UDC 338.45:620.91:004.82
DOI: 10.15587/1729-4061.2026.352950

IDENTIFYING THE EFFECTS OF TECHNOLOGY ACCEPTANCE MODEL CONSTRUCTS ON SMALL-SCALE RENEWABLE ENERGY ADOPTION IN RURAL CONTEXTS

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The object of the study is the adoption of small-scale renewable energy technologies on farms and in rural households. The research problem arises from fragmented and heterogeneous empirical findings obtained in studies based on the technology acceptance model (TAM), which prevent the formation of quantitatively substantiated conclusions regarding the role of key behavioral determinants of renewable energy adoption.

This study identifies and quantitatively synthesizes the effects of perceived usefulness and perceived ease of use on intention and actual adoption behavior within a theoretically focused and statistically rigorous framework. Eight independent studies with a total sample of 2,675 respondents were included. Effect sizes were aggregated using random-effects models and estimated through Fisher's Z transformation.

The results reveal robust and statistically significant positive effects of both perceived usefulness and perceived ease of use on adoption behavior. However, perceived usefulness demonstrates a more stable and structurally consistent influence across rural contexts. The findings indicate that adoption decisions are primarily driven by expected economic and functional benefits, highlighting the importance of emphasizing the practical value of renewable energy technologies in rural implementation strategies.

The distinctive feature of the study lies in its exclusive focus on core TAM constructs and systematic aggregation of effect sizes within rural small-scale renewable energy contexts. The results can be applied in the design of public policies and support programs aimed at enhancing perceived usefulness of renewable energy technologies under conditions of rural economic and infrastructural constraints

Keywords: decentralized energy systems, adoption intention, farmers, energy transition, food security

Received 24.11.2025
Received in revised form 29.01.2026
Accepted 16.02.2026
Published 27.02.2026

***How to Cite:** Kurmanov, N., Kabdullina, G., Kenzhin, Z., Zhambylova, G., Kabdolla, A., Adilbekuly, M. (2026). Identifying the effects of technology acceptance model constructs on small-scale renewable energy adoption in rural contexts. Eastern-European Journal of Enterprise Technologies, 1 (13 (139)), 76–87. https://doi.org/10.15587/1729-4061.2026.352950*

1. Introduction

With the global energy transition and increasing attention to sustainable development issues in the background, adoption of renewable energy sources has gained particular relevance. Growing global energy consumption, climate change, and the need to reduce greenhouse gas emissions require active development of decentralized and environmentally friendly energy solutions, especially at the household and rural levels [1, 2]. The small scale of renewable energy technologies, such as solar photovoltaic systems, solar irrigation pumps, and biogas plants, makes them a potentially accessible tool for increasing energy security and resilience of rural communities [3, 4].

Despite the technological maturity and economic feasibility of many small-scale renewable energy solutions, many countries still struggle to achieve widespread adoption in rural areas [5, 6]. This indicates that technological and economic factors alone cannot guarantee the adoption of innovations by users. In this context, behavioral and cognitive determinants of farmers' and rural households' willingness to adopt and use new energy technologies are particularly important. Understanding these factors is becoming essential for developing effective government support measures, incentive programs, and management decisions in both energy and agricultural sectors.

The Technology acceptance model is one of the most widely used theoretical frameworks for analyzing technology adoption processes. It explains the formation of user intentions and actual behavior through perceived usefulness and perceived ease of use. In recent years, TAM has seen increasing application to analyze adoption of renewable energy sources, primarily in rural and agricultural contexts [7]. The growing interest in this research direction corresponds with the global expansion of decentralized renewable energy systems. According to international energy reports, investments in small-scale and distributed renewable energy technologies have demonstrated steady growth over the past decade, particularly in developing and emerging economies where rural electrification remains a strategic priority. Empirical studies conducted since the mid-2010s cover diverse geographical contexts, including China, Iran, Pakistan, Vietnam, Colombia, and Indonesia, and address various decentralized technologies such as solar photovoltaic systems, solar irrigation pumps, and biogas installations, thus demonstrating the model's potential applicability for explaining energy decisions at the micro level. However, despite the expansion of decentralized renewable energy systems and increasing investment flows, the pace of small-scale renewable energy adoption remains uneven, reflecting persistent financial, infrastructural, and behavioral barriers.

Given the uneven pace of renewable energy adoption and the growing application of TAM in rural contexts, a systematic and quantitatively grounded assessment of behavioral determinants becomes particularly relevant and timely.

2. Literature review and problem statement

The technology acceptance model (TAM) is one of the most widely used and empirically tested theoretical frameworks for analyzing adoption and use of new technologies [8]. The model is based on the assumption that behavioral intention and actual use of a technology are determined by two key cognitive attitudes: PU (perceived usefulness) and PEOU (perceived ease of use) [9]. Due to its concise structure, transparent cause-and-effect logic, and the ability to be quantitatively verified, TAM has become very popular in research across various technological fields.

The results of meta-analytic and systematic studies in recent years confirm TAM's high explanatory power in educational technologies, information systems, and mobile applications. For example, [10] demonstrated the greatest and most consistent influence PU has on behavioral intention, while PEOU influences behavioral intention both directly and indirectly through PU. Authors also emphasize the presence of significant interstudy heterogeneity indicating contextual sensitivity of TAM relationships. Similar conclusions are presented in a comprehensive meta-analysis conducted by [11], thus confirming TAM's dominant role but also documenting variability in strength of PU and PEOU effects depending on the type of technology and the context of its usage.

The expansion of the technology acceptance model beyond traditional ICT contexts is reflected in studies of digital library systems, educational platforms, and other domain-specific technological solutions. In particular, a meta-analysis of mobile and digital library systems demonstrates the robust statistical significance of perceived usefulness and perceived ease of use [12], while related research highlights the dominant role of TAM in studies of healthcare management systems [13]. Building on these digitally oriented applications, contemporary studies on mobile services and artificial intelligence-based systems further confirm TAM's relevance while revealing its contextual limitations. Study [14] reports strong effects of perceived usefulness and perceived ease of use in AI-based systems, although the high technological novelty constrains the generalizability of these findings to more mature technologies, whereas [15] shows that the explanatory strength of TAM constructs varies across technology applications, indicating unresolved context sensitivity. Evidence from [16] suggests that institutional settings significantly moderate TAM relationships, implying that acceptance cannot be explained solely by individual perceptions. A recent meta-analysis [17] further reports substantial variability in TAM path coefficients across contexts, underscoring the lack of stable effect sizes across different technological domains.

Recent research [18] demonstrates the application of the technology acceptance model to renewable energy adoption, particularly in small-scale and decentralized rural contexts. However, unresolved issues remain regarding the stability and comparability of effect sizes across different technologies and rural environments due to contextual heterogeneity and methodological variation. These limitations indicate the need for a theoretically focused meta-analytic study aimed at isolating and quantifying the effects of core TAM constructs in rural renewable energy adoption.

Study [19] investigates solar home system adoption in rural communities and confirms the importance of perceived usefulness, although the conference-based format and localized sample limit the broader generalizability of its conclusions. Research in rural Iran [20] shows that acceptance of solar panel technologies is primarily driven by perceived economic and social benefits, while also indicating that socio-cultural factors shape adoption beyond what is fully captured by core TAM constructs. Similarly, [21] identifies perceived usefulness as the dominant determinant of households' intention to install solar panels, whereas the effect of perceived ease of use remains secondary and varies with education and prior technological experience. Studies on solar-powered irrigation technologies reveal comparable patterns, as [22] demonstrates the strong influence of perceived usefulness on farmers' adoption of solar PV water pumps while highlighting the moderating role of infrastructural and financial constraints, and [23] confirms TAM's applicability in rural Pakistan but reports a limited effect of perceived ease of use in low-literacy settings.

In the context of residential rooftop photovoltaic systems, [24] shows that social networks mediate TAM relationships, suggesting that adoption decisions are embedded in collective rural dynamics rather than individual perceptions alone. Research on biogas and anaerobic digestion technologies similarly emphasizes the primacy of perceived usefulness, as [25] shows that expected productivity gains and cost reductions drive the adoption of low-cost biodigesters despite constraints related to technical complexity, while [26] indicates that the influence of perceived ease of use is conditional on farm size and managerial capacity.

Finally, [27] confirms TAM's relevance in explaining farmers' intentions to adopt alternative fuel machinery in China, but also demonstrates that behavioral intentions are influenced by complementary factors beyond core TAM variables.

Overall, the reviewed studies consistently identify perceived usefulness as the primary driver of small-scale renewable energy adoption, whereas the influence of perceived ease of use remains weaker and highly context-dependent in rural environments characterized by limited technological literacy and structural constraints.

Despite the accumulation of a significant body of empirical research, the results of TAM application in renewable energy remain fragmented. Significant differences are observed across countries, technology types, and analytical methods used, including PLS-SEM, CB-SEM, and regression models. This hampers direct comparisons of results and prevents the formation of unified quantitative conclusions on PU and PEOU effect strength and robustness.

An analysis of existing reviews and meta-analyses reveals a number of unresolved issues. First, the reviewed literature often considers TAM in conjunction with alternative theoretical models, thus blurring the focus on its core constructs. Second, most reviews are primarily descriptive and do not involve rigorous meta-analytic aggregation of effects, limiting quantitative generalization of the results. Third, existing research primarily focuses on the ICT sector while the specifics of the rural context and small-scale renewable energy sources remain addressed insufficiently.

Despite the growing number of empirical studies applying TAM to renewable energy adoption, several issues remain unresolved. The accumulated empirical results remain disparate and heterogeneous. Studies assess the role of key TAM constructs differently: some of them identify perceived usefulness as the dominant factor in technology adoption, while others emphasize perceived ease of use or report weak and inconsistent effects. Differences in study countries, types of renewable energy technologies, levels of rural socioeconomic development, and methodological approaches further exacerbate this heterogeneity. As a result, there is no holistic and quantitatively substantiated understanding of which behavioral factors play a decisive role in adopting small-scale renewable energy technologies.

From a practical perspective, the lack of generalized and comparable findings limits the ability to develop targeted and effective measures to stimulate renewable energy adoption in rural areas. Government agencies and development institutions need to understand which technology attributes – usefulness, ease of use, or other characteristics – should be prioritized in policy and support programs. From a scientific perspective, there remains a need for a theoretically focused and quantitatively rigorous synthesis of empirical data capable of resolving the identified contradictions and enhancing the explanatory value of the TAM model in the energy domain.

Accordingly, against the backdrop of the global energy transition and persistent fragmentation of empirical results, application of a theoretically focused and quantitatively rigorous analysis of behavioral determinants of small-scale renewable energy adoption in rural areas is justified both scientifically and practically. All this allows to assert that it is expedient to conduct a study on systematically identifying and quantitatively synthesizing the effects of core technology acceptance model constructs on small-scale renewable energy adoption in rural environments.

3. The aim and objectives of the study

The aim of this study is to identify the influence of the core constructs of the technology acceptance model - perceived usefulness and perceived ease of use – on intention and/or actual adoption of small-scale renewable energy technologies in rural contexts. This will allow to developing and adjusting policy measures and management decisions aimed at stimulating adoption of renewable energy among farmers and rural households.

To achieve this aim, the following objectives were accomplished:

– to identify and quantify the pooled effect size of perceived usefulness on the intention and/or actual adoption behavior of small-scale renewable energy technologies, including an analysis of statistical significance and interstudy heterogeneity of the corresponding effects;

– to determine and quantify the pooled effect size of perceived ease of use on intention and/or actual adoption behavior of small-scale renewable energy technologies followed by an assessment of robustness and contextual sensitivity of the results;

– to conduct a comparative analysis of strength and robustness of the influence of perceived usefulness and perceived ease of use to identify the dominant behavioral determinant of adoption of small-scale renewable energy technologies in a rural context;

– to assess the presence and extent of potential publication bias in the included empirical studies to test the robustness and stability of the meta-analytic findings.

4. Materials and methods

4. 1. Object of the study, hypotheses, and methodological assumptions

The object of this study is the adoption of small-scale renewable energy technologies on farms and in rural households.

The study examines decentralized renewable energy solutions, including solar photovoltaic systems, solar irrigation pumps, and biogas plants, applied at the household and smallholder levels.

The subject of the study is generalized quantitative relationships between the technology acceptance model's key constructs – perceived usefulness and perceived ease of use – and the intention and/or actual behavior to adopt small-scale renewable energy technologies. The analysis is based on a systematic review and meta-analytic synthesis of previously published quantitative empirical studies.

Based on the theoretical tenets of the technology acceptance model and literature inconsistencies regarding the role of key TAM constructs in the context of small-scale renewable energy technology adoption in rural settings, the research formulates the following hypotheses:

– *H*1. Perceived usefulness has a positive and statistically significant effect on intention and/or actual behavior of farmers and rural households to adopt small-scale renewable energy technologies.

– *H*2. Perceived ease of use has a positive and statistically significant effect on intention and/or actual behavior of farmers and rural households to adopt small-scale renewable energy technologies.

– *H*3. Perceived usefulness demonstrates a stronger and more consistent relationship with the adoption of small-scale renewable energy technologies as opposed to perceived ease of use.

The study's methodological assumptions include conceptual comparability of the TAM model's underlying constructs across various empirical studies despite differences in the measurement scales used. It is assumed that the effects of independent studies can be aggregated by converting them to comparable statistical indicators including correlation coefficients and their transformation into Fisher's *Z* statistics. Intention and actual technology use are considered functionally similar behavioral outcomes, reflecting technological decision making at the individual level.

The study adopts the following methodological simplifications:

– analytical focus is limited to the TAM model's core constructs without including additional variables from extended versions of the model;

– analysis exclusively includes quantitative empirical studies;

– effects are not differentiated by specific types of renewable energy technologies or regional contexts.

For example, effect sizes derived from studies examining solar photovoltaic systems, solar irrigation pumps, and biogas installations across countries such as China, Iran, Pakistan, and Vietnam are aggregated within a unified analytical framework rather than analyzed separately by technology type or region.

These assumptions ensure theoretical integrity of the meta-analysis while also limiting the scope for a more detailed contextual result interpretation.

Fig. 1 presents the study's conceptual logic and the hypothesized relationships between the TAM model's key constructs.

Taken together, the formulated hypotheses and methodological assumptions define a theoretically grounded analytical framework aimed at isolating the effects of the core TAM constructs on renewable energy adoption behavior. The conceptual structure of the study, presented in Fig. 1, reflects the direct relationships between perceived usefulness, perceived ease of use, and intention and/or actual adoption behavior, which constitute the empirical focus of the subsequent meta-analysis. This framework provides the basis for aggregating heterogeneous empirical results within a unified and comparable analytical logic.

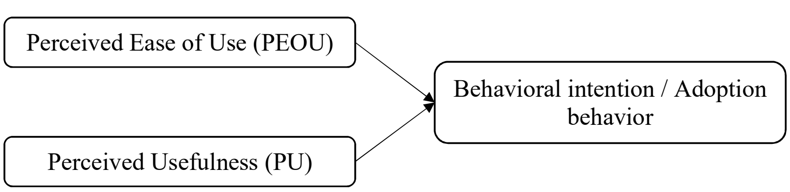

Fig. 1. Conceptual framework of the TAM-based meta-analysis of small-scale renewable energy technology adoption

4. 2. Research design and systematic review protocol

This study utilizes a systematic literature review and quantitative meta-analysis to summarize empirical findings from the TAM (technology acceptance model) in the context of small-scale renewable energy technology adoption in rural settings. The chosen study design ensures a theoretically focused and methodologically replicable aggregation of independent empirical study results.

The systematic review and meta-analysis were conducted following PRISMA 2020 guidelines ensuring transparency in the search, selection, and analysis of scientific publications and minimizing the risk of bias. The study included sequential steps of formulating selection criteria, systematically searching for relevant sources, screening and assessing their relevance to the study objectives, data extraction and coding, and subsequent meta-analytic synthesis of the results.

The empirical base for the study was formed with Web of Science and Scopus publications covering the period of active TAM model application in research on adopting renewable energy technologies. Selection of these sources stems from their high reputation and access to peer-reviewed scientific publications.

4. 3. Search strategy and eligibility criteria

A search for relevant scientific publications was conducted in the international bibliographic databases Web of Science and Scopus offering broad coverage of peer-reviewed empirical research in energy, economics, and social sciences. These sources were selected for their high reputation, strict indexing criteria, and the ability to perform reproducible searches.

The search strategy was developed with study objectives and the technology acceptance model's theoretical framework in mind. The search was conducted using combined queries including key terms reflecting the TAM model, renewable energy technologies, and their adoption and use processes. Query formulations were adapted to the syntactic features of each database and utilized Boolean operators. Table 1 presents detailed search strings.

Table 1

Search strings used in databases

Web of Science (WoS)	Scopus
TS = ((«technology acceptance model» OR TAM) AND («renewable energy» OR «solar energy» OR «solar photovoltaic» OR «solar PV» OR «photovoltaic system*» OR biogas) AND (adoption OR acceptance OR intention OR use))	TITLE-ABS-KEY («technology acceptance model» OR TAM) AND TITLE-ABS-KEY («renewable energy» OR «solar energy» OR «solar photovoltaic»OR «solar PV» OR «photovoltaic system*» OR biogas) AND TITLE-ABS-KEY (adoption OR acceptance OR intention OR use)

Studies were selected based on predefined inclusion and exclusion criteria aimed at ensuring theoretical consistency and methodological comparability of the analyzed works. Quantitative empirical studies based on the TAM model (with its extensions) were included in the analysis, provided they had key constructs of perceived usefulness and/or perceived ease of use and indicators of intention and/or actual behavior to adopt small-scale renewable energy technologies in a rural context. Studies conducted outside the rural context not consistent with the selected theoretical framework or lacking statistical indicators suitable for meta-analytic generalization were excluded. Table 2 presents detailed inclusion and exclusion criteria.

Table 2

Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Time span	2005–2025	Studies published outside the selected time period
Language	English	Other than English
Type of selected sources	Peer-reviewed journal articles and conference papers indexed in Scopus or Web of Science	Books, book chapters, theses, reports, working papers, grey literature
Theoretical framework	Technology acceptance model (TAM), including extended TAM models explicitly incorporating PU and/or PEOU	Studies based solely on TPB, UTAUT, DOI, or other frameworks without TAM core constructs
Key constructs	Perceived usefulness (PU) and/or perceived ease of use (PEOU) with a direct relationship to intention or behavior	Studies not reporting PU or PEOU, or not examining their relationship with adoption outcomes
Context	Farmers, rural households, agricultural producers in rural settings	Urban consumers, industrial users, non-rural populations
Technology	Small-scale renewable energy technologies (solar PV, solar home systems, biogas, solar pumps, decentralized RE solutions)	Energy efficiency measures, smart grids, smart home technologies, large-scale energy systems
Methodology	Quantitative empirical studies (SEM, regression, logit/probit) with extractable effect sizes or convertible statistics	Qualitative studies, conceptual papers, descriptive surveys without effect size information
Outcomes	Behavioral intention, adoption, or actual use of renewable energy technologies	Attitudes, awareness, satisfaction, or perceptions without behavioral outcomes

The inclusion and exclusion criteria presented in Table 2 were formulated to ensure theoretical consistency, methodological comparability, and contextual relevance of the selected empirical studies. Restricting the sample to TAM-based analyses focused on small-scale renewable energy technologies in rural settings reduces construct interpretation ambiguity and enhances the reliability of subsequent quantitative aggregation of results.

4. 4. Study selection and data extraction procedures

At the initial screening stage, identified publication titles and abstracts were reviewed to exclude studies inconsistent with the research topic, the Technology Adoption Model's theoretical framework, and the rural context of renewable energy technology adoption.

Fig. 2 presents overall sequence of study identification, screening, eligibility assessment, and inclusion as a PRISMA flow chart.

The study selection process followed the PRISMA 2020 guidelines [28] and consisted of identification, screening, eligibility, and inclusion stages. After removal of duplicates, 120 records were screened, 40 full-text articles were assessed for eligibility, and 8 studies were included in the quantitative synthesis.

The eligibility assessment stage involved a full-text review of publications in order to determine whether they met the inclusion and exclusion criteria. Special attention was paid to the use of the TAM model, the presence of key constructs of perceived usefulness and/or perceived ease of use, and the presentation of quantitative results suitable for meta-analytic generalization. Following this stage, a final set of studies was compiled for the systematic review and quantitative meta-analysis.

The data extraction and coding procedure was standardized and aimed at ensuring comparability of empirical results across independent studies. For each included publication, data would be extracted on sample characteristics, study context, type of renewable energy technology, analytical methods used, and statistical measures reflecting relationships between TAM model constructs and measures of intention and/or actual technology adoption behavior. Perceived usefulness and perceived ease of use variables were coded as primary explanatory factors while intention and actual technology adoption were considered target behavioral outcomes. Table 3 presents the detailed characteristics and coding scheme of the included studies.

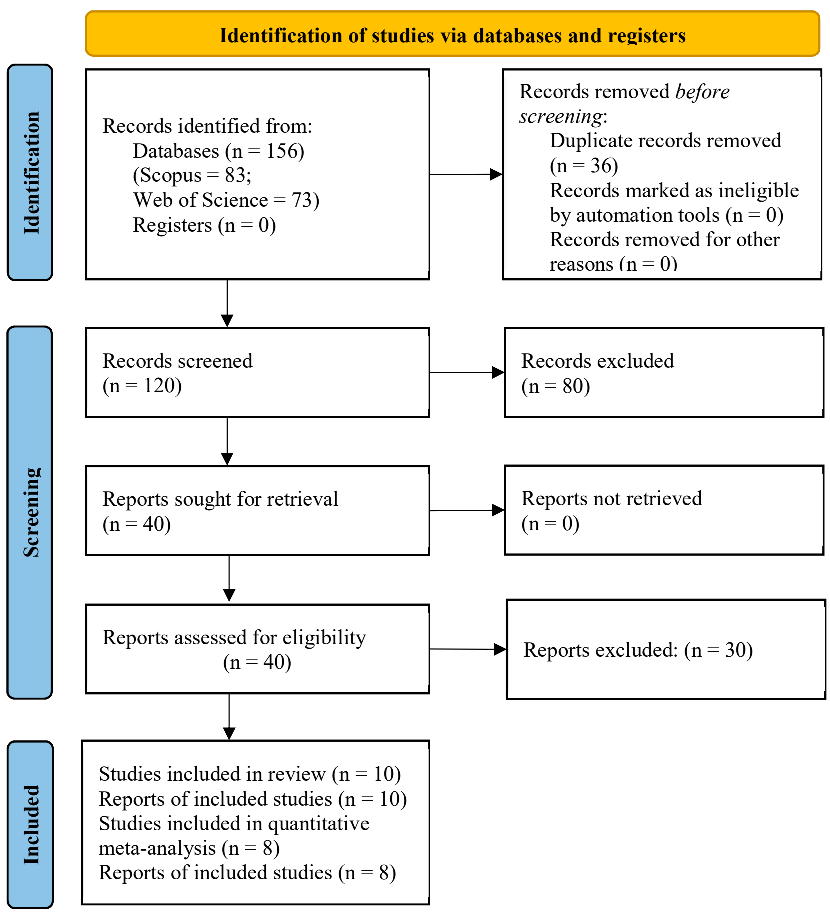

Fig. 2. PRISMA flow diagram of study selection

Source: [28]

Table 3

Characteristics and coding of included studies

Reference	Year	Country	n	Target group	Technology	Method	PU	PEOU	Outcome	Effect size type
[21]	2021	Iran	462	Rural households	Solar PV	PLS-SEM	✔	✔	Intention	r
[22]	2025	Angola	354	Rural farmers	Solar PV pumps	PLS-SEM	✔	✔	Intention/Behavior	$\beta \rightarrow r$
[24]	2022	China	617	Rural households	Rooftop solar PV	CB-SEM	✔	✔	Intention/Use	r
[25]	2021	Colombia	182	Agro-producers	Biogas (AD)	PLS-SEM	✔	✔	Intention	r
[26]	2024	Vietnam	210	Pig farmers	Biogas	Logit (ext. TAM)	✔	✔	Intention	r
[27]	2024	China	281	Rural farmers	Alt. fuel machinery	PLS-SEM	✔	–	Intention	$\beta \rightarrow r$
[29]	2024	Iran	384	Rural households	Small-scale RE	PLS-SEM	✔	✔	Intention	$\beta \rightarrow r$
[19]	2019	Indonesia	185	Rural households	Solar home system	Regression	✔	✔	Intention	r

Overall, the standardized coding procedure ensured methodological consistency across studies and enabled reliable quantitative aggregation of effect sizes within the meta-analytic framework.

4. 5. Meta-analytic techniques and statistical analysis

A quantitative synthesis of empirical results was performed using meta-analytic methods accounting for interstudy variability in obtained effects. A random-effects model was used as the primary analytical strategy accounting for both intra-sample error and interstudy variance in effects. Model parameters were estimated using the restricted maximum likelihood (REML) method.

For effect metrics, let's use correlation coefficients reflecting the relationships between the TAM model's key constructs and indicators of intention and/or actual adoption behavior regarding small-scale renewable energy technologies. To ensure comparability, all correlation coefficients were transformed into Fisher's Z values followed by meta-analytic aggregation. When necessary, the final estimates would be reinterpreted as correlation coefficients.

Interstudy heterogeneity was assessed using the Q statistic and the I^2 statistic reflecting proportion of the total effect variance due to actual differences between studies. Meta-analytic calculations and statistical data processing were performed in the R environment using specialized packages for correlation meta-analysis. This ensured reproducibility of calculations and compliance with modern methodological standards.

The literature search strategy is described in Section 4. 3 and reported in Table 1, while eligibility criteria are summarized in Table 2. The study identification, screening, and inclusion process is presented in Section 4. 4 and illustrated in Fig. 2 (PRISMA flow diagram). Data extraction and coding of TAM constructs, outcomes, and effect size types are described in Section 4. 4 and summarized in Table 3. The statistical synthesis procedures, including Fisher's Z transformation, random-effects modeling (REML), and heterogeneity assessment (Q and I^2), are specified in Section 4. 5, with the corresponding meta-analytic results reported in Section 5 (Fig. 3–6; Tables 4, 5).

5. Results of the identifying of technology acceptance model constructs on small-scale renewable energy adoption

5. 1. Combined effect of perceived usefulness on intention and/or actual adoption of small-scale renewable energy technologies

To address the first objective of the study, it was conducted a quantitative meta-analysis of empirical studies assessing the impact of perceived usefulness on the intention and/or actual behavior of farmers and rural households to adopt small-scale renewable energy technologies. Analysis included eight independent studies ($k = 8$) with a combined sample size of 2,675 respondents.

Fig. 3 shows a forest plot displaying individual effect sizes for each included study, as well as aggregate effect estimate obtained using the random-effects model.

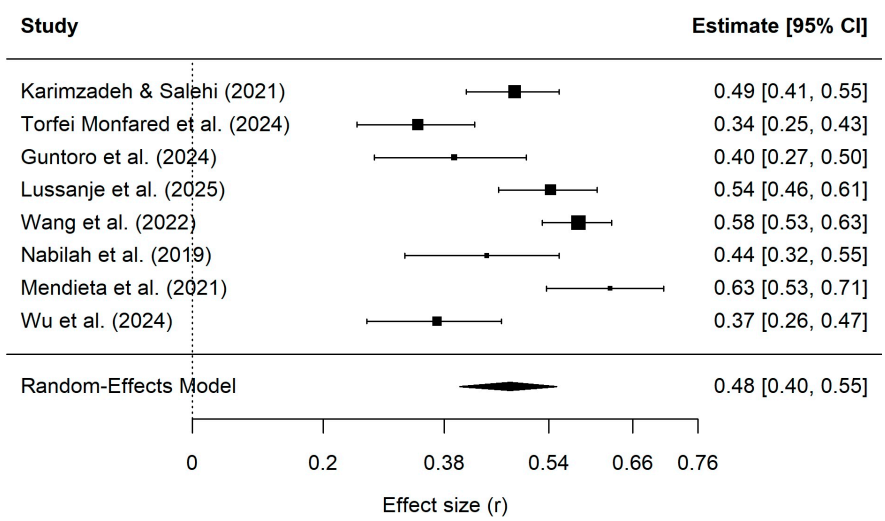

Fig. 3. Forest plot of the pooled effect size for the relationship between perceived usefulness and intention/behavior

Meta-analysis results demonstrate a statistically significant positive relationship between perceived usefulness and intention and/or actual behavior to implement small-scale RES. The aggregate effect size expressed as Fisher's Z was 0.522 with a standard error of 0.049, thus corresponding to an approximate correlation value of $r \approx 0.48$. The 95% confidence interval [0.43; 0.62] excludes zero, and the z-test value ($z = 10.77$; $p < 0.001$) indicates high statistical significance of the effect.

Heterogeneity analysis revealed significant interstudy variability. The Q statistic was 41.75 with $df = 7$ and a significance level of $p < 0.001$, suggesting significant heterogeneity. An I^2 of 83.19% tells that over 80% of the total variation in the observed effects is due to genuine differences between studies rather than random sampling error. The estimate of the between-study variance ($\tau^2 = 0.0153$) and the corresponding value of $\tau = 0.124$ further support the use of a random-effects model.

Despite the high level of heterogeneity, the direction of effect across all included studies remains positive while the effect size ranges from moderate to large. This suggests robustness of the underlying relationship between perceived usefulness and adoption of small-scale renewable energy technologies in a rural context. These results are consistent with theoretical propositions of the technology acceptance model (TAM) that posits that the subjective assessment of a technology's usefulness is a key cognitive factor shaping behavioral intention and actual technology use.

Accordingly, meta-analysis results support hypothesis *H*1 that posits perceived usefulness to have a positive and statistically significant effect on intention and/or actual behavior of farmers and rural households to adopt small-scale renewable energy technologies. The resulting combined effect can be interpreted as large effect size emphasizing the central role of the economic, production, and functional benefits expected from renewable energy use in rural decision-making.

5. 2. Combined effect of perceived ease of use on intention and/or actual adoption of small-scale renewable energy technologies

To address the second objective of the study, it was conducted a meta-analysis of empirical studies assessing the impact of perceived ease of use on the intention and/or actual behavior of farmers and rural households to adopt small-scale renewable energy technologies. Analysis included seven independent studies ($k = 7$) with a combined sample size of 2,394 respondents.

Fig. 4 shows a forest plot displaying individual effect sizes for each included study, as well as aggregate effect estimate obtained using a random-effects model. The plot demonstrates significant variability in individual estimates of PEOU's effect on intention and/or actual technology adoption behavior, suggesting this construct's context sensitivity.

The results of the meta-analysis indicate a positive and statistically significant relationship between perceived ease of use and the intention and/or actual behavior to adopt small-scale renewable energy sources. The aggregate effect size was Fisher's $Z = 0.513$ with a standard error of 0.128, corresponding to an approximate correlation value of $r \approx 0.47$. The 95% confidence interval [0.26; 0.76] does not include zero, and the z-test value ($z = 4.01$; $p < 0.001$) confirms the statistical significance of the result.

At the same time, the heterogeneity analysis revealed an extremely high level of inter-study variability. The Q value was 207.84 with $df = 6$ and a significance level of $p < 0.001$, and the I^2 indicator = 97.32% indicates that the vast majority of the total effect variance is due to real differences between studies. The high value of the τ^2 parameter (0.111) and the corresponding value of $\tau = 0.333$ indicate significant variations in the strength of the PEOU effect depending on the study context.

Despite the identified heterogeneity, the aggregate effect remains positive and statistically significant, confirming the fundamental role of perceived ease of use in shaping intentions and behavioral decisions related to the adoption of small-scale renewable energy technologies. However, compared to Perceived Usefulness, this construct exhibits greater variability in its effects, which may reflect differences in the level of technological maturity, digital skills of users, the institutional environment, and the types of energy solutions used.

Accordingly, meta-analysis results support hypothesis *H*2 that posits perceived ease of use to have a positive and statistically significant effect on intention and/or actual behavior to adopt small-scale renewable energy technologies in a rural context. The resulting combined effect is interpreted as large effect size but its high contextual sensitivity highlights the need to consider local and technological factors when interpreting the PEOU's role in adoption of RES.

5. 3. Comparative analysis of the effects of perceived usefulness and perceived ease of use on small-scale renewable energy technology adoption

To address the third objective of the study, it was conducted a comparative analysis of the combined effect sizes of both perceived usefulness and perceived ease of use in order to assess their relative influence on intention and/or actual behavior to adopt small-scale renewable energy technologies. The comparison is based on aggregated meta-analysis results presented in Tables 4, 5.

According to Table 4, both key constructs of the technology acceptance model demonstrate a positive and statistically significant relationship with intention and/or actual behavior to adopt RES. For perceived usefulness, the combined effect size was $r = 0.48$ (Fisher's $Z = 0.52$; 95% CI [0.43; 0.62]; $p < 0.001$) while for perceived ease of use, $r = 0.47$ (Fisher's $Z = 0.51$; 95% CI [0.26; 0.76]; $p < 0.001$). Accordingly, the aggregate estimates suggest comparable effect sizes while PU's influence is characterized by a somewhat higher and more consistent value.

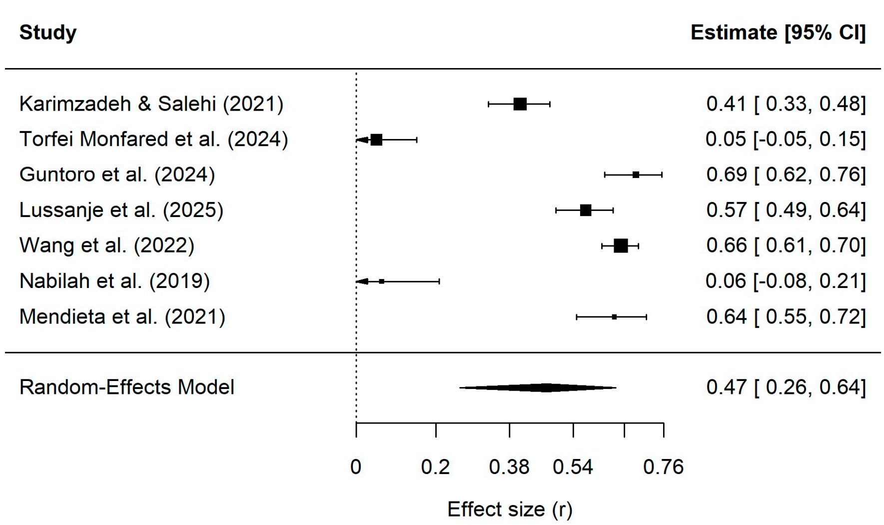

Fig. 4. Forest plot of the pooled effect size for the relationship between perceived ease of use and intention/behavior

Table 4

Summary of meta-analytic results for the relationships between tam constructs and intention/behavior

Relationship	k	Total N	r	Fisher's Z	95% CI (Z)	z-value	p-value	I^2 (%)
PU → Intention/Behavior	8	2,675	0.48	0.52	[0.43; 0.62]	10.77	< 0.001	83.19
PEOU → Intention/Behavior	7	2,394	0.47	0.51	[0.26; 0.76]	4.01	< 0.001	97.32

Notes: k – number of independent studies; Total N – cumulative sample size across studies; r – pooled correlation coefficient; Fisher's Z – pooled effect size estimate; CI – confidence interval; I^2 – proportion of total variance attributable to between-study heterogeneity. All estimates are based on random-effects models using the REML estimator.

Additional differences between the constructs in question are revealed when examining indicators of between-study heterogeneity. For the relationship between Perceived Usefulness and intention and/or actual behavior to adopt small-scale renewable energy technologies, I^2 is 83.19% while for perceived ease of use, it reaches 97.32%. The results tell that the perceived ease of use's impact is characterized by significantly higher variability across study contexts compared to perceived usefulness. The increased heterogeneity in the effects associated with perceived ease of use may be caused by differences in the level of technological sophistication of solutions used, digital skills of users, institutional conditions, and the degree of technological maturity of rural areas across countries.

Table 5

Magnitude and interpretation of pooled effect sizes

Relationship	Fisher's Z	Approx. r	Effect size magnitude
PU → Intention/Behavior	0.52	0.48	Large
PEOU → Intention/Behavior	0.51	0.47	Large

Notes: Effect size magnitude is interpreted following conventional thresholds for correlation-based meta-analyses (small ≈ 0.10, medium ≈ 0.30, large ≥ 0.50 in Fisher's Z terms).

Interpretation of the effect sizes in Table 5 shows how both constructs are classified as large in accordance with generally accepted thresholds for correlational meta-analyses. However, perceived usefulness demonstrates a more stable and less context-dependent relationship with the adoption of small-scale RES further stressing its dominant role in the structure of technology adoption factors.

These results suggest that even though ease of use remains an important element in shaping user intentions and behavior, expected utility is the decisive factor in the adoption of small-scale renewable energy technologies in a rural context. It is expressed in the economic, production, and functional benefits of the technology. This is consistent with the TAM's basic theoretical propositions and confirms PU's primary role in the technology decision-making process.

To summarize, the comparative analysis results support hypothesis $H3$ that states that perceived usefulness has a stronger and more consistent influence on the adoption of small-scale renewable energy technologies compared to perceived ease of use.

5. 4. Publication bias analysis

Funnel plots shown in Fig. 5, 6 were used to assess potential publication bias in the meta-analysis. The analysis was performed separately for the relationships between perceived usefulness and intention/actual behavior to adopt small-scale renewable energy technologies, as well as between perceived ease of use and the corresponding behavioral outcomes.

Fig. 5 shows a funnel plot for estimating publication bias in the relationship between perceived usefulness and intention and/or actual technology adoption behavior. A visual analysis of the effect sizes distribution relative to the aggregate estimate reveals no significant asymmetry, suggesting absence of obvious evidence of publication bias. However, given the limited number of included studies ($k = 8$) and a relatively narrow range of standard errors (0.0404–0.0747), the results need be interpreted with caution. Therefore, the assessment of publication bias for this relationship is exploratory in nature and does not allow for definitive conclusions.

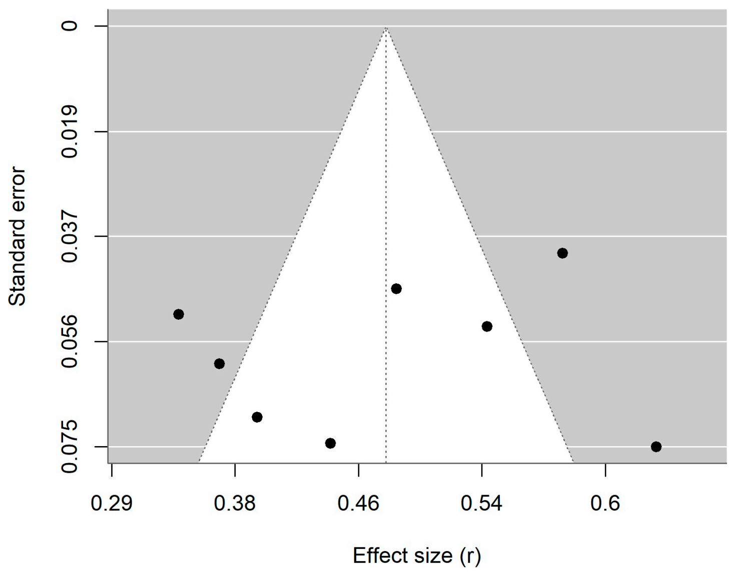

Fig. 5. Funnel plot for publication bias assessment of the relationship between perceived usefulness and intention/behavior

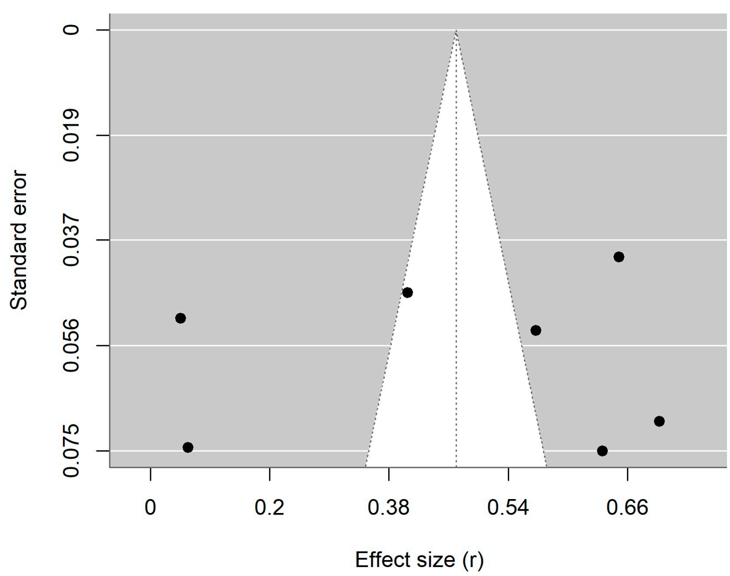

Fig. 6. Funnel plot for publication bias assessment of the relationship between perceived ease of use and intention/behavior

A similar approach was applied to estimate publication bias in the relationship between perceived ease of use and intention and/or actual adoption behavior of small-scale RES. Fig. 6 shows a funnel plot where effect sizes are distributed relatively symmetrically around the aggregate estimate. The absence of significant asymmetry may indicate a low probability of publication bias. However, due to even smaller number of included studies ($k = 7$), statistical power of the visual analysis remains limited, thus requiring caution in interpreting results.

Overall, the conducted publication bias analysis did not reveal convincing evidence of systematic distortion of the results due to selective publication of studies. Nevertheless, given the small number of available empirical studies, the results of the funnel plot analysis should be considered preliminary. This limitation outlines the need for further empirical research based on the technology acceptance model to improve robustness and generalizability of meta-analytic findings.

6. Discussion of meta-analytic results of technology acceptance model constructs in small-scale renewable energy adoption

Results of this quantitative meta-analysis allow for a more in-depth interpretation of the role that key technology acceptance model constructs play in the adoption of small-scale renewable energy technologies in rural contexts. Unlike individual empirical studies where results are often fragmented and contradictory, this analysis provides a quantitatively grounded and theoretically consistent summary of the accumulated data.

The meta-analytic results presented in Fig. 3 and summarized in Table 4 demonstrate a strong and robust positive relationship between perceived usefulness and the intention and/or actual adoption of small-scale renewable energy technologies in rural contexts. The large pooled effect size reported in Table 5 confirms that adoption decisions among farmers and rural households are primarily driven by expectations of tangible economic and functional benefits. This finding is fully consistent with the original propositions of the technology acceptance model, which identify perceived usefulness as the central determinant of technology acceptance behavior [8, 9], as well as with subsequent meta-analyses in digital and service-based domains, where perceived usefulness consistently emerges as the strongest predictor of behavioral intention [10–12, 17]. Importantly, the magnitude and stability of the effect observed in Fig. 3 and Table 4 are comparable to those reported in recent meta-analytic evidence on renewable energy adoption [18]. From a contextual perspective, the strength of the observed relationship aligns with empirical findings in rural energy studies, which emphasize that adoption of solar, bioenergy, and other decentralized technologies is largely motivated by anticipated cost savings, productivity gains, and increased energy autonomy [19–21, 25–27].

In contrast to perceived usefulness, the combined effect of perceived ease of use, illustrated in Fig. 4 and reflected in Table 4, demonstrates greater variability despite remaining statistically significant. As shown in Table 4, the heterogeneity indicator for PEOU is substantially higher, which explains the lower stability of this construct across contexts. This pattern mirrors earlier technology acceptance research, where perceived ease of use often exhibits indirect or diminishing effects once users acquire basic operational familiarity with a technology [9–11]. In the context of small-scale renewable energy technologies, the wide dispersion of effect sizes visible in Fig. 4 suggests that farmers' adoption decisions are less constrained by usability considerations than by financial, infrastructural, and institutional barriers [22, 23, 26]. Rural users appear willing to tolerate higher levels of operational complexity provided that the technology delivers clear economic or production-related advantages, a pattern also documented in studies on solar irrigation systems and biogas technologies in developing regions [24–26].

The comparative analysis presented in Table 4 and Table 5 highlights a clear dominance of usefulness-driven adoption behavior in rural renewable energy contexts, reinforcing the asymmetric structure of the technology acceptance model under conditions of economic and infrastructural constraint. Although the pooled effect sizes are comparable in magnitude, the lower heterogeneity of perceived usefulness compared to perceived ease of use, as reflected in the summary indicators of Table 4, indicates greater structural stability of its influence. This asymmetry, also visually observable in the forest plots (Fig. 3, 4), confirms that expected utility plays a more stable role in shaping adoption decisions.

While a similar asymmetric pattern has previously been observed in digital and organizational technologies [10, 11, 16], the present findings extend this evidence to small-scale renewable energy systems in rural environments. Prior research on rural energy transitions and sustainable development emphasizes that technology adoption in agricultural communities is shaped primarily by long-term economic resilience, energy security, and contribution to local development goals rather than short-term usability considerations [1–4, 6, 7]. Compared to existing empirical and review-based studies, the quantitative synthesis presented in Fig. 3, 4, Tables 4, 5 provides a more precise estimation of these relationships by systematically aggregating effect sizes across heterogeneous contexts, thereby reducing uncertainty regarding the relative importance of TAM constructs in renewable energy adoption.

In addition, the assessment of potential publication bias presented in Fig. 5, 6 further supports the robustness of the obtained findings. The relatively symmetrical distribution of effect sizes around the pooled estimates suggests the absence of substantial publication bias for both relationships. Although the limited number of included studies requires cautious interpretation, the funnel plots do not indicate systematic distortion of results, thereby reinforcing the reliability of the meta-analytic conclusions regarding the relative roles of perceived usefulness and perceived ease of use.

The obtained results directly address a key gap in the existing literature by providing a quantitatively rigorous synthesis based exclusively on the technology acceptance model. By integrating disparate empirical findings into a unified analytical framework, the study advances comparability of effect estimates across heterogeneous contexts. Unlike many existing reviews that combine TAM with alternative theoretical approaches, the present analysis maintains a strict focus on the core constructs of perceived usefulness and perceived ease of use, thereby enhancing theoretical clarity. Moreover, the explicit emphasis on rural settings and small-scale renewable energy technologies contributes to addressing a contextual dimension that has remained underrepresented in prior review-based research.

Overall, this theoretically focused meta-analysis eliminates fragmentation and inconsistency in previously published empirical studies, ensures a quantitatively rigorous generalization of the effects of the technology adoption model's underlying constructs, and addresses a research gap in the literature. The findings provide a scientifically sound basis for developing public policies and programs to stimulate adoption of small-scale renewable energy technologies in rural areas primarily involved to enhance and demonstrate their practical usefulness for farmers and rural households.

From a practical perspective, the study's results highlight the need to shift the emphasis from simplifying user interfaces and technical aspects of technology operation to demonstrating their specific usefulness for rural households and farmers. This means that government support measures, subsidy programs, and information campaigns need to primarily emphasize the RES' economic and production benefits, such as reduced operating costs, increased farm resilience, and energy independence. Ease of use remains an important, albeit secondary, factor, the significance of which increases in certain institutional and technological contexts.

It is important to acknowledge several limitations of this study. First, the number of included empirical studies remains relatively small ($k = 8$) limiting the analysis' statistical power and requiring caution in interpreting the results, particularly with regard to assessing publication bias. Second, the high level of inter-study heterogeneity suggests influence of additional contextual factors that could not be formally accounted for in the current meta-analysis. Third, the analysis included studies conducted in different countries and using different methodological approaches. On the one hand, this increases the external validity of the results, but also complicates their interpretation at the level of specific regions and technology types on the other.

Further development of this study appears to be warranted in several directions. A promising approach is to expand the body of empirical work as new studies accumulate allowing for moderator analysis and a more detailed assessment of the impact of technology type, regional context, and user socioeconomic characteristics. Furthermore, future research could seek to integrate TAM with institutional and policy factors thereby providing a deeper understanding of mechanisms underlying the adoption of renewable energy technologies in rural settings. These developments appear warranted since they logically follow the identified limitations and bear potential to enhance both scientific and practical significance of the findings.

7. Conclusions

1. The meta-analysis revealed PU's robust and statistically significant positive impact on technology adoption: the aggregate effect size was as follows: Fisher's $Z = 0.52$ corresponding to a correlation coefficient of $r \approx 0.48$ at a 95% confidence interval of [0.43; 0.62]. The effect is classified as large and remains positive across all included studies despite the presence of interstudy heterogeneity ($I^2 = 83.19\%$). This confirms perceived usefulness's key role as a fundamental cognitive determinant of RES adoption by rural households and farms.

2. The aggregate effect size was as follows: Fisher's $Z = 0.51$ ($r \approx 0.47$; 95% CI [0.26; 0.76]; $p < 0.001$), which also corresponds to a large effect size and confirms a statistically significant positive relationship between PEOU and technology adoption. However, an extremely high level of interstudy heterogeneity ($I^2 = 97.32\%$) was found, which suggests a pronounced contextual sensitivity of perceived ease of use's impact and dependence on technological, institutional, and user conditions.

3. The results showed both TAM model constructs to exhibit comparable aggregate effects, however, the perceived usefulness's influence is characterized by significantly greater stability and lower interstudy variability compared to that of perceived ease of use ($I^2 = 83.19\%$ versus 97.32%). This allows to conclude that PU plays a dominant role in the structure of RES adoption factors in a rural context and quantitatively confirms propositions of the TAM model's basic version as applied to decentralized energy solutions.

4. Funnel plot analysis of the relationships between perceived usefulness and intention and/or actual technology adoption behavior, as well as between perceived ease of use and corresponding behavioral indicators revealed no significant evidence of systematic publication bias. Distribution of effects is characterized by relative symmetry around the aggregate estimates suggesting acceptable reliability of the meta-analytic conclusions. However, the limited number of included studies ($k = 7–8$) requires discretion in interpreting the results and highlights the need for further empirical research.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

This study has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP23484373 "Modern challenges of state policy: integrating green economy into solving the food security issue in the regions of Kazakhstan").

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

During the preparation of the manuscript, limited use of artificial intelligence tools was applied exclusively for grammar, spelling, and punctuation checking under full human control. Specifically, the GPT-5.2 language model (OpenAI) was used to assist in correcting language inaccuracies in individual sentences without generating or modifying scientific content.

The AI tools were not used for writing or generating any substantive parts of the manuscript, including the Introduction, Literature Review, Materials and Methods, Results, Discussion, or Conclusions, and were not involved in data collection, data analysis, interpretation of results, or formulation of scientific conclusions.

All text processed with the assistance of AI tools was manually reviewed, edited, and validated by the authors. The use of AI tools did not influence the research design, empirical results, or the conclusions of the study.

Authors' contributions

Nurlan Kurmanov: Conceptualization, Methodology, Validation, Supervision, Writing-original draft; **Gulmira Kabdullina**: Formal analysis, Investigation, Writing – original draft; **Zhaxat Kenzhin**: Resources, Data curation, Writing – original draft; **Merey Adilbekuly**: Visualization, Writing – original draft; **Asylkhan Kabdolla**: Writing – review & editing; **Gulfiya Zhambylova:** Software, Project administration, Funding acquisition.

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