women's model, with a negative effect. This suggests that interviews conducted after lunch could influence participants' responses, potentially due to factors such as fatigue, tiredness or lower concentration, which could result in a lower assessment of WTP.

In general, the results from all the three models reveal consistent patterns, showing that biogas is perceived as a desirable technology, particularly by those concerned about the cooking time with traditional practices and those who hold decision-making power within the household. Additionally, larger households and those who gained more information by attending the workshop are more willing to pay for this new technology.

Conclusions

Very little is known about energy transition decisions in remote areas of developing countries. This study analyses the WTAd and pay for biogas produced from the invasive *Typha spp*. plant in northern Nigeria, in the Hadejia Valley Irrigation District. *Typha spp*. biogas is a nature-based solution which converts the threat of an invasive plant into an opportunity to improve the livelihood of local communities. Our analysis reveals that a considerable number of people are willing to adopt biogas (72%). The main factors that aree found to motivate the WTAd are *Gender*, the abundance of nearby *Typha spp.* in the area, the *Cooking time* the feeling of *Togetherness* in the community and *Decision power*. Among the factors that discourage adoption, we find that women have cultural concerns about changing their traditional way of cooking.

The assessment of WTP reveals that a number of variables were found to be positively correlated with higher WTP, including household size, time spent preparing food, biomass use, and attendance at informative workshops. This emphasises the necessity of providing comprehensive information and designing technologies that align with the specific requirements of users, which can enhance the adoption and sustained utilisation of biogas.

The results of this study emphasize the need of undertaking a gender-differentiated analysis when implementing technologies that affect all members of a household, particularly in contexts where cultural factors restrict the involvement of specific groups, as is the case for women in the region under study. Including both men and women in the survey enabled the capture of different perceptions within the household and the identification of discrepancies that could influence effective technology adoption.

The findings indicate that economic factors, such as household income, do not consistently serve as the primary determinant in the decision to adopt biogas and in the WTP for this technology. However, in the male model, income plays a significant role in influencing WTP, indicating that a higher level of household income may increase the likelihood that men are willing to invest more in biogas. This finding is supported by the observations made by some of the participants in the information workshops, who highlighted the high cost and low quality of the fuelwood currently available. These comments indicate that, for men, one of the perceived benefits of biogas is the reduction of energy expenditure in the kitchen. This reinforces their willingness to pay more for an alternative that improves the household economy.

The results indicate that women are more likely to adopt biogas for cooking than men. This may be attributed to the fact that the use of biogas for cooking is directly related to their daily work. This highlights that the benefits and concerns associated with the technology may vary according to their relationship with it and their environment.

Another area of focus is the impact of decision-making authority within the household on the uptake of new technologies. The findings suggest that women with greater power on decision-making are more likely to adopt biogas, which underscores the significance of promoting equal participation in decision-making processes. Furthermore, the prevalence of *Typha spp*. in close proximity to households enhances the likelihood of biogas adoption. Obtaining biogas does not entail an additional burden but rather represents an efficient utilisation of available resources.

One of the primary obstacles to the adoption of biogas for cooking is the necessity for users to alter their traditional cooking methods, which can lead to resistance. To overcome this barrier, it is essential that government and local organisations adopt a collaborative approach in designing the technology to suit the needs and preferences of end-users, which would facilitate uptake. Indeed, our findings indicated that participants who attended the pre-survey workshops demonstrated a higher WTP, which highlights the importance of creating spaces for dialogue and providing the necessary information so that users can make informed decisions and thus ensure the sustainable use of the technology.

In terms of public policy, there is a need to consider the provision of subsidies to women with the aim of increasing their decision-making power in the adoption of biogas, thereby promoting their empowerment in energy and sustainability issues. Furthermore, it is crucial to establish spaces for dialogue between communities, organisations and the government with a view to adapting the technology to local needs. Finally, the creation of local cooperatives for *Typha spp*. management has the potential to generate economic opportunities and strengthen sustainable development.

As future lines of research, it would be important to conduct longitudinal studies to fully understand the sustainability and long-term impact of biogas adoption. These studies would facilitate the observation of how perceptions, challenges and benefits related to the technology evolve, thereby providing a more comprehensive and accurate picture of its effectiveness and adaptability in different contexts.

Finally, we conclude that facilitating access to affordable clean energy based in natural local resources can positively impact multiple aspects in communities, such as health, poverty, gender equality, the environment and the climate. Both governmental and non-governmental interventions must reflect the gender realities present in communities to adequately address the specific needs and capacities of men and women, and thus enhance the benefits for the community as a whole.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Received: 10 April 2024; Accepted: 21 February 2025
Published online: 01 March 2025

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Author contributions

Conceptualization: EI, ML; Data curation: RT; Methodology: EI, ML, RT; Formal Analysis: RT; Supervision: EI, ML; Writing – original draft: RT; Writing – review & editing: EI, ML, RT; Funding acquisition: EI.

Funding

TYPHA Project-Developing economic uses of Typha spp. is an action research component of TRIMING (Transforming Irrigation Management in Nigeria), funded by the World Bank, 2017–2020. IP: Eva Iglesias; and Universidad Politécnica de Madrid. Africa Platform 2019-2020.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-91637-1.

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