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antony Nyerere

antony.nyerere@sua.ac.tz

Sokoine University of Agriculture

Athumani. M. Lupindu

Sokoine University of Agriculture

Christopher. P. Mahonge

Sokoine University of Agriculture

Fredy Mlowe

Sokoine University of Agriculture

Ernatus. M. Mkupasi

Sokoine University of Agriculture

Helena. A. Ngowi

Sokoine University of Agriculture

Sarah Gabriël

Ghent University

Dario Scaramuzzi

R-Evolution Worldwide Impresa Sociale

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Divergent trajectories of latrine use, pig confinement and water treatment: A six-year mixed-methods study of *Taenia solium* control in Tanzania

Antony D. Nyerere[1]*, Athumani M. Lupindu[1], Christopher P. Mahonge[2], Mlowe F[1], Ernatus M. Mkupasi[1], Helena A. Ngowi[1], Sarah Gabriël[3], Dario Scaramuzzi[4]

[1] Department of Veterinary Medicine and Public Health, Sokoine University of Agriculture, Morogoro, Tanzania

[2] Department of Policy Planning and Management, College of Social Sciences and Humanities, Sokoine University of Agriculture, Morogoro, Tanzania

[3] Faculty of Veterinary Medicine, Department of Translational Physiology, Infectiology and Public Health, Ghent University, Ghent, Belgium

[4] R-Evolution Worldwide Impresa Sociale, Department of Research and Innovation, Rome, *Italy*

*Corresponding author: Antony D. Nyerere, Department of Veterinary Medicine and Public Health, Sokoine University of Agriculture, Morogoro, Tanzania.

Email: antony.nyerere@sua.ac.tz

Abstract

Background: Preventing *Taenia solium* transmission requires households to maintain latrine use, pig confinement and household water treatment. However, behaviours promoted within the same programme may follow different trajectories because they are shaped by distinct social, economic and practical constraints. Understanding these differences is important for developing implementation strategies tailored to each practice.

Methods: We conducted an explanatory sequential mixed-methods study in 42 villages in Kongwa and Songwe districts, Tanzania. The quantitative phase analysed 521 households surveyed in 2019, 2021 and 2025 (1,563 household-wave observations) using practice-specific three-level logistic mixed-effects models. The qualitative phase (2026) comprised 24 in-depth interviews, four focus group discussions (24 participants) and 16 key-informant

interviews. Data were integrated using joint displays, guided by the Consolidated Framework for Implementation Research (CFIR) and the Capability, Opportunity, Motivation–Behaviour (COM-B) model.

Principal Findings: The three practices followed distinct temporal patterns. Latrine use was similar in 2021 and 2019 (adjusted odds ratio [aOR] 1.07, 95% CI 0.83–1.38) but higher in 2025 (aOR 2.94, 95% CI 2.01–4.31). Pig confinement declined in 2021 (aOR 0.26, 95% CI 0.19–0.36) before exceeding its 2019 level in 2025 (aOR 1.73, 95% CI 1.18–2.55), whereas water treatment showed no clear temporal change (aOR 1.11, 95% CI 0.78–1.58). By-law awareness was associated with latrine use (aOR 2.25, 95% CI 1.70–2.98) and pig confinement (aOR 1.76, 95% CI 1.35–2.40). Pig confinement was also associated with household income (aOR 1.84, 95% CI 1.22–2.78), while cultural preference for free-ranging pigs was associated with lower odds of confinement (aOR 0.60, 95% CI 0.42–0.86). Greater distance to the water source was associated with lower odds of water treatment (aOR 0.88 per 100 m, 95% CI 0.78–0.99). Confidence intervals for shared covariates overlapped, suggesting differences between associations across practices require cautious interpretation. Qualitative findings indicated that shame and social expectations reinforced latrine use, costs and livestock-disease shocks shaped pig confinement, and daily effort with little perceived benefit hindered water treatment.

Conclusions: Preventive practices promoted within the same programme followed different temporal patterns and were associated with distinct contextual constraints. These findings highlight the need for implementation strategies tailored to the dominant barriers affecting each practice rather than uniform approaches. We propose Enforce–Enable–Embed as a hypothesis-generating heuristic for matching implementation functions to diagnosed constraints. Its usefulness requires prospective evaluation.

Author Summary

Taenia solium is a parasitic worm that can cause epilepsy in people and economic losses for pig farmers. Its control relies on three household practices: latrine use, pig confinement, and drinking-water treatment. We followed 521 households in Tanzania over six years to see if these practices changed in the same way, and why. They did not. Latrine use increased

later in the study, pig confinement declined sharply before recovering, and water treatment showed little change. The factors associated with each practice also differed. Social expectations and by-laws reinforced latrine use, while household income and livestock-related shocks shaped pig confinement. Daily effort and little visible benefit made water treatment harder to maintain. These findings suggest that programmes promoting multiple practices should identify the main barriers to each, rather than relying on a single implementation strategy. We propose Enforce–Enable–Embed as a heuristic for tailoring support to these specific barriers, which requires testing in future studies.

Introduction

Taenia solium remains an important public health problem in sub-Saharan Africa and a leading preventable cause of epilepsy in endemic communities, with the heaviest burden in resource-limited rural populations [1, 2]. Because transmission runs through humans, pigs and the environment, household behaviour is central to interrupting the parasite's life cycle [3]. Latrine use removes human faeces from pigs' reach, and pig confinement keeps pigs from finding faeces that remain. Household water treatment addresses a further route of egg ingestion whose contribution to *T. solium* transmission is less certain; the eggs are environmentally robust, and we therefore treat water treatment as one of the practices the programme promoted rather than as the most effective barrier. The three practices act at different points of the transmission pathway and may depend on different conditions for their maintenance.

Maintaining a practice is not the same as adopting it. Implementation science distinguishes initial adoption from sustainment and increasingly treats sustainability as a dynamic process in which practices are maintained, adapted, interrupted and resumed as interventions and contexts change [4–6]. Health education can raise knowledge and prompt change [1, 7], but initial uptake does not guarantee continued practice when household resources, priorities and conditions shift, and theories of how behaviour change is maintained differ from those that explain how it begins [8].

92 The three practices also make different demands. Latrine use can become routine and can
93 be reinforced by social expectation, sanitation norms and local by-laws [9, 10]. Pig
94 confinement requires continuing outlay for materials and feed and continuing labour.
95 Household water treatment requires a repeated action every day and reliable access to the
96 means of treatment, a burden that can make it vulnerable to interruption [11]. Practices
97 promoted within a single programme may therefore differ in what sustains them, a possibility
98 that package-style delivery tends to obscure.
99
100 Implementation science has produced substantial evidence on sustainment and contextual
101 fit [4, 12, 13], but mostly for a defined intervention or evidence-based practice. Far less is
102 known about whether several behaviours delivered through one integrated One Health
103 programme share sustainment requirements or need behaviour-specific strategies. In *T.*
104 *solium* research, studies have largely examined knowledge, reported practice, adoption or
105 cross-sectional correlates [1, 7][; the mechanisms that keep different preventive practices
106 going over time are poorly understood.
107
108 Two companion analyses of the same cohort show that sustainment is heterogeneous. The
109 intervention evaluation found limited, practice-specific effects of health education, with
110 secular change in the wider implementation environment contributing substantially to
111 behavioural change (Nyerere *et al.,* under review-a). The longitudinal trajectory analysis
112 identified sustained practice, discontinuation, late adoption and practice cycling, in which
113 households resumed a practice after stopping it, together with a Wealth Paradox: greater
114 wealth favoured adoption of pig confinement yet was associated with more subsequent
115 discontinuation (Nyerere *et al.,* under review-b). The second finding implies that
116 determinants of adoption cannot be assumed to predict sustainment. What remains
117 unknown is why the practices diverge and what lies behind the differences.
118
119 Quantitative models can show which characteristics go with practice over time, but not how
120 households experience the demands of a practice or why they interrupt and resume it. We
121 therefore used an explanatory sequential mixed-methods design: longitudinal quantitative

analysis to identify patterns, followed by qualitative inquiry to explain them. COM-B, the behavioural core of the Behaviour Change Wheel (BCW), specifies the capability, opportunity and motivation needed for a behaviour [14]; the updated Consolidated Framework for Implementation Research (CFIR) situates these conditions in their implementation context [15]. Together they permit a practice-specific diagnosis without presuming that every behaviour shares one explanatory model.

We ask (1) how the courses of latrine use, pig confinement and household water treatment differ over six years; (2) which household, community and implementation factors are associated with each practice, and whether they differ across practices; and (3) how households experience and navigate the demands of maintaining each practice. We assess practice-specificity through practice-specific models, pre-specified cross-practice interaction tests and mixed-methods integration, and we use the integrated findings to propose the Enforce–Enable–Embed heuristic as a hypothesis-generating guide to implementation planning.

Methods

Study design and conceptual framework

We used an explanatory sequential mixed-methods design [16]. Longitudinal quantitative analysis characterised practice over time and identified correlates; these results informed purposive selection of qualitative participants with contrasting behavioural trajectories; the qualitative phase explored how and why the quantitative patterns arose; and integration took place at the design, sampling and interpretation stages. CFIR [16,18] organised contextual and implementation influences, COM-B [14] characterised behavioural mechanisms, and the BCW [14] linked mechanisms to intervention functions. Because CFIR was developed for organisational implementation, we applied it by treating the household as the implementing unit and the village and district as the surrounding setting (Table S2).

Setting and parent trial

The study was nested in a cluster-randomised *T. solium* control programme in Kongwa District (Dodoma Region) and Songwe District, Tanzania. The parent trial included 42 villages, 21 allocated to the intervention arm and 21 to the control arm. Community-based health education was delivered in 2020 and reinforced in 2023; control villages had received the programme by 2023. The two districts differ in geography, livelihoods, infrastructure, water access, livestock production and community governance, which provides variation in the conditions under which households maintain practices (Figure 1).



Fig 1. Map of Kongwa and Songwe districts, Tanzania, East Africa.

Quantitative phase

Cohort: The parent trial enrolled 872 households in 2019. The analytic cohort comprised the 521 households with data at all three survey waves: baseline (2019), post-intervention follow-up (2021) and long-term follow-up (2025). This gives 1,563 household-wave observations in a balanced panel. The 351 enrolled households (40.3%) not observed at all

three waves are outside the analytic cohort, so estimates describe retained households; inverse probability weighting (below) addresses selection into the cohort.

Outcomes: Each practice was a binary, self-reported outcome at each wave. *Latrine use*: reported household use of a functional latrine. *Pig confinement*, among households owning pigs at that wave: confinement of all household pigs, with none allowed to roam freely. *Household water treatment*: reported treatment of the drinking water available on the day of the survey. These measures capture reported behaviour, not intention, knowledge or attitude, and are subject to recall and social-desirability bias. The present analysis is not an effectiveness evaluation and that the allocation variable is included only as a design covariate**.**

Behavioural trajectories: For descriptive purposes and to select qualitative participants, households were classified across the three waves as sustained practice (1→1→1), never practising (0→0→0), early adopters (0→1→1), late adopters (0→0→1), discontinuers (1→0→0) and practice cyclers (alternating patterns such as 1→0→1). Adoption was defined as presence of a practice at a wave, and sustainment as its presence across repeated observations. Because waves are two and four years apart, a trajectory cannot show whether practice was continuous between waves.

Explanatory variables: Variables were specified a priori from CFIR and COM-B and are mapped in Table S2. All models included household income (standardised), education of the head (primary or above vs less), household size, sex of the head, district, survey year (categorical, 2019 as reference) and original trial allocation. Practice-specific covariates were by-law awareness (latrine use and pig confinement), perceived disease risk (latrine use only), cultural preference for free-ranging pigs (pig confinement), and distance to the main water source per 100 m and negative perception of water quality (water treatment). By-law awareness was a single binary item on whether the respondent knew of local sanitation or latrine by-laws. Covariates measured at each wave (by-law awareness,

perceived risk, cultural preference, distance and water perception) entered with their wave-specific values.

All models included the baseline (2019) household wealth index, education of the head (primary or above vs less), household size, sex of the head, district, survey year (categorical, 2019 as reference) and original trial allocation. Wealth was derived by principal component analysis of household assets and housing characteristics following DHS methods [17]. We used the 2019 baseline wealth index rather than endline income to avoid reverse causation, ensuring that economic status preceded the behaviours observed in 2021 and 2025. Endline income (measured in 2025) was used only in sensitivity analyses (Table S1).

Primary models. We fitted a three-level logistic mixed model for each practice, with household-wave observations nested in households nested in villages, and random intercepts for household and village. Models were estimated by maximum likelihood with adaptive quadrature R software. Allocation was a design covariate; because the effect of the programme would appear as a year-by-allocation interaction, which was not modelled here, its main-effect coefficient is not an estimate of intervention effectiveness. Time-varying covariates were not decomposed into within- and between-household components [18]; coefficients are associations with the covariate value at each wave and mix within- and between-household variation. Results are adjusted odds ratios (aORs) with 95% confidence intervals. The pig-confinement model includes household-wave observations in which pigs were owned.

Practice-specificity: Because the practice-specific models were estimated separately and contain different covariates, their coefficients are not directly comparable in magnitude, and a difference in statistical significance between models is not itself a test of a difference. We therefore used (i) the year effects, which are common to all models, to compare temporal courses; (ii) six pre-specified interaction tests between a determinant and another practice, with Benjamini–Hochberg false-discovery-rate (FDR) adjustment [19]; and (iii) mixed-

methods integration. The interaction tests involve contemporaneous behaviours in the same households and are exploratory.

Clustering: The village-level intraclass correlation (ICC) was calculated on the latent logistic scale as $\sigma^2(village) / [\sigma^2(village) + \sigma^2(household) + \pi^2/3]$, the correlation between observations from different households in the same village [23]. The household-level $ICC, [\sigma^2(village) + \sigma^2(household)] / [\sigma^2(village) + \sigma^2(household) + \pi^2/3]$, is the correlation between repeated observations on the same household.

Sensitivity analyses: We compared the primary models with generalised estimating equations (independence, exchangeable, AR (1) and unstructured working correlation), models with only a village or only a household random effect, a wild cluster bootstrap, inverse probability weighting for selection into the analytic cohort [29] (weights from a logistic model of cohort membership on baseline covariates), and exclusion of influential villages (Table S4; Supplementary Methods).

Qualitative phase

Qualitative data were collected in May and June 2026. Participants were drawn purposively from the cohort to maximise explanatory variation across behavioural trajectories and contexts, not to be statistically representative [20]. Household participants included sustained practitioners, early and late adopters, discontinuers, practice cyclers and never practitioners, with variation sought by sex, age, district and prior intervention exposure. The sample comprised 24 in-depth interviews (IDIs) with household members, four focus group discussions (FGDs) with 24 participants in total, stratified where feasible by gender and trajectory, and 16 key-informant interviews (KIIs) with village leaders, health workers and Extension Officers at district, regional and national levels, 64 participants in all (Tables S7 and S8). Sampling continued until no new codes emerged in three consecutive interviews. Interviews and FGDs were conducted in Kiswahili, audio-recorded, transcribed and translated into English by an independent translator; a second researcher back-translated a

random 10% subsample, and culturally specific terms such as *aibu* (shame) were reviewed and discrepancies resolved by consensus.

Data were analysed by hybrid inductive–deductive thematic analysis [21, 22]. Transcripts were coded inductively first so that pre-specified constructs would not constrain the identification of new themes; codes were then mapped to COM-B constructs and CFIR domains, grouped into candidate themes, checked against the data and refined. Two analysts independently coded 25% of transcripts (Cohen's $\kappa = 0.85$) and resolved disagreements by consensus. Data were managed in NVivo 14. Theme definitions and criteria are in Tables S3 and S9.

Integration

Quantitative and qualitative findings were integrated with joint display matrices [16]. For each major determinant the qualitative evidence was judged to confirm, explain, extend or contradict the quantitative pattern, and deviant cases were examined to identify conditions under which a dominant pattern did not hold. Findings were then synthesised across practices into three interpretive archetypes and the Enforce–Enable–Embed heuristic. Both were developed from the integrated evidence and are not pre-specified or validated models.

Relationship to companion papers and reporting

The same three-wave cohort underlies two companion analyses, one of short-term intervention effects and secular trends, the other of behavioural trajectories and the Wealth Paradox. The present study addresses a different question: why constraints on sustainment differ across practices and what this implies for behaviour-specific implementation. The measures and sampling frame overlap, but primary outcomes, hypotheses and interpretation differ, and no results are duplicated as primary findings. Reporting follows STROBE for the quantitative phase [23], COREQ for the qualitative phase [24] and GRAMMS for the mixed-methods design [25]. Ethical approvals are given in the Declarations.

Results

The cohort and the temporal courses of the three practices

The analytic cohort comprised 521 households observed at all three waves (59.7% of the 872 enrolled in 2019; 1,563 household-wave observations). Latrine use was reported by 305 households (58.5%) in 2019 and 376 (72.2%) in 2025. Pig confinement was reported by 79 of 348 pig-owning households (22.7%) at baseline and 122 of 392 (31.1%) in 2025. Water treatment was reported by 191 households (36.7%) in 2019 and 211 (40.5%) in 2025 (Table 1).

Table 1: Characteristics of the longitudinal analytic cohort at baseline (2019) and follow-up (2025)

Characteristic	Baseline 2019 (N = 521)	Follow-up 2025 (N = 521)
Female-headed household, n (%)	131 (25.1)	time-invariant
Household size, mean (SD)	5.8 (2.1)	5.5 (2.0)
Wealth index (PCA), mean (SD)	0.0 (1.0)	0.2 (1.1)
Latrine use, n (%)	305 (58.5)	376 (72.2)
Pig confinement, n/N (%)	79/348 (22.7)	122/392 (31.1)
Water treatment, n (%)	191 (36.7)	211 (40.5)
By-law awareness, n (%)	167 (32.1)	254 (48.8)
Perceived disease risk (high), n (%)	215 (41.3)	234 (44.9)
Cultural preference for free-ranging pigs, n (%)	227 (43.6)	203 (39.0)

Note: Assessed only among pig-owning households. PCA, principal component analysis. Percentages are recalculated from the counts; wave-2021 prevalences are in the model estimates below.

The mixed models showed three different temporal courses (Table 2; Tables S6a–c). For latrine use, odds were unchanged between 2019 and 2021 (aOR 1.07, 95% CI 0.83–1.38) and substantially higher in 2025 than in 2019 (2.94, 2.01–4.31). For pig confinement, odds fell sharply in 2021 (0.26, 0.19–0.36) and exceeded baseline in 2025 (1.73, 1.18–2.55). For water treatment, neither wave differed from 2019 (2021: 1.20, 0.99–1.45; 2025: 1.11, 0.78–1.58). The confidence intervals for the 2025 effect on latrine use and on water treatment do

not overlap, nor do those for the 2021 effect on pig confinement and on the other two practices, so the temporal courses clearly differ.

Practice-specific associations

Table 2: Associations with preventive practice, by practice (mixed-effects logistic regression; adjusted odds ratios, 95% CI)

Determinant (CFIR domain, household as implementing unit)	Latrine use	Pig confinement	Water treatment
By-law awareness (Outer: policies and laws)	2.25 (1.70–2.98)***	1.76 (1.35–2.40)***	not in model
Cultural preference for free-ranging pigs (Outer: local attitudes)	not in model	0.60 (0.42–0.86)**	not in model
Distance to water source, per 100 m (Outer: local conditions)	not in model	not in model	0.88(0.78–0.99)*
Household income, per SD (Inner: available resources)	1.35 (0.89–2.05)	1.84 (1.22–2.78)**	1.19 (0.78–1.81)
Education ≥ primary (Individuals: capability)	1.74 (1.12–2.70)*	1.50 (0.99–2.28)	1.28 (0.86–1.89)
Household size, per person (Inner: structural)	1.01 (0.93–1.09)	1.30 (1.10–1.56)**	1.04 (0.95–1.14)
High perceived disease risk (Individuals: beliefs)	1.55 (1.10–2.10) **	not in model	not in model
Negative perception of water quality (Individuals: beliefs)	not in model	not in model	0.99 (0.82–1.19)
Female-headed household	0.51 (0.14–1.86)	0.89 (0.64–1.23)	1.32 (1.05–1.67)*
District: Songwe vs Kongwa	1.68 (1.20–2.35)**	0.73 (0.49–1.10)	1.42 (0.93–2.18)
Year 2021 vs 2019	1.07 (0.83–1.38)	0.26(0.19–0.36)***	1.20 (0.99–1.45)
Year 2025 vs 2019	2.94 (2.01–4.31)***	1.73 (1.18–2.55)**	1.11 (0.78–1.58)
Original allocation: intervention vs control	0.98 (0.77–1.26)	1.15 (0.76–1.75)	0.96 (0.66–1.40)

Note: **p < 0.05; **p < 0.01; ***p < 0.001. Three-level models with household and village random intercepts; "not in model" marks covariates that the conceptual specification did not include for that practice (Table S2). Odds ratios above 1 indicate higher odds of the practice. Coefficients are associations with covariate values at each wave and are not comparable in magnitude across models. The pig-confinement model includes pig-owning household-wave observations.*

Latrine use: social expectation and regulation

Quantitative: Latrine use was associated with by-law awareness (aOR 2.25, 95% CI 1.70–2.98; p < 0.001), high perceived disease risk (1.55, 1.10–2.10; p = 0.005), education of at least primary level (1.74, 1.12–2.70; p = 0.014) and residence in Songwe (1.68, 1.20–2.35; p = 0.002). Household income (1.35, 0.89–2.05) and female headship (0.51, 0.14–1.86) were not clearly associated; the interval for female headship is wide.

Qualitative: Participants described social consequences of lacking or not using a latrine. A male household participant said: "*It is a shame to be known as the household without a latrine – you cannot even host community meetings."* A Village Executive Officer described how *aibu* (shame) could affect a household's standing and its ability to host or receive visitors. Social enforcement was coded in 38 of 64 participants, an internalised sense of dignity and responsibility in 29 ("It is not just about the by-law anymore; it is about who you are") and fear of ridicule in 22. At the same time, 36 participants described by-laws that existed but were not enforced ("*The village by-law is there, but no one enforces it").*

Integration: The strands converge on social and regulatory reinforcement as a feature of latrine use, and the absence of an income association is consistent with reinforcement that operates beyond household economic capacity. The qualitative strand also extends the quantitative one: awareness of a by-law is not the same as enforcement of it, so the survey item should not be read as a measure of enforcement.

Pig confinement: economic contingency

Quantitative: Confinement was associated with by-law awareness (aOR 1.76, 95% CI 1.35–2.40; p < 0.001), household income (1.84, 1.22–2.78; p = 0.004) and household size (1.30, 1.10–1.56; p = 0.004), and inversely with a cultural preference for free-ranging pigs (0.60, 0.42–0.86; p = 0.005). Education of at least primary level was borderline (1.50, 0.99–2.28; p = 0.058), and female headship (0.89, 0.64–1.23) and district (0.73, 0.49–1.10) were

not clearly associated. The temporal course was non-linear: a large fall in 2021 (0.26, 0.19–0.36) followed by a rise above baseline in 2025 (1.73, 1.18–2.55).

Qualitative: Participants did not generally describe non-confinement as a lack of knowledge. They described confinement as an investment in construction, feed, labour and upkeep that they reconsidered when costs rose, disease struck or returns fell: 41 of 64 described explicit cost–benefit calculations and 34 described sensitivity to disease or market shocks. A male pig keeper said: *"I used to keep ten pigs in a pen. Then the disease came. It is not worth the cost to build another." Another said: "When the price of pork dropped, we let them roam again. It was cheaper to let them find food than to buy feed."* Twelve participants described wealthier households that built pens first and stopped after losses ("The richer farmers-built pens first. But when the disease came, they lost more money and stopped.").

Integration: The income association and the accounts of economic reasoning agree that confinement is conditional on resources. The qualitative strand extends the quantitative one by suggesting why confinement can fall as well as rise: recognising its value did not protect it against production shocks. The survey did not record the timing or incidence of disease or price shocks, so linking them to the 2021 fall remains an interpretive hypothesis.

Household water treatment: effort and weak reinforcement

Quantitative: Water treatment was not associated with a time trend (2025 vs 2019: aOR 1.11, 0.78–1.58). Greater distance to the water source was associated with lower odds (0.88 per 100 m, 0.78–0.99; p = 0.036), and female-headed households had higher odds (1.32, 1.05–1.67; p = 0.018). Income, education, household size and district were not clearly associated. Perceived disease risk was not included in the primary water treatment model because it is conceptually distal to water treatment behaviour.

Qualitative*:* Participants emphasized the cumulative effort of treating water every day, after the effort of collecting it, for a benefit that is not visible. A female household head said: "After

walking far for water, you just want to drink – not wait for treatment. The benefit is invisible." Habit fatigue was coded in 33 participants, invisible benefit in 28 and cumulative effort in 25. Others noted that there was no by-law for water treatment and that it was emphasised during outbreaks: "*There is no regulation or by-law for water treatment. It is just emphasised during disease outbreaks like cholera*." Twenty-four participants described water as a task that falls to women.

Integration: The flat trend, the distance association and the accounts of repeated effort converge. The qualitative strand explains why a practice that is not reinforced by visible infrastructure, social expectation or regulation may erode when immediate threats recede. The higher odds in female-headed households may reflect women's responsibility for water rather than stronger motivation, which these data cannot distinguish.

Cross-practice interaction tests

None of the six pre-specified interaction tests was statistically detectable after FDR adjustment (q = 0.375–0.470; Table 3). The interaction terms involve behaviours measured at the same wave in the same households and are open to shared unmeasured household characteristics, simultaneity and reverse causation. They test whether a determinant's association with one practice varies by another practice, not whether determinants differ between practices, and were treated as exploratory.

Table 3: Tests of cross-practice interactions

Outcome model	Interaction tested	aOR (95% CI)	p-value	FDR q
Water treatment	Income × pig confinement	0.85 (0.72–1.01)	0.067	0.375
Pig confinement	Cultural preference × latrine use	1.12 (0.95–1.32)	0.18	0.375
Water treatment	Education × pig confinement	0.91 (0.79–1.06)	0.24	0.375
Pig confinement	Income × water treatment	1.10 (0.94–1.28)	0.25	0.375
Latrine use	By-law awareness × water treatment	1.08 (0.91–1.28)	0.38	0.456
Latrine use	Sex of head × water treatment	1.07 (0.89–1.28)	0.47	0.47

Note. *Benjamini*–Hochberg correction across six pre-specified tests

400 **Village-level clustering**

401 After adjustment, residual clustering remained at village level for all three practices (Table
402 4). Village-level ICCs were 0.13 for latrine use, 0.15 for pig confinement and 0.17 for water
403 treatment; household-level ICCs, which describe the similarity of repeated observations on
404 the same household, were 0.23, 0.28 and 0.28. Households in the same village therefore
405 resembled each other more than households in different villages, most for water treatment.
406 Qualitative accounts pointed to by-law enforcement, livestock-disease exposure, leadership
407 engagement, collective norms, water infrastructure, community health worker activity and
408 community mobilisation as candidate sources of this clustering (Table S5); these are
409 hypotheses, not tested mediators.

410

411 **Table 4: Variance components and intraclass correlations**

Practice	Household variance	Village variance	Village-level ICC	Household-level ICC
Latrine use	0.423	0.543	0.13	0.23
Pig confinement	0.567	0.684	0.15	0.28
Water treatment	0.534	0.766	0.17	0.28

412 *Note:* Latent-scale ICCs from three-level logistic models. $Village-level\ ICC = \sigma^2(village) /$
413 $[\sigma^2(village) + \sigma^2(household) + \pi^2/3]. Household-level\ ICC = [\sigma^2(village) +$
414 $\sigma^2(household)] / [\sigma^2(village) + \sigma^2(household) + \pi^2/3]$.

415

416 **Integrated findings**

417 Table 5 brings the strands together. Each practice showed a distinct combination of temporal
418 course, quantitative correlates and qualitative mechanism, but each also showed more than
419 one COM-B component, so the labels “dominant” and “primary” refer to the weight of the
420 evidence and not to an estimated share of variance.

421

422 **Table 5: Joint display of quantitative and qualitative findings**

Practice	Quantitative pattern	Qualitative mechanism	COM-B and CFIR reading	Meta-inference	Hypothesised implementation response (BCW function; heuristic)

					Accountability and social reinforcement with equity safeguards (restriction, modelling, environmental restructuring); **Enforce**
Latrine use	Flat to 2021, higher by 2025 (aOR 2.94); by-law awareness 2.25; risk 1.55; income not clear	Shame, hosting obligations, internalised identity; by-laws known but often not enforced	Social opportunity (norms, regulation); reflective motivation; capability (education). Outer setting: policies and laws, local attitudes	Convergence; qualitative strand extends (awareness is not enforcement)	
Pig confinement	Fall in 2021 (0.26), rise by 2025 (1.73); income 1.84; cultural preference 0.60; by-law awareness 1.76	Investment in construction, feed and labour; reconsidered after disease and price shocks	Physical (economic) opportunity; social opportunity and automatic motivation (cultural preference). Inner setting: resources; outer setting: local conditions	Convergence; qualitative strand explains volatility (hypothesis)	Material and risk-buffering support (enablement, incentivisation, environmental restructuring); **Enable**
Water treatment	No change (1.11); distance 0.88 per 100 m; female-headed 1.32	Daily effort after collection, invisible benefit, no by-law, outbreak-driven attention; women's task	Physical opportunity (time and effort); automatic motivation (habit); reflective motivation. Outer setting: policies and laws; critical incidents	Convergence; qualitative strand explains the flat course	Reduce effort and build routine, e.g. treatment at the point of collection, prompts (environmental restructuring, enablement, habit formation); **Embed**

Sensitivity analyses

Key estimates were stable across alternative working correlation structures, village-only and household-only random-effect models, a wild cluster bootstrap, inverse probability weighting and exclusion of influential villages (Table S4): aORs for by-law awareness and latrine use ranged 2.19–2.28, for income and pig confinement 1.80–1.86, and for distance and water treatment 0.87–0.89.

Discussion

Three behaviours promoted by one programme followed visibly different courses. Latrine use was flat until 2021 and then rose; pig confinement fell sharply and then recovered; water

treatment did not move. Each course was paired with a different set of correlates and a different qualitative explanation: social expectation and regulation for latrines, costs and shocks for pig confinement, and daily effort with little visible benefit for water treatment. We interpret these as three constraint structures and name them norm-reinforced latrine use, economically contingent pig confinement and effort-eroded water treatment. These are analytical archetypes drawn from the integrated evidence, not validated typologies. Below we say which parts of the inference are strong (the differences in temporal course) and which are weak (the differences in determinants).

Latrine use: Reinforced by norms, but not equivalent to adequate sanitation

Latrine use showed the clearest improvement, but its course needs careful reading. Odds were unchanged between 2019 and 2021, so the 2025 gain cannot be attributed to the 2020 education alone; it followed reinforcement in 2023, the delivery of the programme to control villages and wider changes in sanitation initiatives, enforcement and community expectations that we did not measure. By-law awareness was strongly associated with use (aOR 2.25), and participants spoke of shame, hosting obligations and an internalised sense of responsibility, which fits accounts of how injunctive and descriptive norms shape sanitation behaviour [9, 10]. Three cautions apply. First, awareness is not enforcement: 36 of 64 participants described by-laws that existed but were not enforced, so the survey item cannot be read as a measure of enforcement. Second, awareness and use were reported by the same respondent at the same wave, so shared-method bias and reverse causation are plausible. The item referred to sanitation by-laws, so its association with pig confinement (aOR 1.76) more likely reflects general exposure to village governance, civic engagement or programme contact than pig-specific regulation. Third, use is not adequacy. In the 2025 infrastructure survey of the wider trial population, 82.2% of 713 households had a latrine but only 13.9% had one with a cement floor, complete walls and a roof (Nyerere *et al.,* under review-c). Norms may sustain use of facilities that are structurally poor, and whether such use protects pigs' environments from faecal contamination is unknown.

Pig confinement fell in 2021 (aOR 0.26) and exceeded baseline in 2025 (1.73). Qualitative accounts described continuing demands for construction, feed, labour and upkeep, and a willingness to abandon confinement when disease or prices made it uneconomic. Higher income (aOR 1.84) and household size (1.30) were associated with confinement, and a cultural preference for free-ranging pigs with lower odds (0.60). The 2021 fall is the most striking quantitative result and is not explained by the survey data; the qualitative accounts of disease and price shocks offer a plausible but untested interpretation. Because household income was available from 2025 only, its association with confinement at earlier waves is cross-sectional in effect and cannot show that income preceded confinement. The results refine the Wealth Paradox reported for this cohort (Nyerere et al., under review-b): resources may enable adoption without protecting against discontinuation when production risk changes. This is consistent with frameworks that treat adoption and maintenance as separate dimensions [26, 27] and with evidence that determinants of adoption and of sustainment differ [28]. Confinement may stay desirable in principle while becoming harder to sustain as conditions change, which is the kind of loss of fit that the Dynamic Sustainability Framework describes [6]. We also note that the present models estimate correlates of practice at each wave; they cannot test the discontinuation component of the paradox, which rests on the companion trajectory analysis.

Water treatment showed no secular change (aOR 1.11 in 2025). Greater distance to the source was associated with lower odds (0.88 per 100 m), and participants described treatment as a further daily task after a long walk for water, with no visible benefit, no by-law and attention mainly during outbreaks such as cholera. This agrees with evidence that household water treatment is hard to sustain when it relies on repeated effort and consumables [11, 29, 30]. Female-headed households had higher odds (1.32), and 24 of 64 participants described water as women's work. The association may reflect the concentration of water tasks among women rather than greater motivation. We also stress the limit noted in the Background: because the epidemiological weight of drinking water in *T. solium* transmission is uncertain, water treatment is informative here chiefly as an example of an effort-intensive, weakly reinforced household practice.

493

494 The differences in temporal course are well supported: the year effects come from models
495 with a common structure, and their confidence intervals do not overlap (latrine use in 2025,
496 2.01–4.31, versus water treatment, 0.78–1.58; pig confinement in 2021, 0.19–0.36, versus
497 0.83–1.38 for latrine use and 0.99–1.45 for water treatment). The differences in determinants
498 are weaker. The models contain different covariates by design, so a covariate absent from
499 one model cannot appear as “specific” to another. By-law awareness was associated with
500 both latrine use and pig confinement, with overlapping intervals (1.70–2.98 and 1.35–2.40).
501 Income had overlapping intervals across all three practices (0.89–2.05, 1.22–2.78 and 0.78–
502 1.81). A coefficient that is significant in one model and not in another does not show that the
503 two differ [31]. The cross-practice interaction tests do not address this question, because
504 they ask whether a determinant’s association with one practice varies by another practice,
505 and the pre-specified tests had limited power to detect moderate interactions [32, 33]. A
506 formal test would stack the three outcomes in one model and test practice-by-determinant
507 interactions with shared covariates. We have not done this and recommend it. The claim of
508 practice-specificity therefore rests on the convergence of three lines of evidence: different
509 temporal courses, different correlate profiles, and different qualitative mechanisms. It is
510 strongest for the first and third and provisional for the second.

511

512 Two methodological explanations deserve comment. Baseline prevalences differed (58.5%
513 for latrine use, 22.7% for confinement among pig owners and 36.7% for water treatment),
514 but the courses do not follow a ceiling or floor pattern: confinement had the lowest baseline
515 and fell substantially, whereas latrine use did not change between 2019 and 2021 despite
516 more scope to rise. Self-report may also differ in accuracy across practices, particularly for
517 latrine use, where social desirability may inflate reporting; qualitative accounts of shame
518 show that reporting and norms may be intertwined.

519

520 Our data give only a coarse view of sustainment. The waves are two and four years apart,
521 so “sustained” means reported at all three waves, not continuous, and a household that
522 stopped and restarted between waves would be classed as sustained. Practice cycling was

uncommon in the trajectory classification (15 of 521 households, 2.9%; Table S7), and a pattern such as 1→0→1 can reflect genuine interruption and resumption, episodic or seasonal change, or misclassification of a self-report. The idea that discontinuation may be temporary re-alignment to changing circumstances rather than permanent cessation [6, 34] is plausible and consistent with participants' accounts of resuming practices after disease or outbreaks. It remains a hypothesis. Testing it requires more frequent measurement, verification that does not depend on self-report, and models of transitions between states.

A common implicit assumption in multi-behaviour programmes is that behaviours delivered together need the same implementation strategy to be sustained. Reviews of sustainment show that the components of complex interventions may need different supports to remain in place and that standard implementation strategies address sustainment unevenly [35–37]. Our findings suggest that heterogeneity of this kind can occur among behaviours within one programme and within the same households. The implication is not that integrated programmes should be abandoned. The transmission system is integrated, so the platform can remain integrated, while the implementation function it supplies to each practice is differentiated according to the dominant constraint.

We propose Enforce–Enable–Embed as a decision logic for translating a practice-specific diagnosis into an implementation function. It is not a new theory or an intervention package. *Enforce* means institutional accountability and social reinforcement where practice depends on norms and regulation, as for latrine use. *Enable* means material, financial and risk-buffering support where recurrent resources constrain practice, as for pig confinement. *Embed* means reducing the effort per episode and building routines where repeated effort threatens practice, as for water treatment. The heuristic is aligned with COM-B and the BCW, whose functions it groups (Table 5), and its contribution is the proposed matching of function to diagnosed constraint [38, 39].

The matching makes testable predictions. Where latrine use is norm-reinforced, strengthening accountability and community monitoring should sustain use better than

materials support alone. Where confinement is economically contingent, low-cost materials and protection against production shocks should sustain it through disease and price shocks better than education alone. Where water treatment is effort-eroded, treatment at the point of collection and cues that build routine should sustain it better than reminders. These can be tested in sequential multiple assignment or factorial cluster trials with sustainment, measured by an objective indicator over at least two years, as the primary outcome.

A caution applies to *Enforce*. Regulation that is not matched by the means to comply can penalise households that cannot afford compliance, and is likely to fall hardest on low-income and female-headed households. In practice *Enforce* should be paired with *Enable* and evaluated for equity effects. Because the label is easily read as coercion, “reinforce” may communicate the intended meaning better.

Limitations

First, the quantitative outcome is practice status at each wave, so the models estimate correlates of practice across waves and do not directly model sustainment or discontinuation. Our statements about sustainment rest on trajectory descriptions, the companion analyses and the qualitative accounts, and transition models would answer the first research question more directly. Second, the associations are observational, and residual confounding, measurement error and reverse causation are possible. In particular, household income was measured at endline, and by-law awareness and the practices were reported by the same respondents at the same wave. Third, outcomes were self-reported and may be subject to recall and social-desirability bias, most for latrine use; objective verification of latrine use and water treatment should be used where feasible. Fourth, the practice-specific models contain different covariates and are not directly comparable; practice-specificity of determinants is suggestive and awaits a joint test. Fifth, the interaction analyses had limited power and are exploratory. Sixth, time-varying covariates were not separated into within- and between-household components, so associations mix stable household differences with change over time [40]. Seventh, village-level ICCs do not identify the processes behind clustering; the village-level factors in Table S5 are hypotheses. Eighth,

583 the cohort is restricted to 521 households observed at all three waves (59.7% of those
584 enrolled), and selection into it may relate to mobility and assets despite weighting. Ninth,
585 behaviours in control villages may have been influenced by spill-over from intervention
586 villages, and original allocation is included only as a main effect, so the models do not
587 estimate intervention effectiveness. Tenth, the qualitative sample was purposive and its
588 counts show how widely themes were voiced, not prevalence; it was collected in 2026, a
589 year after the last survey. Eleventh, household income was only available at endline and was
590 therefore excluded from the primary models to avoid reverse causation. Finally, the
591 archetypes and the Enforce–Enable–Embed heuristic are products of this analysis. Their
592 feasibility, acceptability, cost and effect on sustainment are untested, and the study does not
593 show that strategies matched to constraints improve sustainment.
594
595 **Conclusion**
596 Behaviours promoted through one *Taenia solium* programme followed clearly different
597 courses over six years and were linked to different combinations of social reinforcement,
598 economic capacity and repeated effort. The evidence for different temporal courses and
599 different qualitative mechanisms is strong; the evidence for different determinants is
600 suggestive and needs a joint test. The findings support integrated delivery with practice-
601 specific implementation. Programmes should diagnose the dominant constraint on each
602 practice and match the implementation function to it, with attention to equity. Enforce–
603 Enable–Embed offers a way of doing so and should now be tested prospectively, using
604 objective measures of sustained practice.
605
606 **Abbreviations**
607 **aOR:** adjusted odds ratio; BCW: Behaviour Change Wheel; CFIR: Consolidated Framework
608 for Implementation Research; COM-B: Capability–Opportunity–Motivation–Behaviour; FDR:
609 false discovery rate; FGD: focus group discussion; GEE: generalised estimating equations;
610 GRAMMS: Good Reporting of A Mixed Methods Study; ICC: intraclass correlation

coefficient; IDI: in-depth interview; IPW: inverse probability weighting; KII: key-informant interview.

Declarations

Ethics approval and consent to participate: Ethical approval was obtained from the National Institute for Medical Research, Tanzania (NIMR/HQ/R.8a/Vol.IX/4653) and Sokoine University of Agriculture (SUA/ADM/R.1/8/1243), with administrative clearance from the President's Office – Regional Administration and Local Government (PO-RALG; Ref. AB.307/323/01/237). Procedures followed the ethical standards of the responsible committees and the Declaration of Helsinki and its amendments. Written informed consent was obtained from all households at each survey wave and from all qualitative participants, who were free to withdraw at any time. Data were stored on password-protected servers with access restricted to the research team, and anonymised identifiers were used in all analyses.

Consent for publication. Not applicable.

Availability of data and materials:

The de-identified quantitative dataset, data dictionary, study protocol, statistical analysis plan, and analysis code are available from the corresponding author upon reasonable request. However, the qualitative transcripts and raw household data cannot be shared publicly due to ethical restrictions imposed by the National Institute for Medical Research (NIMR), Tanzania, which protect participant privacy in this rural setting. Researchers who meet the criteria for access to confidential data may request access by contacting the NIMR Ethics Committee and the corresponding author.

Competing interests: The authors declare that they have no competing interests

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641 **Authors' contributions:** ADN conceptualized the study, developed the methodology, led
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643 to study design and supervision across field implementation, community engagement,
644 veterinary data and epidemiology. FM curated the data and supported behavioural
645 interpretation. SG and DS provided methodological and analytical guidance, SG on
646 epidemiological methods and DS on implementation science frameworks. All authors
647 critically reviewed and approved the final manuscript.
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655
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Supplementary materials

Table S1: Baseline characteristics of the longitudinal analytic cohort by district

Characteristic	Overall (N = 521)	Kongwa (n = 367)	Songwe (n = 154)	p-Value
Female-headed household, n (%)	131 (25.1)	91 (24.8)	40 (26.0)	0.78
Household size, mean (SD)	5.8 (2.1)	5.9 (2.2)	5.6 (1.9)	0.06
Age of household head, mean (SD), years	46.2 (15.4)	46.8 (15.8)	44.9 (14.5)	0.21
Education of head ≥ primary, n (%)	302 (58.0)	210 (57.2)	92 (59.7)	0.6
Wealth index (PCA), mean (SD)	0.0 (1.0)	0.05 (1.02)	−0.12 (0.95)	0.08
Wealth tertile: low, n (%)	174 (33.4)	118 (32.2)	56 (36.4)	0.18
Wealth tertile: medium, n (%)	174 (33.4)	122 (33.2)	52 (33.8)	—
Wealth tertile: high, n (%)	173 (33.2)	127 (34.6)	46 (29.9)	—
Pig-owning households, n (%)	348 (66.8)	240 (65.4)	108 (70.1)	0.29
Number of pigs owned, mean (SD)	4.2 (3.8)	4.0 (3.6)	4.6 (4.2)	0.15
Latrine use, n (%)	305 (58.5)	215 (58.6)	90 (58.4)	0.97
Pig confinement†, n (%)	79 (22.7)	53 (22.1)	26 (24.1)	0.69
Water treatment, n (%)	191 (36.7)	135 (36.8)	56 (36.4)	0.93
By-law awareness, n (%)	167 (32.1)	112 (30.5)	55 (35.7)	0.26
Perceived disease risk (high), n (%)	215 (41.3)	152 (41.4)	63 (40.9)	0.92
Cultural preference for free-ranging pigs, n (%)	227 (43.6)	162 (44.1)	65 (42.2)	0.69

Note. *Among pig-owning households (n = 348). p-values compare Kongwa and Songwe*

Table S2: Covariates in each practice model, mapped to CFIR and COM-B (household as implementing unit)

Covariate	Latrine use	Pig confinement	Water treatment	CFIR domain	COM-B component
By-law awareness	Yes	Yes	No	Outer setting: policies and laws	Social opportunity (and some capability)
Perceived disease risk (high)	Yes	No	No	Individuals: beliefs	Reflective motivation

Cultural preference for free-ranging pigs	No	Yes	No	Outer setting: local attitudes	Social opportunity; automatic motivation
Distance to water source	No	No	Yes	Outer setting: local conditions	Physical opportunity
Negative perception of water quality	No	No	Yes	Individuals: beliefs	Reflective motivation
Household income	Yes	Yes	Yes	Inner setting: available resources	Physical opportunity
Education ≥ primary	yes	Yes	Yes	Individuals: capability	Psychological capability
Household size	Yes	Yes	Yes	Inner setting: structural characteristics	Physical opportunity (labour)
Sex of household head	Yes	Yes	Yes	Individuals	Equity covariate
District, survey year, allocation	Yes	Yes	Yes	Context and design covariates	—

Note. *By-law enforcement and village leadership were examined only qualitatively.*

Table S3: Thematic inclusion and exclusion criteria

Theme	**Inclusion criteria**	**Exclusion criteria**
Norm internalisation	Explicit references to social enforcement, internalised identity, shame or stigma related to latrine use	Latrine use without a social dimension; personal preference alone
Rational economic disinvestment	Explicit cost–benefit calculations; references to disease risk, market volatility or the Wealth Paradox	General economic hardship; lack of knowledge
Volitional collapse	Habit fatigue, invisible benefits or cumulative effort burden	Occasional lapses; single episodes of non-adherence
Structural barriers	Lack of resources, weak enforcement, infrastructure deficits or gendered responsibility	Knowledge deficits; motivation deficits

Implementation mechanisms	Facilitator quality, community engagement or health-education effectiveness	General references to the intervention without a mechanism
Negative and deviant cases	Cases that challenge dominant patterns (knowledge without behaviour; wealthy discontinuers; gender differences)	Cases that fit dominant patterns

Note. *In the main text the themes are labelled norm-reinforced latrine use, economically contingent pig confinement and effort-eroded water treatment.*

Table S4: Sensitivity analyses for the principal determinant of each practice (adjusted odds ratio, 95% CI)

Analysis	Latrine use: by-law awareness	Pig confinement: household income	Water treatment: distance per 100 m
Primary three-level GLMM	2.25 (1.70–2.98)	1.84 (1.22–2.78)	0.88 (0.78–0.99)
GEE, independence	2.28 (1.73–3.01)	1.82 (1.21–2.75)	0.87 (0.78–0.97)
GEE, exchangeable	2.19 (1.65–2.90)	1.80 (1.19–2.72)	0.89 (0.79–0.98)
GEE, AR(1)	2.22 (1.68–2.94)	1.86 (1.24–2.80)	0.88 (0.79–0.98)
GEE, unstructured	2.26 (1.71–2.99)	1.83 (1.21–2.77)	0.89 (0.79–0.98)
GLMM, village random effect only	2.25 (1.70–2.98)	1.84 (1.22–2.78)	0.88 (0.78–0.99)
GLMM, household random effect only	2.24 (1.69–2.97)	1.83 (1.21–2.77)	0.88 (0.79–0.98)
Wild cluster bootstrap	2.23 (1.68–2.96)	1.83 (1.21–2.76)	0.88 (0.78–0.99)
Inverse probability weighting	2.21 (1.67–2.93)	1.85 (1.23–2.79)	0.88 (0.79–0.98)
Excluding influential villages	2.27 (1.72–3.00)	1.82 (1.20–2.76)	0.89 (0.79–0.99)

Note: *Models adjusted as in Table 2. In a balanced panel, "balanced panel only" and "complete cases only" analyses coincide with the primary sample and are not shown. The criterion for "influential villages" is given in the Supplementary Methods.*

Table S5: Candidate village-level factors that may underlie residual clustering (hypotheses from the qualitative analysis)

CFIR domain	Village-level factor	Hypothesis
Outer setting	By-law enforcement	Villages with stronger enforcement have higher latrine use

Outer setting	Livestock disease exposure (e.g. African swine fever)	Villages with recent exposure have lower pig confinement
Inner setting	Village leadership engagement	Engaged leadership is associated with higher adoption across practices
Inner setting	Collective social norms	Stronger collective norms are associated with higher adoption across practices
Inner setting	Water infrastructure	Better water access is associated with higher water treatment
Individuals	Community health worker activity	More active workers are associated with higher adoption across practices
Process	Community mobilisation	Stronger mobilisation is associated with higher adoption across practices

Note: *These factors come from participants' accounts. Village-level contrasts were not tested, and the table should not be read as a set of findings.*

Table S6a: Full model output: latrine use

Parameter	Coefficient	SE	z	p	aOR	95% CI
Intercept	−1.234	0.456	−2.71	0.007	0.29	0.12–0.71
By-law awareness (yes)	0.811	0.149	5.44	0.001	2.25	1.70–2.98
Household income (SD)	0.3	0.213	1.41	0.158	1.35	0.89–2.05
Education ≥ primary	0.554	0.224	2.47	0.014	1.74	1.12–2.70
Household size	0.01	0.039	0.26	0.797	1.01	0.93–1.09
Female-headed household	−0.673	0.647	−1.04	0.298	0.51	0.14–1.86
Perceived disease risk (high)	0.438	0.155	2.82	0.005	1.55	1.10–2.10
District (Songwe vs Kongwa)	0.519	0.169	3.07	0.002	1.68	1.20–2.35
Year 2021 (vs 2019)	0.068	0.13	0.52	0.603	1.07	0.83–1.38
Year 2025 (vs 2019)	1.078	0.162	6.65	<0.001	2.94	2.14–4.04
Intervention group	−0.020	0.128	−0.16	0.875	0.98	0.77–1.26
Household variance (σ^2)	0.423	0.156				
Village variance (σ^2)	0.543	0.178				
Village-level ICC	0.13					
Household-level ICC	0.23					

Note: *AIC 1876.4; BIC 1942.7; log-likelihood −927.2; 1,563 observations; 521 households; 42 villages. Estimates for fixed effects are reported with Wald 95% confidence intervals, derived from the model standard errors.*

Table S6b: Full model output: pig confinement

Parameter	Coefficient	SE	z	p	aOR
Intercept	−2.134	0.678	−3.15	0.002	0.12
By-law awareness (yes)	0.565	0.156	3.62	<0.001	1.76
Household income (SD)	0.61	0.211	2.89	0.004	1.84
Education ≥ primary	0.405	0.214	1.89	0.059‡	1.5
Household size	0.262	0.091	2.88	0.004	1.3
Female-headed household	−0.117	0.164	−0.71	0.476	0.89
Cultural preference (free-ranging)	−0.511	0.183	−2.79	0.005	0.6
District (Songwe vs Kongwa)	−0.315	0.208	−1.51	0.13	0.73
Year 2021 (vs 2019)	−1.347	0.166	−8.11	<0.001	0.26
Year 2025 (vs 2019)	0.548	0.192	2.85	0.004	1.73
Intervention group	0.14	0.214	0.65	0.513	1.15
Household variance (σ^2)	0.567	0.198			
Village variance (σ^2)	0.684	0.234			
Village-level ICC	0.15				
Household-level ICC	0.28				

Note: AIC 1432.5; BIC 1498.8; log-likelihood −705.2; 1,044 observations from 348 pig-owning households; 42 villages

Table S6c: Full model output: water treatment

Parameter	Coefficient	SE	z	p	aOR	95% CI
Intercept	−1.876	0.512	−3.66	<0.001	0.15	0.06–0.41
Household income (SD)	0.174	0.215	0.81	0.418	1.19	0.78–1.81
Education ≥ primary	0.247	0.199	1.24	0.215	1.28	0.86–1.89
Household size	0.039	0.046	0.85	0.396	1.04	0.95–1.14
Female-headed household	0.278	0.118	2.36	0.018	1.32	1.05–1.67
Distance to water source (per 100 m)	−0.128	0.061	−2.10	0.036	0.88	0.78–0.99
Negative water perception	−0.010	0.094	−0.11	0.914	0.99	0.82–1.19

District (Songwe vs Kongwa)	0.351	0.222	1.58	0.114	1.42	0.93–2.18
Year 2021 (vs 2019)	0.182	0.098	1.86	0.063	1.2	0.99–1.45
Year 2025 (vs 2019)	0.104	0.117	0.89	0.374	1.11	0.78–1.58
Intervention group	−0.038	0.189	−0.20	0.842	0.96	0.66–1.40
Household variance (σ^2)	0.534	0.182				
Village variance (σ^2)	0.766	0.267				
Village-level ICC	0.17					
Household-level ICC	0.28					

Note: *AIC 1965.3; BIC 2037.6; log-likelihood −970.6; 1,563 observations; 521 households; 42 villages. Estimates for fixed effects are reported with Wald 95% confidence intervals.*

Table S7: Composite behavioural trajectory classification of the 521 cohort households and the 48 household qualitative participants

Trajectory	Pattern	Cohort, n (%)	Qualitative participants (n = 48)
Sustained practice	1 → 1 → 1	180 (34.5)	8
Early adopters	0 → 1 → 1	150 (28.8)	6
Late adopters	0 → 0 → 1	31 (5.9)	6
Temporary adopters	0 → 1 → 0	15 (2.9)	4
Early discontinuers	1 → 0 → 0	50 (9.6)	8
Late discontinuers	1 → 1 → 0	60 (11.5)	6
Practice cyclers	1 → 0 → 1	15 (2.9)	4
Never practising	0 → 0 → 0	20 (3.8)	6
Total		**521 (100)**	**48 (100)**

Note*: Trajectories are based on latrine use across the three survey waves. The qualitative sample includes only the 48 household participants (24 in-depth interviews and 24 focus group discussants); the 16 key-informant interviews are excluded as they do not represent household trajectories*

Table S8: Qualitative sample composition

Method	n	Description
In-depth interviews	24	Household decision-makers, purposively sampled across behavioural trajectories

Focus group discussions	24	Four groups of six participants, one per village, stratified by gender and trajectory
Key-informant interviews	16	Village leaders, health workers and Extension Officers at district, regional and national levels
Total	64	

858

859 **Table S9: Thematic framework with definitions, illustrative quotations and participant**

860 **counts**

Sub-theme	Definition	Illustrative quotation	Participants
1a. Social enforcement	External pressure from community members, leaders or by-laws	"It is a shame [aibu] to be known as the household without a latrine – you cannot even host community meetings."	38/64 (59%)
1b. Internalised identity	Move from external compliance to dignity, responsibility or membership	"Having a latrine shows you are a responsible person. It is not just about the by-law anymore; it is about who you are."	29/64 (45%)
1c. Shame and stigma	Fear of exclusion or ridicule for non-compliance	"People talk if you don't have a latrine. They say you are dirty. You cannot even invite visitors."	22/64 (34%)
2a. Cost–benefit calculation	Deliberate weighing of costs against expected benefits	"I used to keep ten pigs in a pen. Then the disease came… It is not worth the cost to build another."	41/64 (64%)
2b. Disease risk and market volatility	Sensitivity to external shocks that affect feasibility	"When the price of pork dropped, we let them roam again. It was cheaper to let them find food than to buy feed."	34/64 (53%)
2c. Wealth paradox	Wealthier households disinvesting despite initial capacity	"The richer farmers built pens first. But when the disease came, they lost more money and stopped."	12/64 (19%)
3a. Habit fatigue	Erosion of motivation under cumulative effort	"After walking far for water, you just want to drink – not wait for treatment."	33/64 (52%)
3b. Invisible benefits	No immediate, visible reinforcement for effortful behaviours	"The water comes from the tap. Boiling is not necessary. And the benefit is invisible – you don't see anything."	28/64 (44%)
3c. Cumulative effort burden	Small daily efforts that add up to declining adherence	"It is not just one thing. You have to collect firewood, boil, cool, store. Every day."	25/64 (39%)
4a. Physical opportunity constraints	Lack of resources, infrastructure or access	"We wanted to build a pen, but timber is expensive. We have to choose between pig pen and food."	42/64 (66%)
4b. Social opportunity constraints	Weak enforcement, limited leader support or absent norms	"The village by-law is there, but no one enforces it. People just do what they want."	36/64 (56%)

4c. Gendered responsibility	Women bearing disproportionate responsibility for water and hygiene	"Water is women's work. We collect it, we store it, we treat it. Men don't think about it."	24/64 (38%)

Note: Percentages are the share of the 64 participants whose transcripts were coded to a sub-theme; participants could be coded to several, and the denominator includes key informants. Theme criteria are in Table S3.

Supplementary methods

SM1. Model specification: For household i in village j at wave t, logit $P(Y_ijt = 1) = \beta_0 + \beta_1(year)_t + \beta_2 X_ijt + u_i + v_j$, with $u_i \sim N(0, \sigma^2_household)$ and $v_j \sim N(0, \sigma^2_village)$. Y is the binary practice, X the covariates in Table S2, and u and v are the household and village random intercepts.

SM2. Intraclass correlations: On the latent logistic scale the level-1 residual variance is $\pi^2/3 \approx 3.29$ [23]. $Village-level\ ICC = \sigma^2_village\ /\ (\sigma^2_village + \sigma^2_household + \pi^2/3)$. $Household-level\ ICC = (\sigma^2_village + \sigma^2_household)\ /\ (\sigma^2_village + \sigma^2_household + \pi^2/3)$. A village-only formula that omits the household variance, which gives 0.14, 0.17 and 0.19, is the correlation in a two-level model and is not used.

SM3. Time-varying covariates: Time-varying covariates entered with their observed wave-specific values, and no within–between decomposition was performed [18]. Coefficients for by-law awareness, perceived risk, cultural preference, distance and water perception are therefore associations with the value at each wave. Household income was available from the 2025 survey.

SM4. Sensitivity analyses: Generalised estimating equations used a logit link with independence, exchangeable, AR(1) and unstructured working correlations. Inverse probability weights were the inverse of the fitted probability of belonging to the analytic cohort, from a logistic model on baseline covariates (wealth, education, district and others) [41]. Influential villages were identified using a leave-one-cluster-out approach,

supplemented by multilevel influence diagnostics. Specifically, we calculated Cook's distance for the fixed-effect estimates and standardized village-level residuals for the random intercepts. Villages were flagged as influential if their Cook's distance exceeded the conventional threshold of 0.5, or if their standardized residual exceeded |2.58| (corresponding to $p < 0.01$). Sensitivity models were then refitted excluding these flagged clusters to ensure that the primary estimates were not disproportionately driven by a small number of villages. Model adequacy was assessed by convergence, residual inspection and AIC/BIC; likelihood-ratio tests favoured models with village random effects ($p < 0.001$).

SM5. Variable construction: The wealth index was the first principal component (28% of variance) of standardised household asset and housing indicators, following DHS methods [17]; it is used descriptively and is not in the models in Table S6. By-law awareness was a binary item: "Do you know of any local by-laws or regulations regarding sanitation or latrine use in your village?" (1 = yes, 0 = no), updated at each wave.

SM6. Cross-practice interaction models: For each pre-specified pair, the model for practice *k* added a determinant X, the status of another practice Z and their product: $logit\ P(Y\hat{}k_ijt = 1) = \beta_0 + \beta_1 X_ijt + \beta_2 Z_ijt + \beta_3 (X_ijt \times Z_ijt) + u_i + v_j$. Because Z is contemporaneous with Y and the practices may share unmeasured household determinants, β_3 is an exploratory statistical association and not evidence of causal spill-over. Absence of a detectable interaction does not show that practices have independent determinants. FDR-adjusted q-values are in Table 3.

Supplementary Files

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