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ADVANCING THE ADOPTION OF GENOME-EDITED RICE IN INDIA: A TECHNOLOGY ACCEPTANCE MODEL-DRIVEN EXTENSION STRATEGY

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ABSTRACT
Genome editing has emerged as a transformative approach for crop improvement, offering precision and efficiency without the regulatory complexities of transgenic modification. Despite India's scientific progress in developing genome-edited rice, farmer-level adoption remains limited. This review explores how behavioural dynamics influence the diffusion of genome-edited technologies and proposes a framework for adoption based on the Technology Acceptance Model (TAM). The study synthesizes peer-reviewed research published between 2000 and 2025, retrieved from Scopus and Google Scholar, to identify behavioural determinants and effective dissemination strategies. Using a theory-informed qualitative synthesis, the review maps TAM constructs Perceived Usefulness, Perceived Ease of Use, Attitude Toward Use, and Behavioural Intention to actionable extension interventions. Approximately forty studies meeting relevance and quality criteria were included for analysis following a PRISMA-inspired screening process. Findings reveal that the adoption of genome-edited rice depends less on scientific readiness and more on social trust, cognitive perception, and institutional credibility. Field demonstrations, peer learning, and ICT-enabled communication enhance perceived usefulness and ease of use, while farmer collectives and gender-sensitive networks strengthen attitude and behavioural intention. The review concludes that embedding TAM-guided behavioural insights into participatory and digital extension systems can significantly improve the scalability and inclusivity of genome-edited rice adoption in India. It underscores the need for empirical field validation and integration of behavioural models into future agricultural innovation policies.

KEYWORDS: Genome-edited rice, Technology Acceptance Model (TAM), Farmer adoption, Behavioural extension, Digital dissemination, India

INTRODUCTION
The integration of advanced genetic technologies in agriculture has opened new possibilities for addressing long-standing challenges in food production, climate resilience and nutritional security. Among these, genome editing particularly through CRISPR/Cas9 systems has attracted global attention for its precision, efficiency and ability to generate non-transgenic crop varieties with enhanced traits (Zhang et al. 2018; Jaganathan et al. 2018). Unlike genetically modified organisms (GMOs), genome-edited crops do not involve the insertion of foreign DNA, which reduces regulatory barriers and improves consumer acceptance. In the case of staple crops such as rice, genome editing offers the potential to significantly improve yield, stress tolerance and nutrient density, contributing directly to food and livelihood security in vulnerable regions (Mishra et al. 2018).
India has made significant advancements in this domain, with the Indian Council of Agricultural Research (ICAR) releasing genome-edited rice varieties such as DRR Rice 100 and Pusa DST Rice-1, both developed for drought tolerance and enhanced productivity (PIB 2024a). In parallel, the regulatory clearance of GM Mustard and the ongoing research on gene-edited tomato reflect an evolving policy environment that increasingly supports new breeding technologies (PIB, 2023; Singh et al. 2024). Despite these scientific and institutional milestones, the on-ground adoption of genome-edited rice remains disproportionately low. This gap mirrors broader challenges in agricultural innovation systems, where technological advancements often fail to translate into behavioral change at the farm level (Rutsaert et al. 2024; Becerra-Encinales et al. 2024b).
This adoption gap is not merely a function of access constraints but is rooted in deeper behavioral, cognitive and institutional dynamics including farmers' risk perception, trust in scientific institutions and the credibility of extension

intermediaries (Li et al. 2024; Dadzie et al. 2022; Deepika 2023). Historically, agricultural extension systems in India have operated through top-down, supply-driven models, assuming that awareness leads directly to adoption (Anderson and Feder 2007). However, such linear frameworks are increasingly inadequate in contexts where farmers face diverse livelihood pressures and varying exposure to markets, climate stress and technology (Swanson and Rajalahti 2010; Feder et al. 2011).

As extension services evolve toward participatory, market-led and climate-smart paradigms, there is a clear need to reframe technology dissemination through a behavioral lens that accounts for farmer motivation, perception and social learning. The Technology Acceptance Model (TAM) provides a robust theoretical foundation for this shift. Originally proposed by Davis et al. (1989) and refined by Venkatesh and Davis (2000), TAM conceptualizes technology adoption through four key constructs Perceived Usefulness (PU), Perceived Ease of Use (PEOU), Attitude Toward Use (ATU) and Behavioral Intention (BI). While widely applied in digital and organizational studies, TAM's potential for explaining agricultural technology adoption particularly genome-edited crops remains underexplored (Thomas et al. 2023; Jimenez et al. 2021).

This review operationalizes TAM as a behavioral framework for agricultural extension and positions it as a tool to design adoption strategies for genome-edited rice in India. Specifically, it aims to map each TAM construct to evidence-based extension interventions that can strengthen farmer readiness for adoption. To guide this effort, the study addresses three core research questions:

1. Which TAM constructs have the strongest empirical support in influencing the adoption of genome-edited crops?
2. Which extension interventions most effectively target these constructs in the Indian context?
3. How can TAM-informed dissemination strategies enhance the scalability and inclusivity of genome-edited rice adoption?

By linking behavioral theory with extension practice, this study contributes to advancing a user-centered, evidence-based roadmap for mainstreaming genome-edited technologies in Indian agriculture.

RESEARCH METHODOLOGY

This article presents a comprehensive literature review aimed at synthesizing existing knowledge on the dissemination and adoption of genome-edited crop technologies, with a specific focus on developing a structured extension framework guided by the Technology Acceptance Model (TAM). The review was conceptualized to bridge the gap between scientific advancements in genome editing and real-world adoption challenges, providing an evidence-based foundation for policymakers, extension agents, and researchers.

Review Design and Approach

A theory-informed qualitative synthesis was employed, using TAM as the guiding framework to organize and interpret the literature. The Technology Acceptance Model, developed by Davis et al. (1989), has been widely applied to explain technology adoption behaviours across sectors, including agriculture. TAM posits that external variables influence two key perceptions- Perceived Usefulness (PU) and Perceived Ease of Use (PEOU) which together shape Attitude Toward Use (ATU) and ultimately drive Behavioural Intention (BI) to adopt a new technology.

This study applied a reverse-engineering approach, identifying extension strategies that can deliberately enhance each of these four constructs, thereby improving the likelihood of adoption among end-users. Although the review was conceptually anchored in genome-edited rice, owing to its relevance in India's food security and policy context related studies on other genome-edited crops (e.g., tomato, maize and wheat) were also examined when they provided transferable insights into adoption behaviour and extension mechanisms.

Data Sources and Search Strategy

The review was conducted using two primary databases: Scopus and Google Scholar, selected for their broad coverage of peer-reviewed literature, review papers, case studies and relevant grey literature. The search covered publications from January 2015 to March 2025, capturing the most recent developments in genome editing, agricultural extension and behavioural science.

A set of Boolean search operators and keyword combinations was used and presented in Table 1.

Table 1: Combination of keywords

Database used	Keyword Combinations
Scopus and Google Scholar	"Genome-edited crops" AND "technology adoption" "CRISPR" AND "agriculture" AND "extension strategies" "Technology Acceptance Model" OR "TAM" AND "agriculture" "farmer behavior" AND "innovation diffusion" "perceived usefulness" AND "agricultural innovation"

Reference lists of selected papers were manually screened to identify additional materials through snowball sampling. Grey literature, policy briefs, institutional reports and extension manuals was included when directly relevant to technology dissemination or behavioural adoption.

Screening and Selection Process

The screening and selection process followed the logic of the PRISMA 2020 framework to enhance transparency and methodological rigour, while remaining qualitative in nature. Searches conducted in Scopus and Google Scholar initially yielded several hundred records related to genome-edited crops and agricultural extension. After removing duplicates and non-relevant titles, approximately two hundred and sixty studies were screened by title and abstract for conceptual alignment with the Technology Acceptance Model (TAM). Subsequently, around ninety full-text articles were examined in detail against the inclusion and exclusion criteria, and approximately forty to fifty studies were finally retained for qualitative synthesis.

Inclusion and Exclusion Criteria

Specific operational criteria were applied to ensure focus and quality (Table 2).

Table 2. Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Language	English publications	Non-English materials
Publication period	2000 – March 2025	Before 2000
Relevance	Studies on genome-edited crops, technology adoption, agricultural extension, or TAM	Studies on gene-editing techniques without dissemination/adoption focus
Document type	Peer-reviewed journals, review papers, reports, case studies	Opinion pieces, editorials, non-empirical content
Conceptual basis	Studies referencing TAM or other behavioural frameworks (e.g., Diffusion of Innovations, ISM)	Studies without conceptual adoption framework
Application scope	Findings relevant to agricultural extension, farmer behaviour, or adoption contexts	Purely molecular or laboratory studies

Quality Appraisal

Each study was evaluated for:

1. **Relevance** – whether it directly contributed to understanding adoption or dissemination of genome-edited crops.
2. **Credibility** – publication type, methodological clarity, and data transparency.
3. **Transferability** – applicability of insights to Indian or comparable agricultural settings.

Studies meeting at least two of these three criteria were retained. All assessments were cross-checked by the authors to minimize bias.

RESULTS AND DISCUSSION

Evolution of Agricultural Extension Approaches

Agricultural extension in India has progressively shifted from top-down dissemination toward participatory, decentralized and demand-driven systems. Early programs such as the Intensive Agriculture District Program (IADP) and the Training-and-Visit (T&V) model reflected a unidirectional view of technology transfer, assuming innovations would flow linearly from research stations to farmers (Anderson and Feder 2004). Over time, the limitations of this approach, limited farmer participation, poor contextual fit, and weak feedback loops became apparent. The establishment of Agricultural Technology Management Agencies (ATMAs) and Krishi Vigyan Kendras (KVKs) marked a decisive move toward locally responsive, farmer-centered extension structures (Becerra-Encinales et al. 2024b).

Recent reforms have further diversified extension practice through digital platforms, climate-smart initiatives and gender-responsive models (Midamba and Ouko 2024; Ragasa et al. 2013). Programs such as the National Innovations on Climate Resilient Agriculture integrate research, demonstrations, and adaptive learning to build resilience. Market-led and ICT-based extension efforts likewise address farmers' information and price risks, strengthening decision-making and income stability (Becerra-Encinales et al. 2024b).

The dissemination of genome-edited rice fits within these evolving paradigms. Current initiatives emphasize participatory field trials, local co-innovation and digital communication channels, approaches consistent with a behavioural orientation that places farmer experience at the center of technology diffusion.

Barriers to the Dissemination of Genome-Edited Crops

Genome-editing technologies hold strong potential for tackling persistent food and nutrition security challenges, yet their adoption remains limited both globally and within India. Although recent advances in rice genome editing demonstrate scientific feasibility, farmer-level uptake remains modest.

Persistent barriers span informational, institutional, and behavioural dimensions. Reviews of biofortified and genome-edited crops identify a low level of awareness about nutritional and agronomic benefits, uncertainty about yield performance, and limited access to certified seed as key constraints (Garcia-Casal et al. 2016; Naik and Ashokkumar 2021). Economic and perceptual barriers further reinforce this hesitation: willingness-to-pay studies show that trust,

perceived safety, and credible market incentives are decisive in shaping acceptance of nutritionally enhanced crops (Norton and Alwang 2020).
At the institutional level, weak seed-delivery and distribution systems slow the diffusion of new varieties, forcing smallholders to rely on older, familiar cultivars (McGuire and Sperling 2016). Such structural gaps limit the visibility of success stories and reduce farmers' opportunities for experiential learning.
Taken together, these factors indicate that diffusion of genome-edited crops requires more than scientific readiness; it demands behaviourally informed dissemination strategies that integrate farmer psychology, social trust, and institutional credibility into extension practice.

Varietal Adoption Trends and Technological Stagnation

Despite rapid scientific progress in rice breeding, farmer adoption patterns reveal a persistent technological stagnation. The continued dominance of older cultivars such as MTU 1010, released in 1999, illustrates how familiarity, market preference and risk aversion shape varietal choice (Prasad et al. 2022b). Empirical analyses show that smallholders' reliance on trusted seed sources and perceived yield stability limits the uptake of new cultivars, even when they offer nutritional or stress-tolerant advantages (Rutsaert et al. 2024; McGuire and Sperling 2016).
In the context of genome-edited rice, these challenges are compounded by weak last-mile delivery mechanisms and limited participatory outreach. Comparative policy reviews indicate that although genome-edited crops classified as site-directed nuclease (SDN-1/2) products are exempt from transgenic GMO oversight in several countries including India since 2022, the communication of this distinction to farmers and consumers remains inadequate (Buchholzer and Frommer 2022; Kondo and Taguchi 2022). This disconnect between policy intent and public understanding continues to constrain early diffusion and acceptance of genome-edited innovations.
Bridging this stagnation demands a behavioural turn in extension practice, one that builds perception, trust and experiential validation rather than relying solely on information dissemination.

TAM-Aligned Dissemination Strategies

The Technology Acceptance Model (TAM) offers a behavioural lens for structuring dissemination around four constructs: Perceived Usefulness (PU), Perceived Ease of Use (PEOU), Attitude Toward Use (ATU), and Behavioural Intention (BI) (Thomas et al. 2023; Jimenez et al. 2021). Each construct can be operationalized through specific extension interventions (Table 3).

Table 3. Mapping TAM Constructs to Extension Interventions and Behavioural Mechanisms in Genome-Edited Rice Adoption

TAM Construct	Extension Intervention	Behavioural Mechanism	Key Evidence	Evidence Strength
PU	Field demonstrations and farmer fairs	Build experiential confidence through visible results and peer validation	Thomas et al. (2023)	High
PEOU	Mini-kit distribution, ICT tutorials, community radio	Simplify learning and reduce perceived complexity	Jimenez et al. (2021); Mishra et al. (2024)	Moderate
ATU	Farmer-to-farmer diffusion, peer-group discussion forums	Strengthen social proof and trust in innovation	Dadzie et al. (2022); Li et al. (2024)	High
BI	Linkages with farmer collectives, price-support schemes	Mitigate risk, reinforce institutional confidence	Prasad et al. (2022b)	High

This mapping clarifies that each behavioural construct can be operationalized through targeted extension interventions. For instance, PU can be enhanced through sensory learning- visual, tactile and community-driven demonstrations while PEOU depends on how intuitively farmers perceive the new technology's benefits. ATU is most responsive to social learning mechanisms, and BI hinges on policy certainty and market incentives.
Collectively, these results respond to the first two research questions by identifying which TAM constructs most influence genome-edited crop adoption and by mapping the corresponding extension interventions that effectively operationalize each construct in the Indian context.
These insights suggest that adoption cannot be viewed as a technical process but as a behavioural sequence requiring structured engagement, trust, and economic assurance.

Global Learning Models

International experience reinforces the need for participatory and user-focused dissemination. In Japan, the genome-edited GABA-enriched tomato was commercialized through free sapling distribution to households, followed by online seed sales and consumer engagement programs, a strategy that normalized genome editing through familiarity and transparency (Kondo and Taguchi 2022; Ishii 2025d). Surveys show that when consumers clearly understand the purpose and benefits of genome-edited crops, acceptance levels rise significantly (Yamaguchi et al. 2024; Kato-Nitta et al. 2022).

In the United States and United Kingdom, genome-editing initiatives have emphasized consumer-centric traits such as flavor, shelf life, and nutritional quality to build trust and perceived usefulness (Kpaka et al. 2021; Buchholzer and Frommer 2022). These global cases highlight that perceived value, visibility and institutional transparency rather than technical sophistication alone, determine the pace of public and farmer acceptance of genome-edited foods.

Synthesis and Policy Implications

Addressing the third research question, this synthesis highlights how TAM-guided dissemination strategies can improve the scalability and inclusivity of genome-edited rice adoption by embedding behavioural insights within participatory, gender-responsive, and digitally enabled extension systems. Evidence across studies shows that technological innovation alone rarely guarantees adoption; success depends on behavioural alignment, institutional credibility, and the perceived usefulness of the technology (Becerra-Encinales et al. 2024b).

In the Indian context, digital extension platforms offer a powerful opportunity to translate behavioural theory into practice. Personalized, ICT-based advisories have demonstrated measurable gains in productivity and decision quality when messages are contextually relevant and interactive (Rajkhowa and Qaim, 2021). Such tools can reinforce the Perceived Ease of Use (PEOU) and Perceived Usefulness (PU) constructs of TAM by providing real-time, actionable insights tailored to farmers' local realities.

Equally important is the integration of gender-responsive strategies, since women farmers often face structural barriers in accessing information, credit, and extension networks (Neway and Zegeye, 2022). Designing outreach programs through Self-Help Groups (SHGs) and Farmer Producer Organizations (FPOs) can enhance trust, strengthen collective learning, and amplify social influence, thereby improving Attitude Toward Use (ATU) and Behavioural Intention (BI).

For scalability, interactive and trust-based digital models that blend participatory learning with behaviourally informed design are more sustainable than one-way awareness campaigns. Frameworks that combine the Technology Acceptance Model (TAM) with systems-oriented perspectives such as the Diffusion of Innovations and the Agricultural Innovation Systems (AIS) approach can provide a holistic understanding of how information flows, trust builds, and innovations diffuse across rural communities (Dulhunty 2022).

Future research should validate these conceptual linkages empirically testing TAM constructs in field settings through behavioural surveys, adoption metrics and longitudinal analyses. Doing so would bridge theory and practice, helping policymakers and extension planners craft interventions that are both scientifically sound and socially attuned.

CONCLUSION

This review demonstrates that while genome-editing represents a major scientific advance for agriculture, its real-world impact depends on how effectively it is communicated, contextualized, and trusted by farmers. The evidence shows that adoption is not merely a technical decision but a behavioural process shaped by perception, experience, and institutional credibility.

Using the Technology Acceptance Model as an analytical lens reveals that each stage of the adoption pathway—understanding usefulness, perceiving ease, forming attitudes, and developing intent—can be strengthened through well-designed extension strategies. Participatory demonstrations, digital communication tools, and peer-based learning can turn awareness into engagement, while supportive institutions and market assurance translate confidence into sustained adoption.

For India, mainstreaming genome-edited rice will require extension systems that are not only technically sound but socially intelligent systems that listen as much as they instruct, adapt to gendered realities, and use behavioural insight to build lasting trust.

This study's main limitation is its reliance on secondary literature rather than field-level validation. Future work should test the proposed framework empirically through mixed-method research that measures behavioural responses, adoption rates, and social feedback over time. Such evidence will help move the conversation from theoretical promise to practical transformation, ensuring that genome-edited crops contribute meaningfully to resilient and inclusive agricultural futures.

Author Contributions

Padma S R conceived the study, guided the overall research design, and supervised the writing process. Anshida M contributed to the literature review, data organization, and assisted in drafting and revising the manuscript. Manisha Bahskaran was responsible for data interpretation, writing key sections of the manuscript, and refining the final version. All authors read and approved the final manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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