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EDITED BY
David M. Butler,
The University of Tennessee, Knoxville, United States

REVIEWED BY
I. Made Wahyu Wijaya,
Universitas Mahasaraswati Denpasar, Indonesia
Putri Ayu Ika Setiyowati,
Airlangga University, Indonesia

*CORRESPONDENCE
Jabulani Nyengere
jnyengere@must.ac.mw

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Beyond the bottle: factors affecting adoption of liquid urine fertilizer among smallholder farmers in Southern Malawi

Jabulani Nyengere[1]*, Tiwongwe Mzumara[1], Harineck Tholo[1], Allena Laura Njala[1], Chikondi Chisenga[1], Tabitha Nindi-Chigwe[1], Weston Mwase[2], Stanly Mataka[3], Ololade Latifat Abdulrahman[4], Judith Adejoke Falola-Olasunkanmi[5], Ruth Wambui Wainaina[6], Jacquiline Ndosi[7], Ato Fanyin-Martin[8], Enoch Kwame Tham-Agyekum[9], Agnes Kapinga[10], Boineelo Pearl Lefadola[11], Lubobi Ferdinand Shamala[12], Gabriel Kanuti Ndimbo[13], Juliana Jepkemoi Cheboi[14], Mayamiko Chisale[15] and Precious Masuku[16]

[1]Ndata School of Climate and Earth Sciences, Malawi University of Science and Technology, Limbe, Malawi, [2]Lilongwe University of Agriculture and Natural Resources, Bunda Campus, Lilongwe, Malawi, [3]Department of Crop Development, Ministry of Agriculture, Irrigation and Water Development, Lilongwe, Malawi, [4]Department of Agricultural Economics and Extension Services, Kwara State University, Malete, Nigeria, [5]Department of Crop Production, Kwara State University, Malete, Nigeria, [6]African Center for Technology Studies, Nairobi, Kenya, [7]Mwalimu Nyerere University of Agriculture and Technology, Butiama, Tanzania, [8]Department of Chemical and Petrochemical Engineering, School of Petroleum Studies, University of Mines and Technology, Tarkwa, Ghana, [9]Department of Agricultural Economics, Agribusiness and Extension, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, [10]Department of Agricultural Economics and Business, University of Dar es Salaam, Dar es Salaam, Tanzania, [11]Department of Family and Consumer Sciences, University of Botswana, Gaborone, Botswana, [12]State Key Laboratory of Tea Plant Biology and Utilization, Anhui Agricultural University, Hefei, China, [13]Faculty of Humanities and Social Sciences, Mkwawa University College of Education, Iringa, Tanzania, [14]Department of Plant Science and Crop Protection, University of Nairobi, Nairobi, Kenya, [15]Ministry of Agriculture, Irrigation and Water Development, Department of Agricultural Research Services (DARS), Bvumbwe Agricultural Research Station, Limbe, Malawi, [16]Word Alive Commission for Relief and Development, Word Alive Ministries International, Blantyre, Malawi

Introduction: The growing demand for affordable and sustainable soil fertility solutions in sub-Saharan Africa has renewed interest in human-derived organic inputs such as urine fertilizer. Despite its agronomic potential, uptake among smallholder farmers remains limited. This study examines the factors shaping awareness, adoption, and intensity of urine fertilizer use among smallholder farmers in Southern Malawi.

Methods: Data were collected from 251 smallholder farmers, all of whom were members of at least one organized farmer group, reflecting the strong institutional embeddedness of rural agriculture. A Triple-Hurdle Model was employed to sequentially analyze the determinants of awareness, adoption conditional on awareness, and intensity of use conditional on adoption. Descriptive statistics complemented the econometric analysis.

Results: Descriptive findings showed that 46 percent of farmers were aware of urine fertilizer, while 32 percent had applied it. In the first hurdle, education level and extension contact significantly increased awareness, whereas odour concerns significantly reduced it. Conditional on awareness, adoption was positively influenced by extension contact and farm size, while perceived costs and odour concerns emerged as key deterrents. The Inverse Mills Ratio was negative and statistically significant, confirming the presence of selection bias between awareness and adoption. In the third hurdle, intensity of use increased with extension contact, farm size, and poultry ownership, but declined significantly with odour-related concerns.

Discussion: The results indicate that while farmer organization enhances information access, actual uptake and sustained use of urine fertilizer depend on effective extension engagement, household resource endowments, and perception management. Addressing sensory concerns and cost perceptions is critical for scaling adoption. Policy interventions should prioritize demonstration-based learning, odor-mitigation strategies, and the integration of urine fertilizer into circular bioeconomy frameworks that link sanitation and agriculture.

KEYWORDS

circular bioeconomy, extension services, smallholder farmers, sustainable agriculture, triple-hurdle model, urine fertilizer adoption

1 Introduction

In the pursuit of sustainable agricultural systems and enhanced food security, a major challenge in developing countries, particularly in Sub-Saharan Africa, remains the high cost (Tapsoba et al., 2020) and limited access (Wang, 2022) to conventional mineral fertilizers. Smallholder farmers, who constitute the backbone of the agricultural sector in nations like Malawi, are often trapped in a cycle of low yields and poverty due to their inability to afford these essential inputs (Martignoni et al., 2022). The reliance on expensive chemical fertilizers not only poses a significant economic burden but also raises environmental concerns related to soil degradation (Kabeyi and Olanrewaju, 2022) and nutrient runoff (ÓhAiseadha et al., 2020). Consequently, according to Klassen and Vreysen (2020), there is a growing imperative to explore and promote innovative, low-cost, and environmentally natural based friendly technologies that can improve agricultural productivity while simultaneously addressing sanitation needs.

Ecological Sanitation (Ecosan) toilets have emerged as a promising technology designed to address both public health and environmental challenges by transforming human waste from a disposal problem into a valuable resource (Verhagen and Scott, 2019). The fundamental principle of Ecosan systems is the closure of the nutrient loop, which safely recovers and reuses the valuable components of human waste, thereby mitigating environmental pollution and promoting sustainable agriculture (Mariwah, 2017). A key technological feature of these systems is the urine-diversion mechanism, which separates urine from feces at the source. This separation is paramount because urine, which comprises a large portion of human waste, is the primary reservoir of essential plant-available nutrients (Yalin et al., 2023). Specifically, it is rich in nitrogen (N), phosphorus (P), and potassium (K), which are the three macronutrients vital for crop development and soil fertility. The collected urine can be processed and used as a liquid fertilizer, offering a sustainable and locally sourced alternative to synthetic fertilizers (Qadir et al., 2020). Meanwhile, the separated feces are treated through processes like dehydration or composting to create a safe source of nitrogen, further contributing to a circular economy model. This integrated approach not only improves sanitation but also enhances food security and reduces reliance on resource-intensive agricultural inputs. Ecological sanitation systems rely on source separation to reduce health risks associated with human excreta reuse. Urine is generally considered to pose lower microbiological risk than feces due to its typically low pathogen load at excretion. However, under real world field conditions, the effectiveness of urine diversion is highly dependent on system design, user compliance, and maintenance practices. Cross contamination between urine and fecal matter may occur during collection, storage, transportation, or field application, particularly in resource constrained settings where infrastructure and hygiene protocols are inconsistently applied. Recognizing these practical risks is essential for accurately interpreting the implications of urine reuse in smallholder farming systems.

In Malawi, maize serves as the staple crop, and its yield is highly dependent on sufficient nitrogen availability (Dimkpa et al., 2023). However, smallholder farmers often face significant challenges in meeting the nitrogen demands of their crops due to the prohibitive cost of synthetic fertilizers (Petersen-Rockney et al., 2021). An effective and economically viable solution is the use of liquid urine fertilizer collected from Ecosan toilets. This alternative offers a readily available and potent source of nitrogen that is significantly more affordable than conventional fertilizers (Nkusi, 2018: Verhagen and Scott, 2019: Leblanc et al., 2019). According to Smith et al. (2022), this practice presents a promising avenue for resource-poor farmers to enhance soil fertility and increase crop yields without incurring substantial financial costs. Furthermore, this approach provides a dual benefit: it not only improves agricultural productivity but also contributes to better household sanitation and hygiene, thereby mitigating the spread of waterborne diseases (Leblanc et al., 2017). The potential of this technology is widely recognized within farming communities, with many farmers already aware of the benefits of using urine as a fertilizer.

While several studies have explored farmers' perceptions and attitudes toward the use of human urine as fertilizer in Malawi and other parts of sub-Saharan Africa, existing research remains limited in scope and depth. Previous works (François et al., 2019; Roxburgh et al., 2020; Lapozo and Mzuza, 2023) have identified safety perceptions, knowledge levels, and prior exposure as key determinants of adoption. However, these studies have largely offered descriptive insights without examining how these factors interact to shape farmers' decision-making processes in adopting liquid urine fertilizer. Moreover, although perceptions of health risks and cultural taboos have been recognised as major barriers, limited empirical attention has been paid to how social norms, trust in information sources, and experiential learning influence farmers' willingness to adopt urine-based fertilizers. Despite the increasing awareness and the clear economic and environmental advantages associated with urine fertilizer, adoption among smallholder farmers remains unexpectedly low (Mathobela et al., 2024). A significant disconnection persists between the perceived benefits of this technology and its practical application at the household and community levels (Nhamo et al., 2024). This low adoption rate continues to constrain the realisation of improved agricultural productivity and sanitation outcomes. The underlying reasons for this disconnect remain poorly understood, and the existing scientific literature lacks a comprehensive analysis of the contextual, socio-cultural, and institutional factors influencing adoption in southern Malawi.

Therefore, there is a pressing need for an in-depth study that integrates socio-economic, behavioral, and institutional perspectives to explain why awareness of urine fertilizer does not necessarily translate into its use. This study aims to fill this critical knowledge gap by rigorously analyzing the factors affecting the adoption of liquid urine fertilizer derived from ecological sanitation toilets by smallholder farmers in Malawi. The analysis will delve into a range of potential determinants, including socio-economic, cultural, institutional, and technical factors. By identifying and understanding these key drivers and barriers, the findings of this research will provide evidence-based insights necessary for designing and implementing sustainable, context-specific interventions to ensure the increased and widespread adoption of this innovative and beneficial technology.

2 Methodology

2.1 Study area and context

The study was conducted in Phalombe District under Traditional Authority (TA) Nkhulambe, situated in Southern Malawi (Figure 1). Phalombe is a predominantly rural district characterized by subsistence agriculture, which serves as the primary source of livelihood for the majority of households. The area lies within Malawi's semi-arid zone, receiving an average annual rainfall of approximately 800–1,000 mm, largely concentrated between November and April (Fiwa et al., 2025). Soils in the district are predominantly sandy loams with moderate fertility, making crop production highly sensitive to input availability and management practices (IUSS Working Group WRB, 2022). Most households in the study area cultivate relatively small parcels of land, typically less than one hectare, and depend predominantly on maize as the principal staple crop. Maize production is often complemented by legumes such as beans and groundnuts, as well as a range of horticultural crops that contribute to household nutrition and provide opportunities for income diversification. Livestock production remains limited in scale, with chickens and goats representing the most common species kept under mixed crop–livestock systems. These animals play an important role in nutrient recycling, income generation, and food security. In recent years, Phalombe has become a focal area for agricultural innovation and adaptive research, particularly in sustainable soil fertility management.

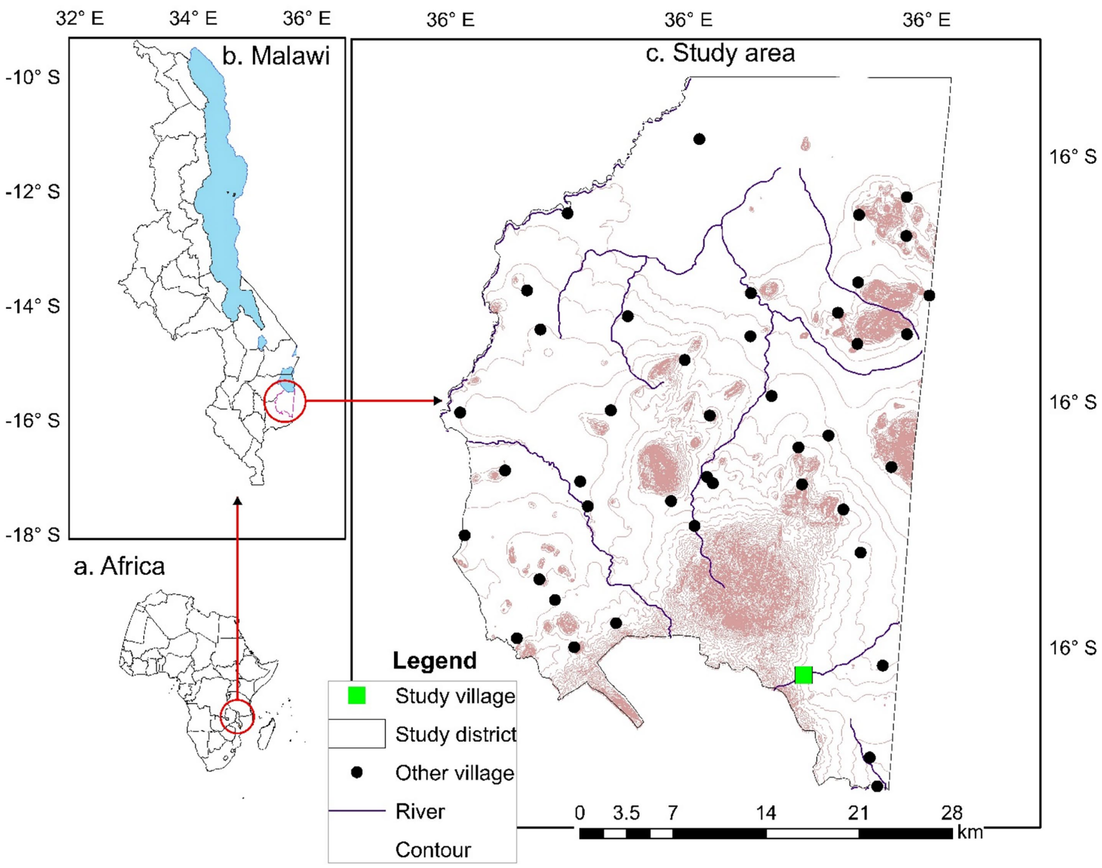

FIGURE 1
Map showing the study site for study village with respect to Africa (a) and Malawi (b) study area (c).

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Development initiatives and research programs have introduced and promoted the use of organic and locally available fertilizers, including urine-based formulations derived from ecological sanitation (Ecosan) systems. These interventions aim to address declining soil fertility, high costs of synthetic fertilizers, and the need for environmentally friendly alternatives suitable for resource-constrained smallholder farmers. The district thus provides a representative and dynamic setting for examining the socio-economic and institutional factors influencing the adoption of liquid urine fertilizer within smallholder farming systems.

2.2 Study design and sampling

A cross-sectional survey design was employed to examine household-level decisions regarding awareness, adoption, and intensity of urine-based fertilizer use. This design was appropriate because it enabled the collection of quantitative data capturing variations in technology exposure and behavioral outcomes among households during the main agricultural season, which in Phalombe District typically spans from November to April, corresponding with Malawi's unimodal rainy season that supports the country's primary rain-fed crop production system (Amosi and Anyah, 2024). The study was conducted among smallholder farmers under Traditional Authority (TA) Nkhulambe in Phalombe District, Southern Malawi. The sampling frame consisted of all households participating in organized farmer groups such as cooperatives, farmer field schools, and village savings and loan associations. These groups provided a well-defined list of active farmers and ensured representativeness of households engaged in community-based agricultural activities.

A stratified random sampling technique was adopted to capture variation across villages while maintaining proportional representation. Villages were first stratified based on population size and accessibility (proximal vs. remote), after which households were randomly selected from each stratum. Respondents were either household heads or principal decision-makers involved in agricultural production, ensuring reliability in responses related to farming practices and input decisions. The total sample size was determined using Cochran (1977) sample size formula for categorical data:

$$n_0 = \frac{Z^2 p(1-p)}{e^2}$$

where.

n_0= initial sample size,

Z= z-value corresponding to the desired confidence level (1.96 for 95% confidence),

p= estimated proportion of households with awareness of urine fertilizer (assumed 0.5 in the absence of prior data to maximize variability), and.

e= desired level of precision (0.06).

Substituting these values:

$$n_0 = \frac{(1.96)^2 \times 0.5 \times (1-0.5)}{(0.06)^2} = 266.8$$

To account for possible non-responses and incomplete questionnaires, a 10% adjustment was applied, yielding an effective target of approximately 270 households. The final realized sample comprised 251 completed interviews, representing a response rate of 93%, which is acceptable for field-based household surveys in rural contexts. This sample size ensured adequate statistical power for estimating parameters within the triple-hurdle econometric framework and allowed robust disaggregation by socio-economic and institutional variables.

2.3 Data collection

Primary data was collected through structured, face-to-face interviews administered by a team of trained enumerators. A comprehensive questionnaire was designed to capture detailed information on household demographic and socio-economic characteristics, land and livestock ownership, access to agricultural extension services, and farmers' perceptions of organic and urine-based fertilizers. In addition, the instrument included modules on awareness, adoption history, intensity of use, and perceived constraints associated with urine fertilizer application. To ensure validity and reliability, the questionnaire was pre-tested in a neighboring community with similar socio-economic and agro-ecological characteristics. The pilot exercise allowed for refinement of question wording, sequencing, and flow, ensuring clarity, cultural appropriateness, and consistency in interpretation across respondents. Enumerators received prior training on research ethics, interviewing techniques, and the technical aspects of urine fertilizer use to minimize interviewer bias and enhance data accuracy. The finalized instrument was then deployed at the household level, with each interview conducted in the respondent's preferred local language to facilitate comprehension and authenticity of responses.

2.4 Variables

The analysis focused on three sequential dependent variables that reflect distinct stages in the adoption process of urine fertilizer: awareness, adoption, and intensity of use. Each stage captures a progressively deeper level of engagement with technology and provides a more nuanced understanding of farmers' decision-making behavior.

2.4.1 Awareness

The variable was defined as a binary variable indicating whether a farmer had ever heard of urine fertilizer and its potential agricultural benefits (1 = aware, 0 = not aware). Adoption was also specified as a binary variable, representing whether an aware farmer had ever used urine fertilizer on their fields (1 = adopter, 0 = non-adopter). Conditional on adoption, intensity of use was measured as a continuous variable capturing the number of applications of urine fertilizer made by a household during the previous 12 months. This variable was censored at zero for non-users, consistent with the requirements of the Tobit specification within the triple-hurdle framework.

2.4.2 Adoption

The explanatory variables encompassed a broad range of demographic, socio-economic, institutional, and perception-based factors hypothesized to influence farmers' decisions. These included the age, sex, and education level of the household head; household size; total farm size; and monthly household income, reflecting demographic and resource endowment characteristics. Institutional factors included frequency of contact with agricultural extension officers and membership in farmer organizations, both of which were expected to enhance information flow and social learning. Ownership of livestock—particularly chickens and goats—was included as a proxy for wealth status and nutrient recycling potential within mixed farming systems.

2.4.3 Intensity of use

To capture behavioral and perceptual dimensions, the study also incorporated subjective variables relating to farmers' attitudes toward urine fertilizer, including concerns about odour, cost, and health risks. These perception-based variables were measured on a binary scale (1 = concern present, 0 = otherwise) and were expected to negatively influence adoption and intensity. Collectively, these variables provided a comprehensive framework for analyzing the multifaceted determinants of awareness, uptake, and utilization intensity of urine fertilizer among smallholder farmers in Southern Malawi.

2.5 Analytical framework

Understanding the adoption of agricultural innovations often requires disentangling multiple stages of decision-making, as farmers may differ not only in whether they adopt a technology but also in how intensively they use it. To account for these sequential decisions, this study employed the Triple-Hurdle Model (THM), an econometric framework that extends the conventional double-hurdle specification (Cragg, 1971) by incorporating an additional layer of behavioral complexity. This approach recognizes that awareness, adoption, and intensity of use represent distinct but interrelated processes influenced by different sets of factors.

The first hurdle models awareness, which determines whether a farmer has ever heard of or received information about urine fertilizer. This stage was estimated using a Probit model, where the probability of awareness is expressed as a function of demographic, socio-economic, institutional, and perceptual variables. The second hurdle captures adoption conditional on awareness, reflecting the decision to apply urine fertilizer in practice. This stage was also estimated using a Probit model but included the Inverse Mills Ratio (IMR) derived from the awareness equation to correct for potential selection bias arising from unobserved factors influencing both awareness and adoption decisions.

The third hurdle focuses on intensity of use, which quantifies the frequency or number of applications of urine fertilizer among adopters. Since this variable is censored at zero for non-users, it was estimated using a Tobit model, appropriate for continuous but limited dependent variables. Together, these three equations form a sequential structure that captures the progression from information exposure to behavioral adoption and sustained utilization. Mathematically, the framework can be summarized as follows:

a. Awareness equation (Probit model):

$$A_i^* = X_i\beta_1 + \epsilon_{1i},$$

where $A_i = 1$ if $A_i^* > 0$, and 0 otherwise.

b. Adoption equation (Probit model with IMR correction):

$$D_i^* = X_i\beta_2 + \lambda_i\rho + \epsilon_{2i},$$

where $D_i = 1$ if $D_i^* > 0$, and 0 otherwise.

c. Intensity equation (Tobit model):

$$Y_i^* = X_i\beta_3 + \epsilon_{3i},$$

observed as $Y_i = Y_i^*$ if $Y_i^* > 0$, and 0 otherwise.

Here, X_i represents the vector of explanatory variables as defined in Section 2.4; $\beta_1, \beta_2, \beta_3$ denote parameter vectors; $\epsilon_{1i}, \epsilon_{2i}, \epsilon_{3i}$ are independently distributed error terms; and λ_i is the Inverse Mills Ratio accounting for sample selection effects.

The THM was chosen for its ability to provide richer behavioral insights compared to single-equation or binary models. It distinguishes between farmers who are unaware of the technology, those who are aware but choose not to adopt, and those who adopt with varying degrees of intensity. This separation not only enhances model accuracy but also allows for more targeted policy implications, since the factors promoting awareness may differ substantially from those influencing actual adoption or intensity of use.

All estimations were conducted using maximum likelihood estimation (MLE) techniques. Model diagnostics included tests for multicollinearity using Variance Inflation Factors (VIF), heteroskedasticity using Breusch–Pagan tests, and significance of the IMR to confirm the presence of selection bias between stages. Robust standard errors were applied to ensure valid inference in the presence of potential heteroskedasticity.

In sum, this analytical framework enables a comprehensive understanding of how socio-economic, institutional, and perceptual factors interact to shape the awareness, adoption, and intensity of urine fertilizer use among smallholder farmers—providing a rigorous foundation for the policy recommendations advanced in later sections.

2.6 Estimation strategy and diagnostics

The estimation followed a sequential procedure consistent with the structure of the Triple-Hurdle Model (THM). Each stage—awareness, adoption, and intensity—was estimated using econometric techniques appropriate for the nature of the dependent variable and its position within the decision process. The model was implemented using maximum likelihood estimation (MLE), allowing simultaneous evaluation of parameter estimates while ensuring statistical efficiency. In the first hurdle, the probability of being aware of urine fertilizer was estimated using a Probit model, where the dependent variable took the value of 1 if the respondent had heard of urine fertilizer and 0 otherwise. The estimation identified factors that increase the likelihood of information exposure, reflecting access to knowledge and institutional linkages. The second hurdle analyzed the determinants of adoption among farmers who were already aware of urine fertilizer. A Probit model with an Inverse Mills Ratio (IMR) correction was employed to account for potential sample selection bias, recognizing that unobserved factors influencing awareness might also affect the adoption decision. A significant IMR term indicated the presence of such bias, justifying the sequential estimation structure. The third hurdle, representing the intensity of use, was estimated using a Tobit regression model because the dependent variable (number of urine fertilizer applications per year) was continuous but censored at zero for non-users. This specification captures variation among adopters while correctly treating non-users as censored observations rather than true zeros. The model thus provides consistent and unbiased estimates of the determinants of usage intensity.

To ensure robustness and reliability of results, a series of diagnostic and validation tests were conducted:

- Multicollinearity among explanatory variables was examined using Variance Inflation Factors (VIF). All VIF values were below the conventional threshold of 5, indicating no serious multicollinearity issues.
- Heteroskedasticity in the Tobit residuals was tested using the Breusch–Pagan test. Where heteroskedasticity was detected, robust standard errors were applied to maintain efficiency and validity of inference.
- Model specification errors were checked through link and goodness-of-fit tests, ensuring correct functional form.
- The significance and sign of the IMR coefficient were used to assess the extent of selection bias between awareness and adoption stages, providing further justification for the THM framework.

The estimation strategy therefore ensured that each behavioral stage—awareness, adoption, and intensity—was empirically validated and statistically robust. This sequential approach not only enhanced explanatory power but also enabled the derivation of nuanced insights into the distinct socio-economic, institutional, and perceptual factors influencing each stage of urine fertilizer adoption among smallholder farmers.

3 Results

3.1 Descriptive statistics and farmer characteristics

A total of 251 smallholder farming households were surveyed across villages under Traditional Authority (TA) Nkhulambe in Phalombe District, Southern Malawi. Table 1 summarizes the key demographic, socio-economic, and institutional characteristics of the sample population. The results depict a community characterized by modest resource endowments, limited farm sizes, and strong participation in organized farmer groups. The average age of household heads was approximately 41.7 years (SD = 12.4), indicating that most respondents were within the productive age bracket actively engaged in farming. The gender distribution was slightly male dominated, with 61% of respondents being men. Educational attainment averaged 7.1 years of formal schooling (SD = 3.9), reflecting a moderate literacy level conducive to participation in agricultural extension and innovation programs.

Households were relatively large, with an average size of 5.4 members (SD = 2.2), and operated small landholdings averaging 1.9 acres (SD = 1.5). These figures are typical of Malawi's smallholder farming systems, where land scarcity and population density constrain production potential. The mean monthly household income was approximately MK 47,800 (SD = 28,600), signifying a predominantly low-income, subsistence-based economy. Livestock ownership was common but limited in scale. Respondents reported an average of 6.8 chickens and 4.1 goats per household, indicating that small livestock serve both as a financial buffer and a potential source of organic nutrient recycling. Importantly, all respondents belonged to at least one farmer organization, such as cooperatives, farmer field schools, or savings and loan associations, highlighting the district's strong culture of collective action. Additionally, 52% of farmers reported having interacted with an agricultural extension officer at least once in the preceding 12 months, underscoring moderate but uneven institutional reach.

TABLE 1 Demographic and socioeconomic characteristics (*N* = 251).

Variable	Mean	% (SD)
Age (years)	41.7	12.4
Sex (male)	61%	–
Education (years)	7.1	3.9
Household size (persons)	5.4	2.2
Farm size (acres)	1.9	1.5
Monthly income (MK)	47,800	28,600
Chickens owned	6.8	4.3
Goats owned	4.1	2.8
Extension contact (past year ≥1)	52%	–
Group membership	100%	–
Awareness of urine fertilizer	46%	–
Adoption (ever used)	32%	–
Intensity (applications/year)	4.7	3.1 (adopters only)

Regarding urine fertilizer, 46% of farmers were aware of its potential agricultural use, while 32% had applied it on their fields. Among adopters, the average number of applications in the previous year was 4.7 times (SD = 3.1). These figures suggest that although awareness levels are growing, actual uptake remains limited, and intensity of use is modest. The gap between awareness and adoption implies the presence of behavioral, economic, or perceptual barriers—issues that are further explored through econometric analysis in subsequent sections.

Collectively, these descriptive statistics portray a farming community characterized by low asset accumulation, strong institutional embeddedness, and growing exposure to innovative soil fertility management practices. The heterogeneity in education, extension contact, and livestock ownership provides a useful empirical foundation for explaining the variation in awareness, adoption, and intensity of urine fertilizer use examined through the triple-hurdle model.

3.2 Awareness (hurdle 1)

Results from the first stage of the triple-hurdle model (Table 2) show that education, extension contact, and poultry ownership were

TABLE 2 Logistic regression for awareness (N = 251).

Predictor	OR (95% CI)	p-value
Age (years)	0.98 (0.96–0.999)	0.041
Education (years)	1.12 (1.03–1.23)	0.009
Extension contacts	1.27 (1.09–1.49)	0.002
Chickens owned	1.04 (1.00–1.08)	0.049
Concern: odour	0.56 (0.35–0.89)	0.014

significant positive predictors of awareness of urine fertilizer among smallholder farmers. In contrast, age and odour concerns were negatively associated with awareness. Each additional year of education increased the odds of awareness by 12% ($p < 0.01$), while each unit increase in extension contact raised the odds by 27% ($p < 0.01$). Ownership of chickens also had a positive effect on awareness, with the odds increasing by 4% per additional bird ($p < 0.05$). Conversely, age was associated with a slight reduction in awareness (odds ratio = 0.98; $p < 0.05$), and farmers who expressed odour concerns were 44% less likely to be aware of urine fertilizer ($p < 0.05$). These findings indicate that awareness is influenced primarily by educational attainment, access to extension services, and household resource endowment, while perceptual and demographic factors contribute to variation in information exposure among farmers.

3.3 Adoption (hurdle 2, conditional on awareness)

The second stage of the triple-hurdle model (Table 3), estimated conditionally on awareness, revealed that extension contact and farm size were significant positive predictors of urine fertilizer adoption, whereas cost concerns and odour concerns exerted significant negative effects. Farmers with more frequent extension contact had 41% higher odds of adopting urine fertilizer ($p < 0.01$). Each additional acre of farmland increased the likelihood of adoption by 21% ($p < 0.05$). In contrast, farmers who perceived urine fertilizer as costly were 53% less likely to adopt ($p < 0.05$), and those expressing odour concerns were 62% less likely to adopt ($p < 0.01$). The Inverse Mills Ratio (IMR) derived from the awareness model was negative and statistically significant (coefficient = −1.08, p = 0.02), confirming the presence of selection bias between the awareness and adoption stages and reinforcing the appropriateness of the triple-hurdle framework for this analysis.

3.4 Intensity of use (hurdle 3)

Analysis of the final stage of the triple-hurdle model (Table 4) shows that the frequency of urine fertilizer application among adopters was strongly influenced by institutional contact, farm resource capacity, and perception-related factors. The coefficients indicate that extension contact, farm size, and poultry ownership were positively associated with intensity of use, whereas age and odour concerns exhibited negative effects. An additional extension interaction corresponded to an average increase of 0.9 urine fertilizer applications per year ($p < 0.01$). Similarly, a one-acre increase in farm size raised application frequency by approximately 1.1 times annually ($p < 0.05$). Poultry ownership contributed positively, with each additional chicken linked to a 0.1 increase in application frequency ($p < 0.05$). In contrast, older farmers tended to apply the fertilizer less frequently (coefficient = −0.05; $p < 0.05$), and those reporting odour concerns applied it 1.4 times fewer per year ($p < 0.05$). Overall, the intensity analysis confirms that institutional engagement and on-farm resource availability enhance the sustained use of urine fertilizer, while perceptional constraints and demographic factors continue to moderate utilization patterns among adopters.

TABLE 3 Logistic regression for adoption (aware subsample, N = 116).

Predictor	OR (95% CI)	p-value
Age (years)	0.97 (0.95–0.99)	0.03*
Extension contacts	1.41 (1.12–1.78)	0.00**
Farm size (acres)	1.21 (1.01–1.45)	0.04*
Concern: cost	0.47 (0.25–0.90)	0.02*
Concern: odour	0.38 (0.21–0.68)	0.00**
IMR (from hurdle 1)	−1.08 (0.45)	0.02*

* and ** denote statistical significance at the 10% and 5% levels, respectively.

TABLE 4 Tobit regression for intensity (N = 251).

Predictor	Coefficient (SE)	p-value
Age (years)	−0.05 (0.02)	0.033
Extension contacts	0.92 (0.28)	0.001
Farm size (acres)	1.10 (0.45)	0.017
Chickens owned	0.10 (0.05)	0.042
Concern: odour	−1.42 (0.62)	0.021

4 Discussion

The study reveals that the adoption of liquid urine fertilizer among smallholder farmers in Southern Malawi is not merely a function of awareness but a multistage behavioral process influenced by socio-economic, institutional, and perceptual factors. The sequential estimation using the triple-hurdle model underscores the need to distinguish between the determinants of awareness, adoption, and intensity of use—each representing a critical threshold in technology diffusion (Greene, 2008; Abdulai and Huffman, 2014). The results indicate that while institutional participation is near universal, uptake remains limited to a third of respondents, reflecting a persistent gap between knowledge and practice.

4.1 Education, extension contact, and information flow

Consistent with adoption theory, education and access to extension services significantly improved farmers' awareness and subsequent adoption of urine fertilizer. Farmers with more years of formal schooling were better positioned to process technical information and perceive the agronomic value of alternative soil fertility technologies (Tapsoba et al., 2020; Martignoni et al., 2022).

The low adoption of urine fertilizer could be linked to the observed moderate literacy level of an average 7.1 years of academic exposure by the population. Similarly, frequent extension contact increased the odds of awareness by 27% and adoption by 41%, aligning with earlier studies that emphasize extension as a critical vehicle for technology dissemination in low-input agricultural systems (Smith et al., 2022; Petersen-Rockney et al., 2021). These findings reinforce the argument that social learning and demonstration-based communication are essential to overcome behavioral inertia and misconceptions surrounding the use of human-derived agricultural inputs (Verhagen and Scott, 2019). According to the social exchange theory (Thibaut and Kelley, 1959), an impactful change in agricultural yield guided by extension personnel will fundamentally influence the social behavior of the community by embracing the proposed technology as they weigh the personal benefits against the costs. This will enhance sustainable growth in agricultural production and subsequently improve livelihood of the population. In observation of male dominance within the community at 61%, it would be recommendable to ensure inclusivity in technology awareness drives to reduce possible adoption bottlenecks.

4.2 Resource endowment and productive capacity

Farm size and livestock ownership were positively associated with adoption and intensity of urine fertilizer use. Larger farms imply greater land heterogeneity and the need for nutrient management innovations (Dimkpa et al., 2023). Ownership of chickens, which serves as an indicator of household asset wealth and capacity for nutrient recycling, was also associated with a higher intensity of urine fertilizer use. This relationship suggests that households with greater livestock assets are better positioned to integrate organic nutrient sources into their farming systems, thereby enhancing the efficiency and sustainability of resource use. This finding corroborates the emerging understanding that integrated crop-livestock systems enhance the uptake of circular bioeconomy technologies, as nutrient flow between livestock and crop systems strengthens the feasibility and regularity of urine-based fertilization (Mathobela et al., 2024). Farmers with broader productive assets may therefore view urine fertilizer as complementary rather than substitutive to existing organic manure practices.

4.3 Perceptions, cultural barriers, and sensory constraints

Despite the clear agronomic and economic advantages of urine fertilizer, cultural and sensory perceptions, particularly concerns related to odour, were found to significantly diminish awareness, adoption, and intensity of use. Similar patterns have been observed in other ecological sanitation settings, where psychological discomfort and deeply rooted cultural taboos have constrained public acceptance and hindered widespread utilization (Nkusi, 2018; Mariwah, 2017). These findings highlight the critical importance of addressing perceptual and cultural barriers through targeted education, sensitization, and participatory engagement to enhance the social acceptability of ecological sanitation technologies. Odour concerns lowered the probability of awareness by nearly half and reduced adoption odds by 62%. This indicates the importance of perception management and knowledge co-creation through participatory demonstrations that normalize human-waste recycling practices (Leblanc et al., 2019). Furthermore, these findings resonate with the broader discourse on the social construction of technology, where cultural narratives shape perceived risk and appropriateness of innovations (Nhamo et al., 2024). Addressing these barriers requires not only technical optimization to minimize odour but also deliberate social marketing that reframes urine fertilizer as a symbol of ecological responsibility and economic pragmatism.

4.4 Urine and fecal contamination risks in Ecosan systems

Although source separated urine is generally considered to pose lower microbiological risk than fecal matter, its relative safety cannot be assumed under real world smallholder farming conditions. Recent studies emphasize that the risk profile of urine derived fertilizers is highly contingent on system design, user compliance, and post collection handling practices, all of which are prone to variability in low resource settings (Roxburgh et al., 2020; Yalin et al., 2023). Cross contamination between urine and fecal matter may occur through improper toilet use, malfunctioning or poorly maintained urine diversion infrastructure, shared collection containers, and unhygienic handling during storage, transportation, or field application (Qadir et al., 2020; Fatta-Kassinos et al., 2023). In the present study, no empirical data were collected on urine treatment methods, storage duration, pH stabilization, or adherence to hygienic handling protocols. Consequently, the analysis does not evaluate compliance with World Health Organization and Food and Agriculture Organization guidelines for the safe reuse of human derived nutrients (WHO, 2022; FAO, 2023).

While urine diversion offers a promising pathway for safe nutrient recovery and aligns with circular bioeconomy principles, its integration into agricultural systems must be explicitly guided by a precautionary risk–benefit framework. Such an approach balances agronomic benefits with necessary public health and environmental safeguards (Yalin et al., 2023; WHO, 2022). The promotion of urine-derived fertilizers should therefore not proceed in isolation but must be accompanied by rigorous and context-specific risk assessment protocols. Potential trade-offs that require careful management include pathogen transmission, residual pharmaceuticals, antimicrobial resistance genes, and heavy metal accumulation in soils and food chains. These risks are particularly pronounced in systems characterized by inadequate treatment, inconsistent user compliance, or limited monitoring infrastructure (Fatta-Kassinos et al., 2023; Hamilton et al., 2020; Yalin et al., 2023). Consequently, efforts to scale urine fertilizer use must be coupled with enforceable safety standards, participatory farmer training on safe handling and storage, and periodic biosafety audits. These measures are essential to mitigate unintended consequences and maintain public trust (FAO, 2023; Qadir et al., 2020). Adopting this integrated perspective ensures that the pursuit of nutrient recycling and Sustainable Development Goal (SDG) attainment (2, 6, and 13) does not compromise food safety or ecosystem health. In doing so, it aligns circular sanitation-agriculture innovations with the broader objectives of sustainable agriculture and One Health.

The absence of standardized treatment and monitoring information represents an important limitation and warrants careful interpretation of the findings. While observed adoption patterns provide valuable insights into social acceptance, perceived utility, and institutional drivers of uptake, they do not constitute evidence of biosafety compliance or effective risk mitigation. This distinction is critical, as inadequate treatment or improper handling of urine-based fertilizers may compromise soil safety, crop quality, and public health, even in systems designed around urine diversion principles (Hamilton et al., 2020; Yalin et al., 2023). These findings reinforce the need for future research and policy frameworks to integrate socio economic adoption analysis with rigorous biosafety assessment to ensure that the promotion of urine reuse aligns with food safety standards and One Health objectives.

4.5 Institutional embeddedness and collective action

A unique finding is the universal membership of respondents in organized farmer groups, suggesting a strong institutional foundation for scaling innovations. However, this did not automatically translate into higher adoption levels, implying that collective structures alone are insufficient without effective facilitation and knowledge brokerage. Group membership may enhance information exposure but not necessarily influence behavioral change unless supported by continuous mentorship and resource mobilization (Verhagen and Scott, 2019; Klassen and Vreysen, 2020). This observation reinforces the view that successful dissemination of sustainable technologies depends on functional institutions that bridge scientific knowledge and local practice, enabling experimentation, peer influence, and adaptive learning (Cookey et al., 2022).

4.6 Economic and policy implications

The negative and significant Inverse Mills Ratio (IMR) indicates an inverse relationship between awareness and adoption, suggesting that the unobserved factors influencing awareness, such as exposure through external projects or promotional campaigns, do not automatically translate into actual behavioral change. This finding shows that awareness alone is insufficient to drive adoption unless it is accompanied by clear economic incentives, practical feasibility, and technical support mechanisms that enable farmers to implement the innovation effectively. Cost perception was a major barrier, reducing adoption by 53%, even though urine fertilizer is materially low-cost. This apparent contradiction suggests that the cost concern is likely a proxy for transaction costs, such as labour for collection, storage infrastructure, and transportation (Qadir et al., 2020). Policies should thus focus on reducing these indirect costs through local infrastructure support and communal urine collection systems integrated into sanitation services. Moreover, the alignment of this initiative with Malawi's climate-smart and circular economy strategies can catalyze funding and institutional backing for upscaling (Nhamo et al., 2024).

4.7 Implications for sustainable agriculture and Ecosan integration

This study provides empirical evidence supporting the dual benefits of integrating ecological sanitation and sustainable agriculture. By closing nutrient loops, urine fertilizer contributes to both environmental protection and food security, echoing global calls for circular resource use (Yalin et al., 2023; Qadir et al., 2020). The findings affirm that ecological sanitation can move beyond household-level waste management toward a systemic strategy for nutrient recovery and reuse, aligning with Sustainable Development Goals (SDGs) 2, 6, and 13. For Malawi and similar agrarian economies, urine fertilizer adoption can contribute to nitrogen self-sufficiency, reduce import dependency, and promote climate adaptation through soil organic matter improvement.

4.8 Limitations and future research

While the triple hurdle model employed in this study provides robust insights into the sequential nature of awareness, adoption, and intensity of urine fertilizer use, future research should extend this work through longitudinal and experimental designs to track behavioral change over time and establish causal relationships. Integrating biophysical assessments such as soil fertility indicators, crop yield responses, and economic returns would further strengthen understanding of the long term agronomic and livelihood impacts of urine-based fertilization. Equally important is a more explicit examination of gendered dynamics, particularly the roles and responsibilities of women in sanitation management, nutrient recovery, and fertilizer application, as these dimensions are central to the effectiveness and sustainability of ecological sanitation initiatives (Martignoni et al., 2022). In addition, greater attention should be paid to cultural norms, beliefs, and taboos, which continue to shape risk perceptions and strongly influence farmers' willingness to adopt urine derived fertilizers.

A major limitation of the present study is the absence of direct biosafety and public health assessments of urine fertilizer. Future research should therefore incorporate microbiological, parasitological, and chemical analyses to evaluate pathogen survival, pharmaceutical residues, and antimicrobial resistance risks under locally relevant storage, treatment, and application conditions. Longitudinal field trials that explicitly link adoption behavior with soil quality, crop contamination, and food safety outcomes are particularly necessary to ensure that the promotion of urine fertilizer is aligned with public health protection, regulatory standards, and broader One Health objectives.

Furthermore, while this study provides robust evidence on the socio-economic and institutional factors shaping awareness, adoption, and intensity of urine fertilizer use, it does not evaluate the microbiological, parasitological, or chemical safety of urine-derived inputs. No laboratory-based assessments were conducted to examine the presence of pathogens, pharmaceutical residues, heavy metals, or antimicrobial resistance genes. As such, the observed adoption patterns should not be interpreted as validation of agronomic safety, food safety, or public health suitability. Therefore, future research must integrate direct biosafety and public health assessments to ensure that the promotion of urine fertilizer aligns with established safety standards. Specifically, studies should include: (1) pathogen reduction efficiency, assessed through microbiological and parasitological analyses to evaluate the survival of pathogens such as *E. coli* and helminth eggs under locally relevant storage and treatment conditions; (2) pharmaceutical residue analysis, including screening for antibiotics, hormones, and other bioactive compounds to assess potential risks of antimicrobial resistance and ecological disruption; and (3) the validation of safe application protocols through field trials to test and optimize locally feasible treatment methods, for example storage duration, pH elevation, and dilution ratios, alongside application techniques that minimize risks to farmers, consumers, and the environment.

Although source-separated urine is often considered relatively low-risk compared to fecal matter, potential hazards remain, particularly in contexts where storage duration, treatment conditions, and handling practices are inconsistent. Emerging evidence indicates that human-derived fertilizers may contain residual pharmaceuticals and antimicrobial compounds that warrant careful risk assessment before large-scale agricultural reuse. The absence of such analyses represents a key limitation of this study and underscores the need for integrated socio-economic and biophysical research frameworks when promoting ecological sanitation-based nutrient recycling systems.

5 Conclusion and policy recommendations

This study provides robust empirical evidence that the adoption of liquid urine fertilizer among smallholder farmers in Southern Malawi is shaped by a complex interaction of educational, institutional, economic, and perceptual factors. Adoption emerges not as a single binary decision but as a sequential and cumulative process that progresses from awareness to initial use and ultimately to sustained application. Farmers with higher levels of education, more frequent contact with agricultural extension services, and greater resource endowment, particularly in terms of farm size and livestock ownership, were consistently more likely to adopt urine fertilizer and apply it more intensively. These findings underscore the central role of human capital, institutional engagement, and productive capacity in facilitating the uptake of circular and resource efficient agricultural innovations.

Despite these enabling conditions, substantial barriers to adoption remain. Negative perceptions related to odour and perceived costs continue to exert a strong deterrent effect across all stages of the adoption process. These barriers are not merely technical in nature but are deeply embedded in socio cultural norms, risk perceptions, and knowledge gaps surrounding the reuse of human derived inputs in agriculture. The study further reveals that collective organization through farmer groups, while effective in facilitating information exchange, does not automatically translate into behavioural change unless supported by targeted capacity building, sustained extension engagement, and experiential learning. This finding highlights the limitations of institutional membership alone and points to the need for more deliberate and practice-oriented approaches to technology diffusion.

Overall, the results demonstrate that liquid urine fertilizer represents a viable, low cost, and environmentally sustainable nutrient source with the potential to improve soil fertility, enhance crop productivity, and contribute to improved sanitation outcomes. However, realizing this potential requires adoption strategies that move beyond simple technology availability. Effective scaling must be anchored in social acceptance, continuous institutional support, and coherent policy integration that bridges the agriculture and sanitation sectors.

Based on these findings, several policy relevant actions are recommended. Strengthening demonstration based learning through the establishment of practical field demonstration plots can enhance farmer confidence in the safe collection, storage, and application of urine fertilizer. Agricultural extension services should be capacitated to incorporate urine fertilizer management into routine advisory systems, ensuring that farmers acquire both technical competence and practical experience. Addressing perceptual and cultural barriers is equally critical and can be achieved through context specific awareness campaigns and social marketing strategies that reframe urine fertilizer as a safe, productive, and economically rational input. Supporting resource constrained farmers through collective infrastructure, including shared urine collection, treatment, and distribution facilities managed by farmer cooperatives, can reduce individual transaction costs while promoting hygienic handling practices. At the policy level, formal recognition of Ecosan derived fertilizers within national agricultural, sanitation, and climate smart agriculture frameworks is essential. Integrating urine fertilizer into fertilizer subsidy programs and sustainable agriculture policies would attract investment, encourage innovation, and institutionalize nutrient recycling within Malawi's broader development agenda. Furthermore, promoting research, innovation, and enterprise development, particularly through youth and women led initiatives in urine collection, treatment, and commercialization, can stimulate local economies and strengthen the circular bioeconomy.

Importantly, increased adoption of urine fertilizer should not be interpreted as confirmation of its biosafety or food safety. Efforts to scale urine-derived fertilizers must therefore proceed alongside the development and enforcement of evidence-based treatment guidelines, biosafety standards, and regulatory oversight mechanisms. Integrating urine fertilizer into national policy frameworks should be contingent upon rigorous safety protocols that protect farmers, consumers, and the environment. Aligning adoption promotion with public health safeguards is essential to ensure that ecological sanitation contributes not only to agricultural sustainability and food security but also to broader One Health objectives. Furthermore, considering the absence of agronomic and food safety indicators in our study, including measurements of soil pathogen load, crop contamination, and post-harvest food safety risks. Future research should also integrate socio economic adoption analysis with controlled agronomic trials and laboratory based biosafety assessments. Such integrated approaches would enable a more comprehensive evaluation of sustainability by linking behavioral uptake with soil health, crop performance, and consumer safety outcomes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Malawi University of Science and Technology Research Ethics Committee (MUSTREC). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JabN: Methodology, Investigation, Writing – original draft, Writing – review & editing, Conceptualization, Visualization, Formal analysis, Validation, Data curation, Project administration. TM: Supervision, Methodology, Writing – review & editing, Visualization, Formal analysis. HT: Formal analysis, Visualization, Writing – original draft, Methodology, Writing – review & editing, Conceptualization. AN: Writing – original draft, Visualization, Writing – review & editing, Methodology, Validation. CC: Validation, Writing – review & editing, Supervision, Formal analysis, Visualization. TN-C: Visualization, Methodology, Writing – review & editing. WM: Writing – review & editing, Visualization, Validation, Supervision. SM: Methodology, Supervision, Visualization, Writing – review & editing. OA: Visualization, Writing – review & editing. JF-O: Writing – review & editing, Visualization. RW: Visualization, Writing – review & editing. JacN: Writing – review & editing. AF-M: Writing – review & editing, Visualization. ET-A: Writing – review & editing, Visualization. AK: Methodology, Writing – review & editing, Visualization. BL: Writing – review & editing, Visualization. LS: Visualization, Writing – review & editing. GN: Writing – review & editing, Visualization. JC: Writing – review & editing, Visualization. MC: Writing – review & editing, Writing – original draft, Formal analysis, Visualization. PM: Writing – review & editing, Validation, Data curation, Methodology, Visualization, Writing – original draft, Formal analysis.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declared that Generative AI was used in the creation of this manuscript. Editing language and proofreading.

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