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ARTICLE

An Integrated TPB-TAM-Environmental Behavior Theory Approach to Agricultural By-Products Acceptance: A Structural Equation Modeling Analysis of Sugarcane Bagasse Food Containers

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ABSTRACT

Amid accelerating climate change and the global shift toward sustainable consumption, agricultural by-products have gained attention as low-carbon alternatives to conventional plastic packaging. This study explores the psychological and behavioral mechanisms underlying consumer acceptance of sugarcane bagasse containers, aiming to advance understanding of how agricultural residue-based innovations drive sustainable packaging adoption. An integrated framework (EPIM-LCP) is developed by synthesizing the Technology Acceptance Model (TAM), Theory of Planned Behavior (TPB), and Environmental Behavior Theory (EBT). Based on empirical data from 450 respondents in Guangxi, China, Partial Least Squares Structural Equation Modeling (PLS-SEM) was employed to test eleven hypotheses. Results reveal that environmental concern and environmental values significantly enhance low-carbon awareness, which positively shapes consumer attitudes. Perceived usefulness and ease of use influence attitudes, mediating their impact on acceptance intention. Attitude, subjective norms, and perceived behavioral control all significantly predict adoption intention, with attitude being the most influential factor. Two key mediation pathways are identified: (1) environmental cognition → low-carbon awareness → attitude → intention; and (2) technical perception → attitude → intention. The model exhibits strong predictive validity through PLS-Predict analysis. This research contributes to sustainable packaging literature

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by being one of the first to integrate TAM, TPB, and EBT for agricultural by-products adoption. The findings offer theoretical insights into consumer psychology while providing practical implications for designers, marketers, and policymakers promoting bio-based packaging solutions.

Keywords: Agricultural By-Products; Sugarcane Bagasse Containers; Bio-Based Packaging; Technology Acceptance Model (TAM); Theory of Planned Behavior (TPB); Environmental Behavior Theory (EBT); Structural Equation Modeling (SEM)

1. Introduction

1.1. Research Background

With the intensification of global climate change and the growing urgency to achieve carbon neutrality, the utilization of agricultural by-products and the promotion of green consumption have become central to global sustainability agendas [1]. The packaging industry, as a high-emission, high-resource industry, is under ever-greater pressure to adopt environmentally friendly practices—both to limit ecological damage and to improve its competitiveness in a green economy.

Bio-packing materials from agricultural wastes have gained popularity as an alternative to normal plastics due to their renewable source, biodegradable status, and reduced environmental impact. Policy incentives and increasing demand in the market are supporting their uptake in green packaging. Among them, bagasse, a sugarcane industry by-product in the form of fibers, has been of special interest as a value-added product that can be transformed into biodegradable containers and trays. Its reuse is a quintessential representation of the circular economy, promoting waste-to-resource conversion and less dependency on plastic. Bagasse-based containers are also very resistant to oil, water-proof, and thermally stable, hence very suitable for high-frequency applications such as takeaway and fast food outlets.

Despite these environmental and functional advantages, consumer adoption remains relatively limited due to low market penetration and insufficient public awareness. Existing academic research has primarily addressed macro-level aspects such as material performance, life cycle assessment (LCA), and regulatory frameworks, while micro-level insights into consumer behavior and decision-making mechanisms remain sparse.

Notably, few studies have developed integrative models that bring together environmental cognition, behavioral attitudes, and technology-related perceptions to explain the psychological processes that shape consumer acceptance of eco-friendly packaging based on agricultural by-products. To bridge this gap, the present study adopts a consumer-centered approach and uses sugarcane bagasse containers as a representative case. Drawing on the Technology Acceptance Model (TAM), the Theory of Planned Behavior (TPB), and Environmental Behavior Theory (EBT), it proposes the Eco-product Intention Model – Low Carbon Pathway (EPIM-LCP) to systematically examine how perception, environmental values, and behavioral intention interact in shaping user acceptance.

This study contributes theoretically by advancing a multidimensional framework to better understand consumer adoption of eco-friendly packaging based on agricultural by-products., while also providing practical guidance for policymakers, designers, and marketers aiming to promote sustainable alternatives. Empirical findings from the study shall underpin product optimization, enrich environmental communication measures and strategies, and inform more general initiatives promoting sustainable consumption.

1.2. Objectives of the Study

The main aim of the study is to examine the psycho-behavioural pathways and psychological processes involved in the acceptance by consumers of agricultural by-products, taking sugarcane bagasse containers as a typical case. As the speed of the global trend toward green consumption accelerates, biodegradable packag-

ing from agricultural residue is progressively seen as a sustainable option to replace conventional plastic materials. Specifically, sugarcane bagasse has emerged as a notable new candidate because of its biodegradable nature as well as the potential to combat carbon emissions, thus becoming a potential solution in high-frequency food delivery and ready-to-eat food packaging applications.

Despite technical and environmental advancements in converting agricultural by-products into packaging materials, research remains limited in explaining how consumers perceive and adopt such innovations. Existing studies tend to focus on material properties or life cycle performance, offering fragmented theoretical insights that lack coherence in predicting consumer adoption behavior or uncovering the underlying motivational drivers.

To address this gap, the present study develops an integrated theoretical model—the Eco-product Intention Model – Low Carbon Pathway (EPIM-LCP)—which merges the Technology Acceptance Model (TAM), the Theory of Planned Behavior (TPB), and Environmental Behavior Theory (EBT). The model incorporates key variables such as perceived ease of use, perceived usefulness, environmental concern, environmental values, low-carbon awareness, user attitude, subjective norms, and perceived behavioral control, offering a holistic framework to analyze how consumers form their intention to adopt eco-friendly packaging based on agricultural by-products.

Special emphasis is placed on the mediating roles of low-carbon awareness and user attitude, to better understand how environmental cognition is translated into behavioral intention. The study uses structured questionnaires and applies Partial Least Squares Structural Equation Modeling (PLS-SEM) to empirically test the model's validity and predictive power.

By integrating multiple theoretical perspectives and providing empirical evidence, this research not only contributes to a more comprehensive understanding of consumer behavior toward agricultural by-products but also delivers practical implications for product designers, sustainability communicators, and policy advocates. Ultimately, it aims to support the broader diffusion of agricultural waste-based packaging innovations within the sustainable consumption landscape.

1.3. Research Significance

As global efforts to combat climate change intensify and carbon neutrality strategies accelerate, the promotion of green consumption and the transition away from conventional plastics have become critical pillars of sustainable development. Among various alternatives, agricultural by-products, particularly sugarcane bagasse, have gained increasing attention for their renewable nature, biodegradability, and potential to reduce environmental impacts. However, despite their environmental benefits, consumer acceptance and behavioral engagement remain major barriers to the widespread adoption of packaging innovations based on agricultural residues. Current research has primarily focused on technical performance and design optimization, with limited exploration of the psychological and behavioral mechanisms underlying consumer adoption—thus constraining public awareness and market uptake of agricultural by-product-based solutions.

This study holds both theoretical and practical value. From a theoretical perspective, it addresses the limitations of single-model approaches by integrating the Technology Acceptance Model (TAM), the Theory of Planned Behavior (TPB), and Environmental Behavior Theory (EBT) into a unified framework. By linking perceptual attributes, environmental motivations, and behavioral predictors, the research advances interdisciplinary understanding of consumer decision-making related to eco-friendly innovations derived from agricultural residues. It contributes to the growing body of knowledge in environmental psychology and sustainable behavior by positioning agricultural by-products as a focal point of inquiry.

On a practical level, the study provides empirical insights into how perceived usefulness, environmental concern, and awareness of resource reuse influence consumers' willingness to adopt packaging derived from agricultural by-products. These findings offer actionable guidance for companies to refine product features and user experiences, for policymakers to design targeted communication and incentive strategies, and for marketers to shape public perception and foster be-

havioral change. Especially in light of global plastic bans and the expansion of green supply chains, this research supports collaborative efforts across sectors to mainstream sustainable packaging practices. Ultimately, by addressing the gap between technological readiness and consumer adoption, the study helps shift the use of agricultural by-products from being policy-mandated to being genuinely demand-driven.

2. Literature Review

2.1. Overview of Agricultural By-Products Adoption and Eco-Packaging Research

With increasing climate change and global efforts aimed at sustainable development, the valorization and utilization of agricultural by-products has become a strategic priority among both policymaking circles and industries [2]. Agricultural by-products—those that are agricultural residue-derived and produce comparatively low carbon emissions at every stage in their life cycle, from extraction of the source to manufacturing, application, and disposal—represent alternatives to petroleum-derived inputs that are increasingly gaining attention [3]. Although the general category of low-carbon products encompasses high-technology solutions such as low-emission cars and low-energy equipment, the use of agricultural by-products in daily-need consumer goods—especially green packaging—has been gaining ever-stronger traction.

Eco-packaging is one of the most notable uses of agricultural by-products, inspired by its renewable, biodegradable, and resource-conserving characteristics [4,5]. Its underlying philosophy relates to reducing environmental impact whilst preserving the necessary functional integrity of the product. Contemporary research shifts beyond the optimization of the material aspect and life cycle analysis (LCA) to analyze the behavioral drivers of the uptake. Empirical work increasingly proves that adoption choices are governed by both evident factors such as price and physical appearance as well as abstract factors such as environmental concern, perceived social norms, personal beliefs, and views toward new technology [6,7]. Following their development, the application of theory from behavioral science to eco-packaging adoption is now an established area of research [8].

Of the bio-based materials of agricultural by-products, the most notable is sugarcane bagasse in view of its high abundance, biodegradability, renewability, and thermal stability [9]. As a sugar industry cellulose residue, bagasse is increasingly used to produce biodegradable packaging in the form of containers and trays. In contrast to the conventional plastic alternative, bagasse-based packaging fares better in carbon savings, the ease of recyclability, and end-of-life environmental safety [10]. Its use is particularly common in one-time packaging applications such as fast food, takeaway, and ready-to-eat foods.

Even with its environmental advantages, the actual market adoption of bagasse packaging is still limited. The existing literature has primarily concerned itself with the performance of the materials, biodegradation characteristics, and policy incentives. But comparatively scant regard has been given to the psychological and behavioral processes underlying the intentions of consumers to adopt agricultural by-product-based solutions. The theory gap thus underlies public perception as well as practical application of such innovations, thus curtailing their environmental benefits. To combat the problem, an evident need emerges for a holistic model that rigorously integrates environmental cognition, technological perception, and control of behavior into an explanation of the ways in which consumers accept and adopt environment-friendly packaging from agricultural by-products. The next section therefore presents and discusses three influential theoretical models—Technology Acceptance Model (TAM), Theory of Planned Behavior (TPB), and Environmental Behavior Theory (EBT)—and prepares the platform for constructing a holistic analytical framework for predicting agricultural by-product adoption behavior.

2.2. Theoretical Foundations for Consumer Adoption of Agricultural By-Products

2.2.1. Environmental Behavior Theory (EBT)

Environmental Behavior Theory (EBT) focuses particularly on the role of individuals' environmen-

tal knowledge, values, and attitudes in determining low-carbon action. Environmental concern (EC) and environmental values (EV) are precursors in the theory to low-carbon awareness (LCA), in turn influencing attitudes (ATT) and behavioral intentions [11–13]. Stern's Value-Belief-Norm theory proposes that pro-environmental values induce norms of action in compliance with ecological beliefs, while Schultz and Zelezny found that concern about environmental issues increases awareness and engagement in low-carbon action. Empirical research provides further proof of these correlations [14]. Huang et al. revealed that climate and environmental awareness both positively influence low-carbon behavior [15]. Environmental concerns and education were highlighted by Van Hoang and Tung as having a highly positive effect on people's green consumption intention and low-carbon participation [16]. Wu et al. also demonstrated that high environmental values enhance low-carbon cognition and green perception [17], resulting in pro-environmental behavior.

Notably, LCA, in turn, affects behavior directly as well as mediates the EC/EV-product attitudes relationship. The higher the level of low-carbon awareness, the more positive the attitudes toward Agricultural by-products, thus the adoption intention [17]. Hence, EBT serves as a strong theoretical platform to explain the cognitive as well as motivational processes that lead to consumers' adoption of sustainable packaging alternatives such as sugarcane bagasse containers. Based on the aforementioned theoretical and empirical findings, this study proposes the following hypotheses:

H1. *Environmental concern (EC) positively influences low-carbon awareness (LCA).*

H2. *Environmental values (EV) positively influence low-carbon awareness (LCA).*

H3. *Low-carbon awareness (LCA) positively influences attitude (ATT) toward product use.*

Subsequent research has confirmed the mediating effect of low-carbon awareness in the environmental concern – environmental values – product attitude relationship. Taufique et al. demonstrated that environmental beliefs indirectly encourage positive green attitudes by raising low-carbon cognition [18]. Zhao et al. proposed that environmental values do not straightway decide behavioral intention [19], but they reinforce one's cognitive and attitudinal inclination toward low-carbon behavior via a process of cognitive activation. Wang et al. also confirmed a mediating process from environmental education to environmental cognition to the formation of attitudes [20]. These studies collectively comprise a cognitive path model: EC/EV → LCA → ATT, a robust theoretical background for the proposed mediating hypothesis of the current study:

H10. *Low-carbon awareness (LCA) positively mediates the relationship between environmental factors (EC and EV) and usage attitude (ATT).*

2.2.2. Technology Acceptance Model (TAM)

The Technology Acceptance Model (TAM) developed by Davis describes users' intentions to adopt new technology using two main perception dimensions: perceived usefulness (PU) and perceived ease of use (PEOU) [21]. PU defines the extent to which the user perceives a product to increase efficiency, whereas PEOU indexes the perceived ease of using a product. In this study, TAM is employed to explore consumer adoption of sugarcane bagasse containers as innovative Agricultural by-products. Prior research has consistently validated TAM in green product contexts. As an example, Venkatesh & Davis and Yang et al. have both established that PEOU has a positive effect on PU (validating H4) [22,23]. PU is shown to also be positively affecting user attitudes, as postulated by Chen & Tung and Yadav & Pathak [24,25], the grounding of H5. PEOU's impact on attitude (H6) is also established; Ma et al. and Nath et al. point toward ease of use as vital for first acceptance of sustainable commodities [26,27]. Consequently, TAM offers both the conceptual underpinning and empirical justification of the following hypotheses:

H4. *Perceived Ease of Use (PEOU) has a positive effect on Perceived Usefulness (PU).*

H5. *Perceived Usefulness (PU) has a positive effect on Attitude (ATT).*

H6. *Perceived Ease of Use (PEOU) has a positive effect on Attitude (ATT).*

2.2.3. Theory of Planned Behavior (TPB)

Ajzen's Theory of Planned Behavior (TPB) rests on the theory that a person's behavior is a product of the function of three variables in combination: attitude toward the behavior (ATT), the subjective norm (SN), and the perceived behavioral control (PBC) [28]. TPB has been widely used in the study of green consumption behavior. Previous empirical work has shown that green product attitude has a very strong effect in causing consumers' intention to use them [29,30]. Additionally, the subjective norms—the social pressure of the customer's family, peers, or even the community at large—also contribute to green purchase intention [31]. Finally, perceived behavioral control, i.e., the perceived capacity and the available resources to the customer to engage in the behavior, is a reliable predictor of green purchase behavior [32]. Accordingly, this study proposes the following hypotheses:

H7. *Attitude (ATT) has a positive effect on Product Acceptance Intention (PAI).*

H8. *Subjective Norms (SN) have a positive effect on Product Acceptance Intention (PAI).*

H9. *Perceived Behavioral Control (PBC) has a positive effect on Product Acceptance Intention (PAI).*

Recent TAM-based studies identify the mediating role of attitude (ATT) in the relationship between perceived ease of use (PEOU), perceived usefulness (PU), and behavioral intention. Studies by Verma & Sinha and Osman et al. confirm that user attitudes significantly mediate the effect of technical views of intention [33,34], highlighting the role of attitude formation in the promotion of adoption behavior. Therefore, this study further proposes:

H11. *Attitude (ATT) positively mediates the relationship between product perception variables (PU and PEOU) and Product Acceptance Intention (PAI).*

2.3. Applications of TAM, TPB, and EBT in Eco-Product Adoption Research

In the recent past, the Technology Acceptance Model (TAM), the Theory of Planned Behavior (TPB), and Environmental Behavior Theory (EBT) have been widely employed to explore the adoption of Agricultural by-products by consumers, through multidimensional mechanisms to represent green consumption behavior. TAM has been proven to be a useful theory in estimating the acceptance of new environmental technology and green packaging. Wang et al. expanded TAM to show that the intention of Chinese consumers to adopt biodegradable packaging relied primarily on perceived usefulness (PU) and perceived ease of use (PEOU) and that attitude acted as a mediator [20].

TPB, on the other hand, emphasizes the development of behavioral intention and the predictive role of its variables. TPB has been found to exhibit high explanatory potential in empirical studies in the domains of green consumption, sustainable behavior, and environmental management. Illustratively, Paul et al. referenced the salience of the predictor role of attitude and perceived control in predicting green purchasing intention of residents in Hong Kong and residents of Macau [30]. Mufidah et al. compared Taiwanese and Indonesian respondents and found that perceived control and subjective norms had an effect in both cultural settings in the adoption intention of Agricultural by-products—illustrating the cross-cultural validity of TPB [35].

In the EBT domain, studies have developed from environmental value and concern research to examination of the cognitive-behavioral processes of pro-environmental action. Taufique et al. proposed that environmental concern and trust in environmental labeling can cause green behavioral intention by the positive effect of attitudes [18]. Ogiemwonyi et al. also found that pro-environmental attitudes mediate the relationships among variables including environmental responsibility, concern, and consequence awareness, and green consumption behavior [36]. Additionally, Chang and Hsiao [37], based on the Cognitive-Affective-Conative (CAC) model, concluded that green perceived value serves as a main connector among environmental cognition, low-carbon behavioral intention, and intermediate beliefs.

Although each of these theories contributes to the value, most empirical research utilizes them independently. Hence, their potential to fully encapsulate the complexity of adoption of eco-products is restricted. To

fill the knowledge gap, the current research combines TAM, TPB, and EBT to a single conceptual framework—the Eco-friendly Product Intention Model for Low-Carbon Packaging (EPIM-LCP)—with a view to rigorously examining the interactions among environmental motivations, technological perception, and intention to change behavior. The integrated model proposes to achieve a better explanation of the adoption processes of sugarcane bagasse-based packaging products.

2.4. Research Gaps and Theoretical Integration

Although the adoption of green packaging and Agricultural by-products continues to expand, current research still reveals significant gaps in theoretical integration and behavioral mechanism modeling. Most existing studies rely on a single theoretical framework—such as the Technology Acceptance Model (TAM), the Theory of Planned Behavior (TPB), or the Value-Belief-Norm (VBN) theory. While each model offers explanatory value within its respective dimension, they fall short of capturing the full cognitive-to-behavioral transformation that consumers undergo when adopting sustainable products [1]. For instance, TAM emphasizes the role of perceived usefulness and ease of use in shaping adoption intentions but overlooks internal drivers like environmental awareness and value orientation. TPB, though accounting for social norms and perceived behavioral control, provides limited insight into environmental cognition and personal ecological values.

Most studies focus on the direct relationship between attitude and intention, paying insufficient attention to the mediating mechanisms linking cognition, attitude, and behavioral intention. In particular, the bridging role of low-carbon awareness (LCA) between environmental concerns, values, and attitudes remains underexplored. Previous research has suggested that environmental concerns and values often influence behavioral intention indirectly through LCA [15]. However, such mediating mechanisms have mainly been validated in the context of green travel or energy consumption, with little investigation in the domain of single-use low-carbon packaging.

Although some studies have attempted to integrate models—such as TAM with TPB or VBN with TPB—systematic fusion of technological perceptions, behavioral norms, and environmental cognition remains rare. Additionally, compared to the more developed research on digital platforms and smart technologies, studies focusing on consumer acceptance of bio-based packaging products—such as sugarcane bagasse containers—remain underdeveloped and lack robust empirical validation.

To address these gaps, this study proposes the Eco-friendly Product Intention Model for Low-Carbon Packaging (EPIM-LCP). Grounded in TAM, the model incorporates key constructs from TPB—subjective norms and perceived behavioral control—and integrates environmental concern, environmental values, and low-carbon awareness from EBT. This comprehensive framework delineates a psychological pathway from environmental drivers to environmental cognition, technological perception, usage attitude, and ultimately behavioral intention. EPIM-LCP contributes to bridging the theoretical fragmentation in green packaging research and offers a novel empirical lens through which to explore consumer adoption of low-carbon packaging solutions.

2.5. Conceptual Framework

Building upon the preceding literature review and theoretical foundations, this study integrates the Technology Acceptance Model (TAM), the Theory of Planned Behavior (TPB), and Environmental Behavior Theory (EBT) to develop the Eco-product Intention Model – Low Carbon Pathway (EPIM-LCP). This conceptual model aims to systematically explore the psychological mechanisms and behavioral pathways driving consumer adoption of Agricultural by-products—specifically sugarcane bagasse containers—in environmentally conscious contexts.

The EPIM-LCP model incorporates core constructs from the three theoretical perspectives to comprehensively map the key determinants of product acceptance intention (PAI) and the mediating mechanisms involved. From the environmental dimension, environmental concern (EC) and environmental values (EV), derived from EBT, serve as external motivational fac-

tors influencing low-carbon awareness (LCA), which in turn affects behavioral attitudes. From the technological perspective, perceived usefulness (PU) and perceived ease of use (PEOU), drawn from TAM, reflect consumers' evaluations of the product's functional value and usability, both of which shape attitude (ATT). In the behavioral dimension, attitude (ATT), subjective norms (SN), and perceived behavioral control (PBC)—key elements of TPB—collectively influence acceptance intention (PAI), highlighting the structural explanatory power of TPB.

Importantly, the model positions LCA and ATT as pivotal mediating variables, linking environmental drivers to attitude formation and bridging technological perceptions to behavioral intention. Based on this framework, the study proposes eleven hypotheses, encompassing both direct relationships and two key mediating pathways. These hypotheses are designed to empirically validate the logical linkages among environmental motivations, perceived technology attributes, and behavioral intention.

As shown in **Figure 1**, the proposed conceptual framework provides a structured foundation for subsequent empirical testing and structural equation modeling, offering a robust pathway to understand Agricultural by-products adoption behavior.

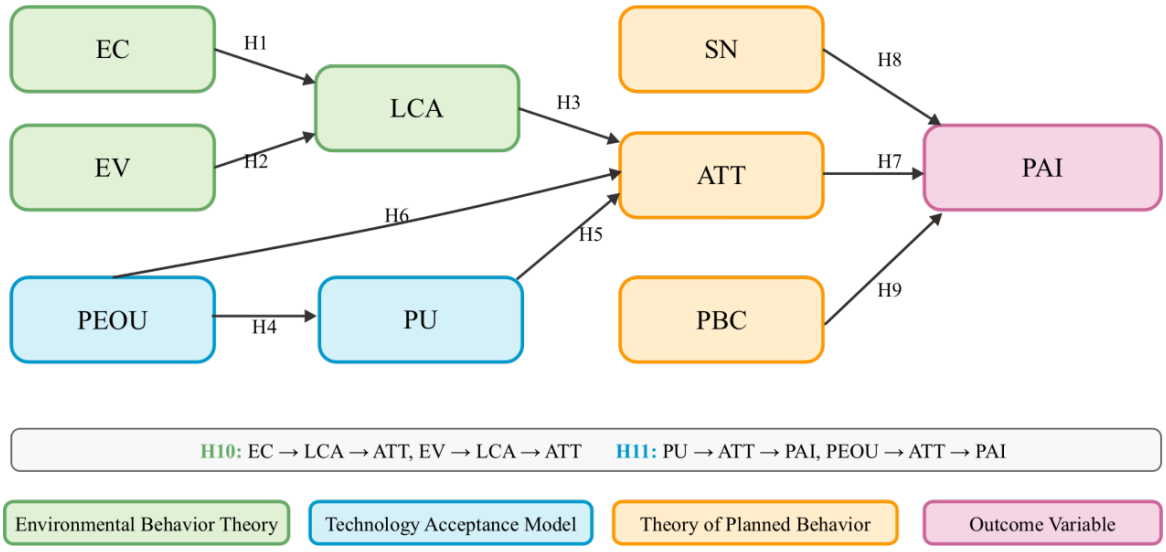

Figure 1. Conceptual Model of Agricultural By-Products User Acceptance Based on the Integration of TPB, TAM and Environmental Behavior Theory.

3. Methodology

3.1. Model Development Process

3.1.1. Justification for TPB–TAM–EBT Integration

To rigorously study the paths that lead to the adoption of low-carbon packages, the current study combines the Theory of Planned Behavior (TPB), the Technology Acceptance Model (TAM), and Environmental Behavior Theory (EBT) into a single Structural Equation Modeling (SEM) framework adapted to the bagasse container context. The integration of the theories remedies the narrow explanatory capability of single-theory designs in characterizing behavioral motivation and predicting adoption, thus increasing both explanatory range and usability.TPB focuses on the direct effect of attitude (ATT), subjective norms (SN), and perceived behavioral control (PBC) to determine behavioral intention and has been extensively used in environmental behavior studies. Yet, TPB ignores the essential perceptual mechanisms of technology adoption. TAM ensures that such perceptual mechanisms of perceived ease of use (PEOU) and perceived usefulness (PU) are accommodated, particularly in situations in which the features of the product, such as functionality and ease of use, determine the choices of users, as happens to be the case with bagasse containers.EBT takes the mod-

el a step further by including ecological-psychological motives such as environmental concern (EC), environmental values (EV), and low-carbon awareness (LCA) to draw attention to the role of environmental cognition in the determination of behavior. Together, TPB accounts for the role of social and control drivers of intention, TAM accounts for the role of the perception of function, and EBT adds the role of environmental values in motivation. Their integration forms a comprehensive and theoretically coherent model that offers a robust foundation for examining consumer acceptance of low-carbon innovations.

3.1.2. Variable Selection and Construct Operationalization

In the integrated theoretical framework of TPB, TAM, and Environmental Behavior Theory (EBT), the current study identifies and operationalizes nine latent dimensions that, altogether, summarize the most important dimensions of environmental cognition, technological perception, and behavioral intention—balancing theoretical conceptualization and practical application. In the environmental cognition aspect, environmental concern (EC), environmental values (EV), and low-carbon awareness (LCA) are used to measure consumers' levels of concern for environmental issues, ecological values, and low-carbon living consciousness. Based on TAM, perceived usefulness (PU) and perceived ease of use (PEOU) are employed to measure consumers' self-evaluations of the usability of the bagasse container and easiness of operation. Attitude (ATT) as mediating variable mediates the relationship from cognition to behavior by indicating users' overall evaluative orientation. Subjective norms (SN) and perceived behavioral control (PBC) of TPB account for social pressure and self-efficacy, respectively. The last one, product acceptance intention (PAI), is the dependent variable that reflects consumers' intention to adopt sugarcane bagasse containers in the future. All the variables are ascertained by using a specially prepared questionnaire with items from widely accepted literature and tailored to the study setting, a five-point Likert scale. The system of such concepts provides the basic platform for the modeling of the process of consumer acceptance as well as cognitive processes of behavior toward agricultural by-products.

3.2. Measurement Instrument

3.2.1. Scale Sources and Adaptation

To preserve the integrity and rigor of the measurement tool, a measurement model of the study was developed based on the combined theoretical framework of TPB, TAM, and Environmental Behavior Theory (EBT). Established scales from the literature that were previously tested were adapted and applied in the study, tailored to the application environment of the sugarcane bagasse food containers. Environmental concern (EC), environmental values (EV), and low-carbon awareness (LCA) were used in the study from EBT based on references from Stern [38], Dunlap et al. [39], and Whitmarsh et al. [40]. Perceived ease of use (PEOU) and perceived usefulness (PU) were used in the study from the TAM model by Davis and Venkatesh et al. [21,41]. Concept adoption from the TPB model resulted in the adoption of attitude (ATT), subjective norm (SN), and perceived behavioral control (PBC) [28]. Product acceptance intention (PAI) integrated concepts from both TAM and TPB in the measurement of consumers' adoption intention of sugarcane bagasse containers. All the measures were operationalized using a five-point Likert scale (Strongly Disagree = 1; Strongly Agree = 5) with each measure having been assigned four questions. The questionnaire went through the process of standardized translation, cultural adaptation, expert assessment, and piloting (n = 30) to preserve the face validity of language and measurement validity. The entire measurement scale structure is presented in **Table 1** (Construct Measurement Scales).

3.2.2. Likert Scale Design and Measurement Items

The study used a five-point Likert scale (1 = strongly disagree, 5 = strongly agree) to assess each of the latent constructs, measuring respondents' levels of agreement to various statements. The Likert scale is very familiar in social science and consumer behavior research for its stability, ease of use, and easy administration. Every

question was written as a clear, concise declarative statement, avoiding double negatives or vaguenesses to maintain consistency of meaning and ease of comprehension. The measurement items were drawn from pre-existing literature and adapted to the sugarcane bagasse containers' context to represent four thematic dimensions, including environmental motivation, technological perception, behavioral attitude, and adoption intention. Nine latent constructs with a total of 36 measurement items, each with four, were developed. Before official data collection, a pilot test (n=30) was conducted to check the linguistic clarity and the logical ordering of the questions in order to establish them in the Chinese setting and their reliability and validity. The entire measure of measurement items and their sources is shown in **Table 1**.

Table 1. Construct Measurement Scales.

Item Statement
1. Environmental Concern (EC) [38–40]
EC-1: I am very concerned about current environmental issues.
EC-2: Increasingly serious environmental pollution is one of the issues I often think about.
EC-3: I believe environmental protection is an important challenge facing society today.
EC-4: Compared with other social issues, I pay more attention to environmental issues.
2. Environmental Values (EV) [11,39]
EV-1: I believe humans should live in harmony with nature.
EV-2: I think environmental protection is more important than economic development.
EV-3: I believe everyone has a responsibility to protect the environment.
EV-4: I am willing to make personal efforts for environmental protection.
3. Low-Carbon Awareness (LCA) [24,40]
LCA-1: I understand the impact of plastic waste on climate change and carbon emissions.
LCA-2: I recognize the importance of low-carbon lifestyles in reducing greenhouse gas emissions.
LCA-3: I know choosing Agricultural by-products can reduce my personal carbon footprint.
LCA-4: I clearly understand the impact of personal consumption behavior on carbon emissions.
4. Perceived Usefulness (PU) [21,41]
PU-1: I believe using sugarcane bagasse containers can effectively reduce carbon emissions.
PU-2: I think using sugarcane bagasse containers helps with resource recycling.
PU-3: I think sugarcane bagasse containers meet my daily dining needs.
PU-4: Overall, I find sugarcane bagasse containers useful.
5. Perceived Ease of Use (PEOU) [21,41]
PEOU-1: I think sugarcane bagasse containers are convenient to use.
PEOU-2: Using sugarcane bagasse containers does not require additional learning or adaptation.
PEOU-3: I feel the way to use sugarcane bagasse containers is not significantly different from traditional containers.
PEOU-4: Overall, I find sugarcane bagasse containers easy to use.
6. Attitude (ATT) [28,42]
ATT-1: I think using sugarcane bagasse containers is a wise choice.
ATT-2: My attitude towards using sugarcane bagasse containers is positive.
ATT-3: I believe using sugarcane bagasse containers is beneficial.
ATT-4: I enjoy the feeling of using sugarcane bagasse containers.
7. Subjective Norm (SN) [28,43]
SN-1: Important people in my life think I should use sugarcane bagasse containers.
SN-2: People I respect would support my use of sugarcane bagasse containers.
SN-3: My family and friends hope I use eco-friendly containers like sugarcane bagasse containers.
SN-4: Public opinion encourages the use of eco-friendly containers such as sugarcane bagasse containers.
8. Perceived Behavioral Control (PBC) [28,44,45]
PBC-1: Whether I use sugarcane bagasse containers is entirely up to me.
PBC-2: I have the ability to obtain and use sugarcane bagasse containers.
PBC-3: I can easily obtain sugarcane bagasse containers.
PBC-4: The price of sugarcane bagasse containers is acceptable to me.
9. Product Acceptance Intention (PAI) [28,41]
PAI-1: I am willing to accept and use sugarcane bagasse containers.
PAI-2: I expect to use sugarcane bagasse containers in the future.
PAI-3: Given the opportunity, I would choose sugarcane bagasse containers over traditional plastic containers.
PAI-4: I would prefer sugarcane bagasse containers as my primary food container.

Note: Items: 4-item scale. Likert scale: 5 (1 - strongly disagree; 5 - strongly agree).

3.3. Data Collection

3.3.1. Sampling and Respondent Profile

This study employed a non-probability convenience sampling method, targeting individuals aged 18 and above who had ordered takeout at least three times within the past three months. Given that sugarcane bagasse containers are primarily used in takeaway and fast-food contexts, the selected sample demonstrates strong relevance for evaluating product adoption. The survey was administered online via platforms such as Wenjuanxing between October and December 2024, focusing on respondents in the Guangxi Zhuang Autonomous Region of China. Distribution was further supported through the research team's social networks. A total of 450 valid responses were collected (see **Table 2**). The sample exhibited a balanced distribution across key demographic variables such as gender, age, education, and income, ensuring both structural representativeness and diversity. Male respondents accounted for 59.8%, while females made up 40.2%. The majority (83.7%) were between the ages of 18 and 45, aligning with the core demographic of takeaway consumers. In terms of education, 54.9% held a bachelor's degree or higher, indicating a generally well-educated sample. Income levels were predominantly mid-range, with 58.4% earning between RMB 3,001 and 8,000 per month. Regarding product experience, 51.8% had used sugarcane bagasse containers once or twice, 43.6% had heard of them but not used them, and only 4.7% were frequent users. These figures suggest moderate awareness but relatively low usage frequency, indicating untapped market potential. The sample structure provides a robust foundation for subsequent model testing and analysis of consumer adoption behavior toward low-carbon packaging.

Table 2. Descriptive Statistics of Sample Characteristics (N=450).

Category	Classification	Frequency	Percentage (%)
Gender	Male	269	59.8
	Female	181	40.2
Age	Under 18	5	1.1
	18–25 years	136	30.2
	26–35 years	131	29.1
	36–45 years	110	24.4
	46–55 years	50	11.1
	56 years and above	18	4
Education Level	High school / Vocational or below	61	13.6
	Associate degree	142	31.6
	Bachelor's degree	183	40.7
	Master's degree	53	11.8
	Doctorate and above	11	2.4
Monthly Income	Below 3,000 RMB	90	20
	3,001–5,000 RMB	146	32.4
	5,001–8,000 RMB	117	26
	8,001–12,000 RMB	61	13.6
	12,001–20,000 RMB	29	6.4
	Over 20,000 RMB	7	1.6
Familiarity with Bagasse Containers	Heard but never used	196	43.6
	Used 1–2 times	233	51.8
	Frequently used	21	4.7

3.4. Data Analysis Methods

3.4.1. Normality and Common Method Bias

Before conducting structural equation modeling (SEM), this study tested data normality using Mardia's multivariate skewness and kurtosis statistics. Results indicated a significant deviation from multivariate normality, thereby supporting the application of Partial Least Squares SEM (PLS-SEM), which is well-suited for non-normally distributed data due to its robust estimation capabilities. Since all questionnaire data were gathered from a single source at the same point in time, the study also dealt with the possibility of common method bias (CMB). A full collinearity test suggested by Kock and Lynn to evaluate and control the CMB was used [46]. This consisted of regressing the entire latent constructs onto a randomly generated dummy variable and checking the variance inflation factors (VIF). Since all the VIF scores were less than 3.3, the possibility of common method bias was low.

3.4.2. Measurement Model: Reliability and Validity Tests

Before investigating structural relationships, a strict measurement model verification procedure was followed to identify reliable and accurate measurement of latent variables. Partial Least Squares Structural Equation Model (PLS-SEM) by using SmartPLS 4.0 has been used in the study to test internal consistency, convergent validity, as well as discriminant validity. Internal consistency has been measured in accordance with Cronbach's Alpha and Composite Reliability (CR) and accepted to be greater than 0.70. To verify the convergent validity, the factor loading should be greater than 0.70, and the Average Variance Extracted (AVE) should be 0.50 and above to verify that each indicator had captured the intended variable correctly.

Discriminant validity was tested using two complementary ways: the Fornell-Larcker criterion, in that the square root of each construct's AVE should be higher in relation to that of its relationship with other constructs; and the Heterotrait-Monotrait Ratio (HTMT), in the case of a figure of less than 0.90, indicating clear statistical discriminant among the constructs. Furthermore, the calculation of the Variance Inflation Factors (VIF) served to preclude the possibility of any problem of multicollinearity. These calculations conformed to the suggested PLS-SEM guidelines of Hair et al. and Henseler et al. and are fully explained in Chapter 4 [47,48].

3.4.3. Structural Model: Path Analysis, Mediation, and Predictive Power

With reliability and validity of the measurement model confirmed, the study went ahead to conduct the path analysis, mediation test, and predictive estimates with Partial Least Squares Structural Equation Modeling (PLS-SEM) using the SmartPLS 4.0 software. The primary aim was to evaluate the theoretical utility and practical value of the proposed model. To establish the postulated direct relations among the variables, bootstrapping techniques with 5,000 to 10,000 iterations produced the path coefficients (β), standard errors (SE), t-statistics, and concomitant p-values.

The mediation paths were probed using bootstrapped confidence intervals to establish the indirect effects' significance, thereby ascertaining if the mediation effect was full or partial. The process served to clarify the relationship among the latent variables, subsequently enhancing the model's interpretative richness.

To evaluate the predictive ability of the model for out-of-sample prediction, the method of PLS-Predict, with a 10-fold cross-validation approach, was used. Predictive performance was compared to that of a standard linear regression model (LM) based on performance measures such as Stone-Geisser's Q^2_predict and Root Mean Squared Error (RMSE).

Positive value of the Q^2_predict and lower RMSE compared to the LM model reflected stronger predictive performance. The outcomes not only confirmed that the integrated model conforms to theoretical predictions well but also established the method as credible in the determination of influential factors and paths that underpin the acceptance of Agricultural by-products by consumers. These establish a strong platform for the promotion of green consumption as well as the design of customized behavioral interventions.

4. Results and Discussion

This chapter presents the empirical findings derived from the PLS-SEM analysis and offers an in-depth discussion based on the proposed research model, hypothesized relationships, and theoretical framework. The content is organized sequentially, covering descriptive statistics of key variables, assessment of the measurement model, evaluation of the structural model, and theoretical implications. By systematically linking statistical outcomes with conceptual reasoning, this chapter aims to validate the robustness of the integrated model and to identify the critical pathways driving consumer acceptance of Agricultural by-products.

4.1. Descriptive Statistics

Descriptive statistics were employed to summarize the central tendencies and dispersion of the nine latent constructs based on a sample of 450 respondents. As shown in **Table 3**, the mean values range from 3.813 to 4.143, indicating an overall positive attitude among participants. Environmental Values (EV) recorded the highest mean (M = 4.143, SD = 0.732), reflecting strong respondent endorsement of ecological principles and environmental responsibility. This was followed closely by Environmental Concern (EC, M = 4.098) and Perceived Usefulness (PU, M = 4.072), suggesting a high level of awareness regarding environmental issues and functional approval of sugarcane bagasse containers. Attitude toward use (ATT) showed the lowest mean (M = 3.813) and the highest standard deviation (SD = 1.058), indicating considerable variation in individual evaluations. Subjective Norms (SN) and Perceived Behavioral Control (PBC) had relatively lower mean scores, suggesting room for improvement in perceived social influence and behavioral agency. Overall, the data reflect moderate-to-high levels of environmental cognition, low-carbon awareness, and technological perception, providing a solid empirical foundation for subsequent structural model analysis and preliminarily validating the theoretical alignment of the integrated framework.

Table 3. Descriptive Statistics of Main Variable (N=450).

Variable	Minimum	Maximum	Mean	Std. Deviation
EC	1.000	5.000	4.098	0.814
EV	1.250	5.000	4.143	0.732
LCA	1.000	5.000	4.004	0.814
PEOU	1.250	5.000	3.987	0.861
PU	1.000	5.000	4.072	0.852
SN	1.000	5.000	3.833	1.030
PBC	1.000	5.000	3.920	0.836
ATT	1.250	5.000	3.813	1.058
PAI	1.000	5.000	3.872	0.860

Note: EC=Environmental Concern; EV=Environmental Values; LCA=Low-Carbon Awareness; PEOU=Perceived Ease of Use; PU=Perceived Usefulness; SN=Subjective Norm; PBC=Perceived Behavioral Control; ATT=Attitude; PAI=Product Acceptance Intention.

4.2. Preliminary Data Diagnostics

4.2.1. Normality Test

Before conducting structural equation modeling, it is essential to assess whether the dataset meets the assumption of multivariate normality, which informs the suitability of the chosen modeling technique. Although Partial Least Squares Structural Equation Modeling (PLS-SEM) is known for its flexibility with non-normally distributed data, explicitly testing for normality helps justify the methodological rigor and appropriateness

of model selection. In line with Cain et al. and Hair et al. recommendations [47,49], the present study used Mardia's multivariate skewness and kurtosis tests to assess the distributional features of the data. Mardia's test is one of the established diagnostic measures employed before SEM analysis to check the possibility of non-normality. The findings were a statistically significant value of 55.171 for the value of beta (β) in multivariate skewness ($p < 0.01$) and 175.710 for the value of beta (β) in the kurtosis ($p < 0.01$). These values suggested a definite departure from non-normality in the multivariate setting. These results justify the usage of PLS-SEM since the approach is robust and insensitive to non-normal data—something that is typical of many actual survey data. An affirmation of non-normality by the test offers a sound methodological justification to use PLS-SEM in the following path and mediation analyses.

4.2.2. Common Method Bias Test

Since all the data in the study were gathered from the same participants using the same questionnaire once, the possibility of common method bias (CMB) cannot be dismissed. For accuracy of model estimation, the entire collinearity check procedure suggested by Kock and Lynn was used in the current study [46]. The procedure is based on PLS-SEM frameworks and includes the implementation of a dummy latent variable to which all the constructs are regressed. Variance inflation factors (VIFs) are subsequently calculated for all the constructs. A value of VIF greater than 3.3 indicates the possibility of multicollinearity or measurement error overlap, indicating an issue of common method bias (CMB).

Nine underlying latent factors—Environmental Concern (EC), Environmental Values (EV), Low-Carbon Awareness (LCA), Perceived Ease of Use (PEOU), Perceived Usefulness (PU), Attitude (ATT), Subjective Norms (SN), Perceived Behavioral Control (PBC), and Product Acceptance Intention (PAI)—were used to regress against the dummy variable. All the VIF values were less than 3.3, as illustrated in **Table 4**, indicating that no common method bias existed, thus ensuring the validity of the dataset. These results add to the validity of measurement and structural model analysis so that the empirical findings are ensured to be interpretable.

Table 4. Full Collinearity Testing.

Variable	EC	EV	LCA	PEOU	PU	SN	PBC	ATT	PAI
VIF	2.022	1.985	2.463	2.171	2.146	2.007	2.334	2.623	2.486

Note: EC=Environmental Concern; EV=Environmental Values; LCA=Low-Carbon Awareness; PEOU=Perceived Ease of Use; PU=Perceived Usefulness; SN=Subjective Norm; PBC=Perceived Behavioral Control; ATT=Attitude; PAI=Product Acceptance Intention.

4.3. Measurement Model Evaluation

In order to ensure the statistical validity of the structural equation model, the measurement model is tested in a methodical fashion in this section, relying on reliability and validity. Partial Least Squares Structural Equation Model (PLS-SEM) with the aid of SmartPLS 4.0 is used to test the measurement of the nine core latent variables based on three dimensions, i.e., internal consistency reliability, convergent validity, and discriminant validity.

4.3.1. Reliability and Convergent Validity

Reliability analysis examines the consistency and stability of the measures of the constructs, most commonly through the employment of Cronbach's Alpha and Composite Reliability (CR). Based on the recommendations of Hair et al. [47], internal consistency measures of more than 0.70 for both measures signify acceptable internal consistency. Convergent validity is founded on the degree to which a construct effectively accounts for the variance of its corresponding items and is measured using measures of factor loadings and Average Variance Extracted (AVE). Factor loadings must be greater than 0.70, and AVE measures should be greater than 0.50 under satisfactory convergence of the items.

As evident from **Table 5**, Cronbach's Alpha measures for all nine constructs fell in the range of 0.807 to

0.877, whereas the respective measures of CR ranged from 0.874 to 0.915, both greater than the 0.70 benchmark. Standardised factor loadings for each of the measurement items are greater than 0.70, supporting high correlations among the respective items and their respective constructs. Additionally, the AVE measures ranged from 0.635 to 0.730, supporting strong convergent validity. These cumulative findings substantiate that the measurement instruments possess high internal reliability, precise construct structure, and high measurement robustness, furnishing a secure platform to carry out subsequent structural model analysis.

Table 5. Reliability and Convergent Validity of Constructs.

Variable	Item	Factor Loading	Cronbach's alpha	CR	AVE
ATT	ATT1	0.860	0.877	0.915	0.730
	ATT2	0.849			
	ATT3	0.832			
	ATT4	0.877			
EC	EC1	0.850	0.852	0.900	0.693
	EC2	0.827			
	EC3	0.834			
	EC4	0.818			
EV	EV1	0.812	0.838	0.892	0.674
	EV2	0.827			
	EV3	0.800			
	EV4	0.843			
LCA	LCA1	0.763	0.807	0.874	0.635
	LCA2	0.846			
	LCA3	0.728			
	LCA4	0.844			
PAI	PAI1	0.815	0.859	0.904	0.703
	PAI2	0.880			
	PAI3	0.811			
	PAI4	0.845			
PBC	PBC1	0.852	0.824	0.884	0.655
	PBC2	0.758			
	PBC3	0.847			
	PBC4	0.777			
PEOU	PEOU1	0.818	0.833	0.889	0.666
	PEOU2	0.840			
	PEOU3	0.781			
	PEOU4	0.824			
PU	PU1	0.881	0.847	0.897	0.685
	PU2	0.839			
	PU3	0.793			
	PU4	0.796			
SN	SN1	0.808	0.843	0.895	0.680
	SN2	0.826			
	SN3	0.840			
	SN4	0.823			

4.3.2. Discriminant Validity: Fornell–Larcker and HTMT

Discriminant validity indicates that latent measures are statistically unique, so that every variable measures its respective concept as intended, and is not overlapping with other concepts. To also increase the measurement model's robustness, discriminant validity is tested both by Fornell-Larcker criterion and by the Heterotrait–Monotrait ratio (HTMT). As argued by Fornell and Larcker [50], a construct has satisfactory discriminant validity whenever a square root of its Average Variance Extracted (AVE) is greater than the correlations of the same with other constructs. As evident from **Table 6**, square roots of AVE of all the constructs are greater than the corresponding inter-construct correlation coefficients, reflecting evident conceptual separability without overlap. Further, to confirm the same, the HTMT method suggested by the work conducted by Henseler et al. is used [48]. HTMT assesses the ratio of correlations of the same-construct to correlations of different-construct, using 0.90 (0.85 as tighter validation) as the widely accepted cut-off point. In the current study, all the HTMT values are lower than 0.90 (as evident from **Table 7**), reestablishing robust discriminant validity among all the constructs. The findings from both the methods cumulatively establish that the measurement model has evident distinction among the latent variables, hence supporting the validity of the structural model as well as subsequent analysis of paths.

Table 6. Fornell-Larcker Discriminant Validity Test Results.

	ATT	EC	EV	LCA	PAI	PBC	PEOU	PU	SN
ATT	**0.854**								
EC	0.452	**0.832**							
EV	0.405	0.549	**0.821**						
LCA	0.586	0.583	0.617	**0.797**					
PAI	0.696	0.562	0.492	0.529	**0.838**				
PBC	0.509	0.593	0.588	0.606	0.599	**0.810**			
PEOU	0.582	0.515	0.476	0.531	0.524	0.535	**0.816**		
PU	0.593	0.426	0.430	0.416	0.522	0.545	0.645	**0.828**	
SN	0.475	0.553	0.549	0.591	0.545	0.615	0.454	0.477	**I**

Table 7. HTMT Discriminant Validity Test Results.

	ATT	EC	EV	LCA	PAI	PBC	PEOU	PU	SN
ATT									
EC	0.519								
EV	0.467	0.649							
LCA	0.690	0.701	0.746						
PAI	0.798	0.657	0.579	0.630					
PBC	0.590	0.702	0.699	0.733	0.707				
PEOU	0.678	0.610	0.570	0.647	0.619	0.646			
PU	0.682	0.496	0.506	0.495	0.607	0.647	0.763		
SN	0.548	0.650	0.651	0.712	0.636	0.726	0.539	0.560	

4.4. Structural Model Results

This section presents and interprets the results of the structural model estimated using the PLS-SEM method. The evaluation covers path coefficient estimation, hypothesis testing, and effect size analysis, aiming to validate the causal relationships among latent constructs and assess the relative influence of each path. Significance testing for all path coefficients was

conducted via SmartPLS 4.0 using bootstrapping with 10,000 resamples.

4.4.1. Path Coefficients and Hypothesis Testing

As illustrated in **Figure 2** and detailed in **Table 8**, all nine direct effect hypotheses (H1–H9) received statistical support, indicating significant positive relationships among environmental factors, perceived technology variables, and behavioral constructs [51,52]. Within the Environmental Behavior Theory (EBT) path, Environmental Concern (EC) had a significant positive impact on Low-Carbon Awareness (LCA) (β = 0.349, p < 0.001), supporting H1. Likewise, Environmental Values (EV) significantly influenced LCA (β = 0.425, p < 0.001), validating H2. Furthermore, LCA had a strong positive effect on Attitude (ATT) (β = 0.352, p < 0.001), supporting H3. These results suggest that individuals' environmental cognition and value orientation play a crucial role in fostering favorable attitudes toward eco-products. In the Technology Acceptance Model (TAM) path, Perceived Ease of Use (PEOU) showed a strong positive effect on Perceived Usefulness (PU) (β = 0.645, p < 0.001), offering robust support for H4. PU, in turn, positively influenced ATT (β = 0.329, p < 0.001), confirming H5. PEOU also significantly affected ATT (β = 0.184, p = 0.005), supporting H6. These findings validate TAM's core mechanism, wherein perceptions of usefulness and ease of use jointly shape user attitudes. Regarding the Theory of Planned Behavior (TPB) path, ATT exhibited a highly significant positive impact on Product Acceptance Intention (PAI) (β = 0.493, p < 0.001), strongly supporting H7. Subjective Norms (SN) also showed a significant effect on PAI (β = 0.155, p = 0.001), supporting H8. Similarly, Perceived Behavioral Control (PBC) had a significant positive influence on PAI (β = 0.253, p < 0.001), confirming H9. Effect size (f^2) analysis further substantiates these findings. PEOU had a large effect on PU (f^2 = 0.713), and ATT had a large effect on PAI (f^2 = 0.404). EV's impact on LCA (f^2 = 0.236), LCA's impact on ATT (f^2 = 0.178), and EC's influence on LCA (f^2 = 0.159) were all medium effects. Meanwhile, the effects of PBC, PU, and SN on PAI were classified as small.

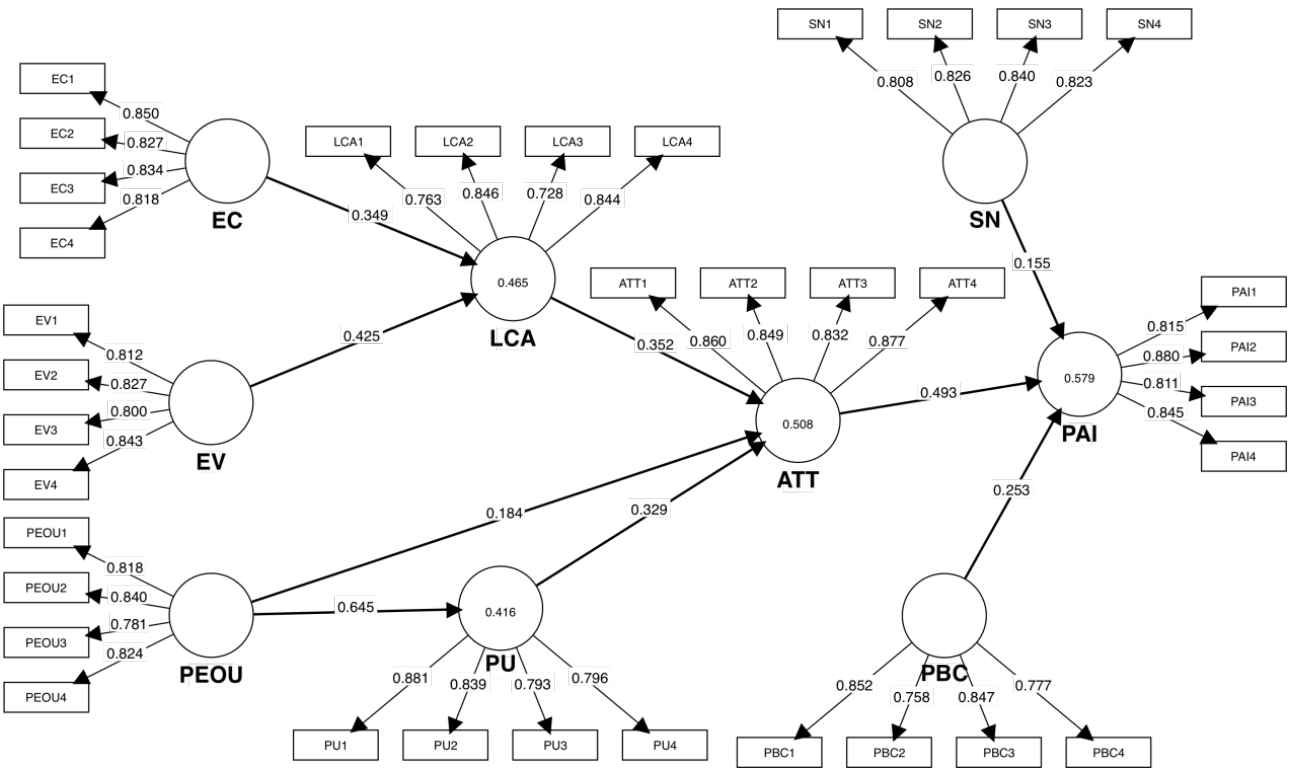

Figure 2. Structural Equation Modeling Analysis Results.

Table 8. Direct Path Relationship Test Results.

Relationships	Std.beta	Std.Dev	T-value	P-value	PCI LL	PCI UL	f^2	effect Size
H1:EC -> LCA	0.349	0.058	5.984	0.000	0.249	0.441	0.159	Medium
H2:EV -> LCA	0.425	0.05	8.413	0.000	0.34	0.507	0.236	Medium
H3:LCA -> ATT	0.352	0.045	7.865	0.000	0.275	0.423	0.178	Medium
H4:PEOU -> PU	0.645	0.047	13.806	0.000	0.56	0.714	0.713	Large
H5:PU -> ATT	0.329	0.059	5.594	0.000	0.234	0.426	0.126	Small
H6:PEOU -> ATT	0.184	0.072	2.554	0.005	0.069	0.307	0.034	Small
H7:ATT -> PAI	0.493	0.063	7.849	0.000	0.386	0.593	0.404	Large
H8:SN -> PAI	0.155	0.051	3.037	0.001	0.072	0.241	0.033	Small
H9:PBC -> PAI	0.253	0.062	4.07	0.000	0.157	0.361	0.085	Small

Note: Effect size standards—$f^2 \geq 0.35$ indicates a large effect; $0.15 \leq f^2 < 0.35$ indicates a medium effect; and $0.02 \leq f^2 < 0.15$ indicates a small effect [51,52].

Overall, the structural paths were well-defined, with all core hypotheses supported by both statistical significance and effect size measures, revealing a robust and predictable causal pathway linking environmental cognition, technology perceptions, and behavioral intentions.

4.4.2. Mediation Effects

To further investigate the underlying mechanisms among the constructs, this study conducted a mediation analysis to examine indirect pathways between variables. Mediation analysis not only helps to uncover how one construct influences another indirectly but also verifies how multiple theoretical constructs are interconnected through mediators to form an integrated explanatory path. The analysis employed the bootstrapping technique in SmartPLS 4.0 with 10,000 resamples, and the significance of indirect effects was determined based on p-values and confidence intervals. As shown in **Table 9**, all standardized coefficients for the hypothesized mediation paths are statistically significant ($p < 0.01$), providing empirical support for the proposed indirect effects. Specifically, perceived usefulness (PU) indirectly influences product acceptance intention (PAI) through attitude (ATT) ($\beta = 0.162$, $p < 0.001$), suggesting that users' perceptions of usefulness first shape their positive attitudes, which then enhance their willingness to adopt bagasse-based containers. Similarly, perceived ease of use (PEOU) exerts both a direct influence on ATT and an indirect effect on PAI via ATT ($\beta = 0.091$, $p = 0.007$), confirming the TAM mechanism in which perceived usability impacts behavioral intention through attitude formation. In the environmental pathway, environmental concern (EC) and environmental values (EV) influence PAI indirectly through a dual mediation chain involving low-carbon awareness (LCA) and ATT. The indirect effect of the EC → LCA → ATT pathway is $\beta = 0.123$ ($p < 0.001$), while that of the EV → LCA → ATT pathway is $\beta = 0.149$ ($p < 0.001$), highlighting how environmental beliefs and values translate into behavioral intentions by enhancing low-carbon awareness and shaping positive attitudes. These findings demonstrate that users' acceptance of Agricultural by-products is shaped not only by direct influences but also by complex psychological and cognitive mechanisms, thereby validating the comprehensiveness and explanatory power of the integrated TPB-TAM-EBT model.

Table 9. Mediation Effect Test Results.

Relationships	Std.beta	Std.Dev	T-value	P-value	PCI LL	PCI UL
LCA -> ATT -> PAI	0.174	0.032	5.5	0	0.127	0.23
PEOU -> PU -> ATT -> PAI	0.105	0.025	4.239	0	0.07	0.152
EC -> LCA -> ATT -> PAI	0.061	0.016	3.837	0	0.039	0.091

Table 9. *Cont.*

Relationships	Std.beta	Std.Dev	T-value	P-value	PCI LL	PCI UL
EV -> LCA -> ATT -> PAI	0.074	0.016	4.687	0	0.051	0.103
PEOU -> ATT -> PAI	**0.091**	**0.037**	**2.456**	**0.007**	**0.037**	**0.159**
PU -> ATT -> PAI	**0.162**	**0.035**	**4.595**	**0**	**0.11**	**0.227**
EC -> LCA -> ATT	**0.123**	**0.027**	**4.501**	**0**	**0.082**	**0.172**
EV -> LCA -> ATT	**0.149**	**0.025**	**5.954**	**0**	**0.111**	**0.193**
PEOU -> PU -> ATT	0.212	0.042	5	0	0.147	0.288

4.4.3. Predictive Relevance

Based on the establishment of the structural relationship paths and mechanisms of mediation, the study went ahead to also evaluate the practical utility of the model through an examination of its predictive accuracy using the PLS-Predict method. As a more and more embraced procedure within partial least squares structural equation modeling (PLS-SEM), the PLS-Predict serves to evaluate a model's accuracy in predicting out-of-sample, hence measuring its utility in actual decision-making and forecasting applications.With the product acceptance intention (PAI) as the central dependent measure, SmartPLS 4.0 was used to calculate predicted values of each indicator based on 10-fold cross-validation, and these were subsequently matched with the actual observed values. Two main indicators were employed: (1) Q^2_predict (Stone-Geisser's Q^2), an index of predictive relevance—with values greater than zero ascertaining acceptable predictive accuracy, and (2) RMSE (Root Mean Square Error), capturing the difference in predicted and actual values. By comparing the RMSE of the PLS-SEM model with that of a benchmark linear regression model (LM), the predictive superiority of the PLS model can be evaluated.

As evident in **Table 10**, all the values of Q^2_predict for the PAI indicators (PAI1–PAI4) are positive, varying from 0.288 to 0.343, supporting the strong predictive validity of the model. Additionally, the PLS-SEM model consistently provides lower RMSE values compared to the linear model for all the indicators, further supporting its increased predictive accuracy in out-of-sample contexts. These findings affirm that the TPB-TAM-EBT integrated model is not only statistically significant but also practically useful in predicting consumer acceptance of Agricultural by-products including bagasse-based containers. It offers a strong analytical tool for market forecasting, user response modeling, and encouraging sustainable consumption behavior.

Table 10. PLS-Predict.

Indicator	Q^2predict	PLS-SEM_RMSE	LM_RMSE	PLS-LM
PAI1	0.343	0.756	0.764	−0.008
PAI2	0.328	0.876	0.886	−0.01
PAI3	0.288	0.862	0.887	−0.025
PAI4	0.301	0.903	0.923	−0.02

4.5. Discussion

The empirical analysis indicates that environmental concern (EC) and environmental values (EV) affect indirectly the consumers' attitudes toward Agricultural by-products (ATT) by promoting their low-carbon awareness (LCA), that subsequently increases their intention to adopt such products (PAI). This process supports the traditional "value–belief–cognition–behavior" chain in Environmental Behavior Theory, highlighting

cognitive awareness as the mediator in the formation of behavior.

The perceived ease of use (PEOU) of a technology strongly contributes to the perceived usefulness (PU) of the technology, and both play an important role in influencing the intention to accept a product through the building of positive attitudes, validating the fundamental mechanisms of the Technology Acceptance Model (TAM). As a result, in markets in which low-carbon goods are still in the early stages of adoption, the development of user perceptions of function and convenience is essential. Within the Theory of Planned Behavior (TPB) theory, the strongest predictor for acceptance intention (PAI) is the attitude (ATT) of the technology, overpowering both subjective norms (SN) and perceived behavioural control (PBC), implying that internal thought processes of the consumers control behavioural decisions. This empirical verification supports the use of attitude-based strategies in environmental product design and promotion.

Moreover, the study confirms two key mediating mechanisms: first, environmental factors influence attitudes via low-carbon awareness; second, technical perceptions influence acceptance intention via attitude. These dual pathways reflect the synergistic operation of multiple psychological mechanisms driving consumer adoption of Agricultural by-products, highlighting the integrative model's theoretical robustness and explanatory power. The predictive performance also shows the superiority of the PLS model over standard linear ones in predicting product acceptance intention, indicating that the combined TPB-TAM-EBT approach has high practical utility. Together, the suggested model has good theoretical consistency, logic of pathways, and predictions, presenting a robust explanation of how motivations in an environment, perceptions of technology, and intentions in behavior are causally connected—giving a clear and empirically supported structure for theory development in sustainable consumer behavior.

5. Conclusions and Future Research

This study examines sugarcane bagasse-based containers as a representative application of Agricultural by-products in sustainable packaging and develops an integrated structural equation model (EPIM-LCP) by combining the Technology Acceptance Model (TAM), the Theory of Planned Behavior (TPB), and Environmental Behavior Theory (EBT). The model systematically investigates the behavioral pathways and psychological mechanisms that drive consumer acceptance of Agricultural by-products. Based on empirical data collected from 450 valid respondents, several key findings emerge: First, environmental concern (EC) and environmental values (EV) significantly enhance low-carbon awareness (LCA), which subsequently influences attitudes (ATT) toward the use of sugarcane bagasse containers. This confirms the cognitive–attitudinal mediation mechanism articulated by EBT. Second, within the TAM framework, perceived ease of use (PEOU) exerts a strong positive influence on perceived usefulness (PU), and both constructs indirectly shape acceptance intention (PAI) through attitude, validating the core structure of TAM. Third, under TPB, attitude (ATT), subjective norms (SN), and perceived behavioral control (PBC) all significantly predict acceptance intention, with attitude emerging as the strongest predictor. The mediating role of LCA and ATT is further confirmed, establishing two core pathways: (1) environmental cognition → low-carbon awareness → attitude → intention, and (2) technical perception → attitude → intention. Predictive analysis using PLS-Predict confirms the model's strong out-of-sample forecasting capability.

Theoretically, this study is among the first to integrate TAM, TPB, and EBT into a unified framework specifically applied to the context of Agricultural by-products, addressing the limitations of fragmented single-theory approaches. By incorporating low-carbon awareness as a mediating variable, the EPIM-LCP model bridges the gap between cognitive understanding and behavioral intention, enriching the conceptual foundation for green consumer behavior and environmental psychology. The multidimensional framework enables a more comprehensive understanding of how consumers process information and form intentions toward adopting packaging innovations derived from agricultural residues.

Practically, the findings offer actionable guidance for stakeholders aiming to accelerate the adoption of Agricultural by-products in consumer markets. For

businesses, emphasizing both the usefulness and ease of use in product design can significantly improve user attitudes and adoption rates. Policymakers are encouraged to strengthen environmental education and public awareness campaigns to enhance low-carbon consciousness. Marketers may leverage social norms and emotional engagement strategies to reinforce pro-environmental behavior. To enhance international relevance, stakeholders in different countries should tailor these strategies to local cultural, economic, and regulatory contexts. In high-income countries with well-established sustainability frameworks, emphasis could be placed on product innovation, carbon labeling, and green branding to attract environmentally conscious consumers. Meanwhile, in emerging economies, where awareness and infrastructure may still be developing, government-led incentives, subsidies, and public-private partnerships could be more effective in boosting market adoption. Additionally, cross-border collaboration in technology sharing and harmonized sustainability standards may accelerate the global diffusion of agricultural by-product-based packaging solutions. Taken together, these implications support a behavioral shift from passive policy compliance to active consumer-led adoption of agricultural residue-based packaging solutions.

Despite its contributions, the study presents several limitations that warrant further research. First, the use of cross-sectional data restricts analysis of behavioral change over time. Future studies could employ longitudinal or experimental designs to capture causal dynamics more precisely. Second, the data were collected primarily from Guangxi, China, which may limit the generalizability of the findings. Expanding the study across different cultural and regional contexts would enhance external validity. Third, while the EPIM-LCP model integrates key constructs from TAM, TPB, and EBT, it does not account for emotional, trust-based, or risk-related variables that may also influence adoption decisions. Future research could enrich the model by including these factors. Lastly, although sugarcane bagasse was used as the focal material, the framework could be extended to assess consumer behavior toward other Agricultural by-products, such as PLA, wheat straw, or rice husk packaging, to validate the model's scalability and broader relevance.

In summary, this study offers a robust theoretical and empirical foundation for advancing the understanding of consumer acceptance of Agricultural by-products, providing critical insight for driving sustainable packaging innovation and supporting the transition to a circular bioeconomy.

Author Contributions

Conceptualization, M.F.; methodology, M.F.; formal analysis, M.F.; investigation, M.F.; data curation, M.F.; writing—original draft preparation, M.F.; writing—review and editing, C.B.; supervision, C.B. All authors have read and agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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