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Thai Millennials' Engagement with Carbon Footprint Tracking: Extended TAM Approach

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ABSTRACT

This study investigates the adoption of carbon footprint tracking apps (CFAs) among Thai millennials, a critical element in addressing climate change. CFAs have yet to gain significant traction among users despite offering personalized missions. Employing an extended Technology Acceptance Model (TAM) framework, we examine factors influencing CFA adoption intentions based on a sample of 30 environmentally conscious Thai millennials. Our findings indicate that perceived ease of use and enjoyment are crucial drivers of CFA adoption. Trust significantly impacts perceived usefulness, while enjoyment influences perceived ease of use. The study underscores the importance of user experience (UX) and enjoyment in driving adoption, highlighting the need for intuitive interfaces and engaging features. This research provides comprehensive insights into CFA adoption in Thailand by integrating TAM with external trust and perceived enjoyment factors. These findings offer valuable guidance for app developers, policymakers, and marketers, emphasizing the critical role of user experience and fun in fostering widespread CFA adoption. We discuss implications for stakeholders and suggest directions for future research, including larger-scale studies and cross-cultural comparisons within Southeast Asia. This research contributes to SDG 13 (Climate Action) and SDG 12 (Responsible Consumption and Production).
Keywords: Carbon Footprint Tracking Apps (CFA); Technology Acceptance Model (TAM); Millennials; Intention of Adoption; Sustainable Development Goals (SDGs)

1. Introduction

Global warming presents an unprecedented challenge, with anthropogenic greenhouse gas emissions[1, 2] identified as a primary driver, as highlighted in the Global Risk Report[3]. The UN's Sustainable Development Goals (SDGs), particularly SDG 13 and SDG 12, emphasize the urgent need to transition towards more sustainable production and consumption patterns. Reducing consumer carbon emissions is pivotal in this endeavor.

The need for sustainable production and consumption has been extensively explored across academic disciplines, advocating a comprehensive approach to promote environmental sustainability[4]. Many consumers are oblivious to their carbon emissions and the ecological consequences of their lifestyle choices[5]. Addressing these issues requires behavior change, necessitating emissions monitoring. Carbon footprint calculators facilitate this process by measuring greenhouse gas emissions across various sectors and offering advice on reducing CO_2 emissions[6].

Thailand's push towards sustainable production and consumption reflects the country's unique environmental challenges and cultural context. Notable strides have been made in integrating sustainability into the development agenda and aligning national policies with the SDGs[7]. Consumer awareness and behavior towards sustainability in Thailand are evolving, evidenced by the rising interest in carbon footprint tracking apps (CFAs) among Thai millennials. Understanding these trends is crucial for optimizing app design, enhancing user engagement, and ensuring a lasting impact on eco-conscious behaviors[8].

Despite the growing interest in Carbon Footprint Tracking Applications (CFAs), a significant knowledge gap persists concerning the factors influencing their adoption and sustained use among Thai millennials. This study addresses this lacuna in the literature by conducting an in-depth analysis of user behaviors, preferences, and motivations within the context of CFA adoption in Thailand. To achieve this, we employ an extended Technology Acceptance Model (TAM) framework, which incorporates additional constructs beyond the traditional model to better capture the complexities of technology adoption in this specific cultural context[9, 10].

Existing literature provides a fundamental understanding of psychological factors driving shifts in behavior and tech acceptance. However, a specific focus on Thai millennials' motivations and challenges in their adoption and continuous use of carbon footprint tracking apps still needs to be more present. The research objectives of this exploratory study are threefold: (1) to elucidate the underlying motivations driving the sustained use of CFAs, (2) to identify and analyze the barriers impeding CFA adoption, and (3) to formulate evidence-based, actionable recommendations for app developers and policymakers. Using this extended TAM framework, our study seeks a more comprehensive understanding of CFA adoption among Thai millennials, considering technological and user-centric factors[11]. Based on a sample of 30 environmentally-conscious Thai millennials, this research aims to lay the groundwork for developing more effective and user-friendly eco-conscious technology solutions. By examining the interplay between perceived usefulness, perceived ease of use, trust, and perceived enjoyment in CFA adoption, we aspire to contribute to fostering sustainable practices in Thailand, with potential implications for similar cultural contexts[12].

2. Literature Review

2.1. Carbon Footprint

The concept of carbon footprint, which measures individual or organizational greenhouse gas emissions, has become a focal point in environmental literature. Esteemed scholars have emphasized its vital role in comprehending ecological impact[13], while others have stressed the necessity for precise measurement methods[14]. Recent research has delved into sectoral contributions to global carbon footprints, highlighting the significant impact of transportation and energy production industries[15]. Additionally, studies have investigated how personal consumption patterns affect greenhouse gas emissions, underscoring the crucial role of individual decisions in combating climate change[16]. The influence of digital tools is apparent, as is an examination of how mobile apps raise awareness and promote low-carbon lifestyles. Policy interventions have also attracted attention. Fuso Nerini, Tomei et al.[17] underscore the pivotal role of governmental strategies in reducing national carbon footprints. These studies offer a holistic understanding of carbon footprints' complexities, encompassing sectors, individual behaviors, technological integrations, and policy frameworks.

In recent years, the importance of carbon footprint has grown significantly within industries and among consumers. It is a valuable tool for evaluating the ecological impact of goods, services, and activities, facilitating the measurement and reduction of climate impact. This concept aligns with climate objectives, particularly the goal of limiting global warming to 1.5 °C. The definition provided by Wright, Kemp, and Williams[18], which focuses on carbon dioxide (CO_2) and methane (CH4) emissions, informs contemporary approaches to carbon footprint assessment. The practice has garnered widespread attention from the public, mainly through educational initiatives and media coverage, making it an effective means of raising consumer awareness about environmental impacts.

2.2. Carbon Footprint Apps

In recent years, growing concerns about climate change and environmental sustainability have sparked increased interest in minimizing personal and business carbon footprints. Carbon Footprint Apps (CFAs) have emerged as valuable tools designed to measure, track, and mitigate carbon emissions. This section examines the landscape of CFAs, focusing on their effectiveness, user adoption, and impact on promoting sustainable behavior change.

CFAs serve multiple functions in the pursuit of environmental sustainability. Primarily, they act as educational instruments, enhancing awareness about individual and organizational contributions to carbon emissions. By providing personalized data, these apps foster a deeper understanding of the need to mitigate climate change[19, 20]. This educational aspect aligns with consumers' growing emphasis on environmental literacy, particularly millennials.

User experience and interface design play crucial roles in CFA adoption. Research suggests user-friendly apps with intuitive interfaces and personalized recommendations significantly enhance engagement and encourage continued usage[21]. This finding underscores the importance of user-centric design principles in developing environmental technology solutions.

Moreover, CFAs can drive sustainable behavior change through various features. Gamification elements, goal-setting mechanisms, and social comparison features effectively motivate users to adopt eco-friendly habits and reduce their carbon footprint[22]. These behavioral change strategies align with broader technology acceptance and usage theories, including the extended Technology Acceptance Model (TAM) framework employed in this study.

Despite their potential, CFAs face several challenges. Issues related to data accuracy, privacy concerns, and user trust persist. To enhance the credibility and effectiveness of these apps, developers must focus on implementing standardized methodologies, ensuring reliable data sources, and employing transparent algorithms[23]. These challenges highlight the need for ongoing research and development in this field.

The CFA market offers various applications catering to different user needs and preferences. Apps are available for multiple smartphone operating systems, including Android and iOS, with functionalities ranging from specific CO_2 emission calculators (e.g., for flights) to comprehensive personal carbon footprint assessments. Some apps even integrate CO_2 tracking with fitness programs, demonstrating the potential for synergies between environmental and health-related technologies.

While the development and adoption of CFAs have been studied extensively in Western contexts, a notable gap exists in understanding their adoption and use in other cultural settings, particularly among Thai millennials. This study aims to bridge this gap by examining the factors influencing CFA adoption within the Thai cultural context, considering unique perceived enjoyment and environmental attitudes in the questionnaires that may shape technology acceptance and usage patterns[24].

Future research could benefit from comparative studies examining CFA adoption across different regions, particularly Southeast Asia. Such comparisons would provide valuable insights into the role of cultural, economic, and technological factors in shaping environmental technology adoption and usage patterns[25, 26].

This comprehensive approach to studying CFAs, considering their features, effectiveness, challenges, and cultural context, provides a solid foundation for understanding their potential impact on promoting sustainable behaviors among Thai millennials.

2.3. Technology Acceptance Model

To explore the adoption of Carbon Footprint Apps (CFAs), we employ the Technology Acceptance Model

(TAM), a widely recognized framework in information systems research for explaining technology adoption or rejection. Developed by Davis, Bagozzi and Warshaw[9], TAM builds upon the Theory of Reasoned Action (TRA) introduced by Fishbein and Ajzen[27]. TAM extends TRA's causal relationships[28] by clarifying how individuals accept information technology, considering factors such as personal abilities, technology characteristics, task requirements, and contextual limitations[29]. Furthermore, the theory of planned behavior (TPB), developed by Ajzen[30], is an extension of TRA. It adds the concept of perceived behavioral control to the original TRA model. Insights from TPB-based studies include Thanapongporn, Saengchote and Gowanit[31] understanding the broader context of environmental behavior among Thai millennials[32].

Critical components of TAM include Perceived Usefulness—the degree to which users believe a system will improve their performance—and Perceived Ease of Use—the extent to which users expect using a system to be effortless. Davis[33], argues that ease of use positively affects the intention to use technology. This 'Intention to Use' reflects a person's readiness to adopt and employ new technology, signifying their willingness based on perceived usefulness and user-friendliness.

Researchers have recently extended the original TAM to better explain technology adoption in various contexts. For instance, Venkatesh and Bala[10] proposed TAM3, which incorporates additional factors such as subjective norm, image, job relevance, output quality, and result demonstrability. These extensions provide a more comprehensive framework for understanding technology adoption, particularly relevant for environmental technologies like CFAs.

While TAM has been widely applied in Western contexts, its application in ASEAN countries, particularly Thailand, requires careful consideration of cultural context factors. For instance, Pornsakulvanich[24] found that Thai users' technology adoption is significantly influenced by enjoyment or fun, which may not be as prominent in individualistic Western societies.

Recent literature has paid substantial attention to adopting digital tools supporting sustainable consumption. Mishra, Akman and Mishra[34] found that the intention to adopt such tools strongly correlates with their perceived usefulness in facilitating eco-friendly behaviors. Aichner and Jacob[35]

emphasized that perceived ease of use significantly impacts users' intentions, suggesting that user-friendly interfaces and functionalities enhance adoption rates.

Comparative studies have revealed interesting regional differences in technology adoption patterns. For example, Alalwan et al.[25] found that in Jordan, perceived risk played a more significant role in mobile banking adoption compared to Western countries. Such findings highlight the importance of considering regional factors when applying TAM to different contexts, including CFA adoption in Thailand.

Furthermore, Hertwich and Peters[36] indicated that awareness and concern about environmental issues are crucial in motivating people to use digital technologies for eco-friendly consumption. Their research reveals that individuals with heightened ecological awareness are more inclined to adopt such tools. Moreover, Kollmuss and Agyeman[37] found that social norms significantly influence the intention to adopt digital tools for sustainable consumption.

Understanding these factors can offer valuable insights into fostering increased adoption rates for digital solutions promoting sustainable behaviors, particularly within the Thai context. This study will contribute to this understanding by examining how TAM components and cultural and social factors influence CFA adoption among Thai millennials.

2.4. Predictor Variables in Technology Acceptance Model

The Technology Acceptance Model (TAM) incorporates several predictor variables for understanding technology acceptance. Originally, Davis, Bagozzi and Warshaw[9] outlined perceived usefulness and perceived ease of use as primary factors significantly influencing users' intentions to adopt new technologies. As research in this field progressed, additional variables were introduced to enhance the model's explanatory power.

Venkatesh and Davis[38] expanded the original TAM into TAM2, introducing subjective norms and cognitive instrumental processes while emphasizing external factors such as system quality. This extension provided a more comprehensive framework for understanding technology adoption in various contexts.

Building on these developments, Venkatesh and Bala[10] introduced TAM3, which incorporates the Determinants of Perceived Ease of Use Model. Based on the

anchoring and adjustment framework of decision-making, this model suggests that people form initial impressions of a system's usability from their general beliefs about computers and their use. Venkatesh and Bala[10] proposed that as users become more familiar with a new system, two adjustments influence their perception of its ease of use. These adjustments encompass six factors: self-efficacy, perception of external control, anxiety, playfulness, perceived enjoyment, and objective usability.

Trust has emerged as a crucial factor in technology adoption, particularly for applications handling personal data like CFAs. Gefen[39] highlighted that trust in technology and service providers profoundly influences perceived usefulness and ease of use, underlining its critical role in user acceptance. In the context of CFAs, trust in the accuracy of carbon footprint calculations and data privacy protection will likely significantly impact user adoption intentions.

Perceived enjoyment, an emerging predictor variable, has received increasing attention for its impact on technology acceptance. Research by Venkatesh and Bala[10] indicated that users' perceptions of enjoyment or fun associated with technology use positively influence their attitudes and intentions to use it. Users viewing technology as enjoyable enhances their perceived usefulness and ease of use, affecting their acceptance behavior. This factor may be particularly relevant for CFAs, where sustained engagement is crucial for long-term behavior change.

Understanding these predictor variables is vital for comprehending user acceptance and guiding technology design, especially for environmental-focused systems like carbon monitoring apps. However, despite extensive research, a gap remains, particularly for Thai millennials in middle-income countries like Thailand. Prior studies have focused primarily on Western contexts, leaving room to understand unique factors influencing adoption in this demographic and geographic context.

For instance, Pornsakulvanich[24] found that social influence plays a more significant role in technology adoption among Thai users than for their Western counterparts. Perceived risk was crucial in mobile banking adoption in Jordan, highlighting the importance of considering regional variations in technology acceptance.

Our research aims to fill this knowledge gap by investigating the key factors and external variables driving the adoption of carbon footprint applications (CFAs) among Thai millennials. Our framework uniquely includes external variables like trust and perceived enjoyment within the TAM model. As shown in **Figure 1**, this new conceptual structure enhances the TAM by incorporating external factors that influence its core elements, such as perceived ease of use and usefulness, ultimately affecting CFA adoption.

This innovative approach distinguishes our study from previous research, which often struggled to capture the intricate relationships between these variables in CFA adoption and the promotion of low-carbon behavior among Thai millennials. By considering established TAM variables and specific factors of trust and perceived enjoyment, our study aims to provide a more comprehensive understanding of CFA adoption in the Thai context, potentially offering insights applicable to other Southeast Asian countries.
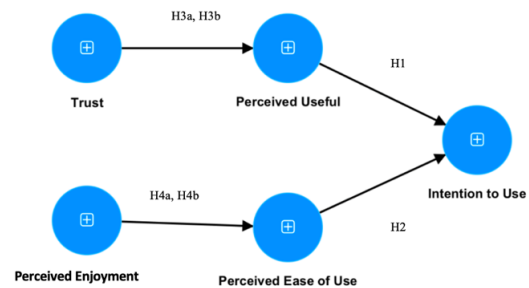

Figure 1. Conceptual framework with hypothesis.

3. Hypothesis Proposed

This section presents the hypotheses developed based on the Technology Acceptance Model (TAM) and its extensions, tailored to the context of Carbon Footprint Applications (CFAs) among Thai millennials.

3.1. Perceived Usefulness

Perceived usefulness, a core construct of TAM, refers to the degree to which a person believes that using a particular system would enhance their performance[9]. In the context of CFAs, perceived usefulness relates to users' belief that the app will effectively help them monitor and reduce their environmental impact.

In the context of carbon footprint tracking applications, perceived usefulness is pivotal in shaping users' intentions to adopt and utilize these apps. Users are more inclined to embrace carbon footprint tracking applications if they per-

ceive them as practical tools for monitoring and reducing their environmental impact. Features such as personalized emission reports, goal-setting functionalities, and suggestions for eco-friendly behaviors boost users' views on the apps' value and encourage long-term use. Based on this, we suggest the following hypothesis:

Hypothesis 1. *Perceived usefulness is positively related to the intention to use.*

3.2. Perceived Ease of Use

TAM highlights how users' perception of a technology's simplicity strongly influences their intention to use it[9]. Perceived ease of use reflects how effortless users believe a system or technology will be to operate. Numerous studies in different domains consistently demonstrate that this perceived simplicity is crucial in whether people adopt new technologies[40, 41].

In the Thai context, perceived ease of use might be particularly important due to millennials' varying levels of technological literacy. As Vantamay[42] noted, a wide range of digital proficiency among Thai youth could impact their perception of CFA usability.

In the context of carbon footprint tracking applications, perceived ease of use is critical in promoting adoption and sustained usage. Users are more inclined to embrace these applications if they perceive them as intuitive and user-friendly, featuring functionalities that facilitate effortless tracking of their environmental impact. Improving perceived ease of use entails incorporating clear instructions, intuitive interfaces, and streamlined data input processes into the application design. Therefore, we hypothesize:

Hypothesis 2. *Perceived ease of use is positively related to the intention to use.*

3.3. Trust

Perceived usefulness is the belief that using a particular system or technology will enhance work performance. Trust, conversely, refers to users' faith in the system's dependability, safety, and honesty[38]. When adopting technology, people are more likely to embrace and use a system they see as both valuable and trustworthy. Many studies have shown that perceived usefulness greatly influences users' attitudes and

behaviors when adopting various technologies[9]. Likewise, trust is critical to how users view a technology's credibility and reliability[43].

Trust, an essential extension to the original TAM, refers to users' faith in the system's reliability, security, and honesty[39]. In the context of CFAs, trust encompasses confidence in data accuracy, privacy protection, and the overall credibility of the app.

Empirical studies spanning diverse domains consistently underscore how crucial trust and perceived benefits are when people adopt new technologies. For example, in online shopping, consumers are more inclined to buy if they trust the security measures implemented by the platform and perceive the website as beneficial for their shopping needs[44]. Likewise, in healthcare technology, patients are more inclined to adopt telemedicine platforms if they trust the privacy and confidentiality of their medical information and perceive the technology as beneficial for managing their health[45].

In the specific context of carbon footprint tracking applications, trust, and perceived usefulness are expected to influence user adoption significantly. Users must have confidence that the application securely manages their data and provides accurate information about their carbon emissions. Moreover, people are more inclined to use the app if they believe it effectively tracks and lowers their ecological footprint.

Therefore, in designing and promoting carbon footprint tracking apps, developers should prioritize building trust and emphasizing the app's usefulness to encourage users' adoption. By addressing users' concerns about trustworthiness and highlighting the practical benefits of the app, developers can enhance users' intention to adopt the technology, ultimately contributing to efforts to mitigate climate change. Therefore, we hypothesize that:

Hypothesis 3a. *Trust has a positively significant relation to perceived usefulness.*
Hypothesis 3b. *Trust positively relates to perceived usefulness toward the intention to use CFA.*

3.4. Perceived Enjoyment

Venkatesh and Bala[10] merged TAM2 with the model explaining factors that determine Perceived Ease of Use to

create a comprehensive framework of Technology Acceptance, commonly known as TAM3. Adjustments within this integrated model are pivotal in shaping users' perceptions of technology acceptance. One of the critical adjustments identified is Perceived Enjoyment, which pertains to how users find using a specific system enjoyable, irrespective of the performance outcomes resulting from system use. It emphasizes the hedonic aspects of technology use and recognizes that people are more prone to use a fun and captivating system.

Research across various contexts has demonstrated that perceived enjoyment positively influences users' intentions to adopt technology. For instance, in mobile banking and e-commerce, perceived enjoyment enhances users' attitudes and intentions [28, 46].

Perceived enjoyment is anticipated to be significant in adopting carbon footprint tracking apps (CFA). Users' pleasure in using CFAs, such as engaging features and personalized missions, may impact their intention to continue using the apps. Integrating perceived enjoyment with TAM constructs can provide a crucial understanding of what motivates using CFAs among Thai millennials, thereby contributing to efforts to mitigate climate change.

For instance, Angosto et al. [47] it underscored the importance of perceived enjoyment in fitness and physical activity apps. In this context, individuals may enjoy tracking their buying patterns, getting updates on their environmental impact, viewing greenhouse gas emission data, or comparing these with reference values and personal sustainability goals. Beyond the technological aspects, tracking carbon footprints could offer hedonic benefits by evoking positive feelings and warmth associated with sustainable behavior, which might influence various transactional aspects, including service satisfaction.

While studies in Western contexts have shown the importance of perceived enjoyment in technology adoption [28, 46], its role in CFA adoption among Thai millennials may differ. The Thai concept of "sanuk" (fun) is deeply ingrained in daily life and could significantly influence how enjoyment impacts technology use [42].

Based on these findings, we hypothesize that perceived enjoyment will motivate users to engage with carbon footprint tracking apps. In this research, we define perceived enjoyment as how fun or exciting a person thinks using a carbon footprint app is and how much they link it with pleasure. Based on this, we propose the following hypothesis:

Hypothesis 4a. *Perceived enjoyment has a positively significant relation to perceived enjoyment.*

Hypothesis 4b. *Perceived enjoyment positively relates to perceived enjoyment toward the intent to use CFA.*

The conceptual framework and all proposed hypotheses are illustrated in **Figure 1**.

4. Methodology Design

4.1. Design & Procedure

A carbon footprint tracking application prototype called "Carbon Crush" was developed exclusively for research. This prototype was the foundation for showcasing the user experience (UX) and user interface (UI) to the study participants. **Appendix A** depicts the application's description and screenshots, accompanied by a brief overview. The "Carbon Crush" app enables users to monitor their carbon emissions by calculating the carbon footprint of their consumption activities and comparing them against their environmental impact reduction targets. Additionally, users can earn reward points for engaging in eco-friendly actions. The app provides suggestions for low-carbon activities that users can integrate into their daily routines and grants access to a community of environmentally conscious individuals dedicated to climate mitigation. Participants can input details about their housing, transportation, food, and consumption habits, allowing the app to compute their carbon emissions in each category and overall carbon footprint. Users can set sustainability goals and monitor their progress over time, receiving feedback on the environmental implications of their consumption choices. In essence, the app functions as a tool to assist users in embracing a more sustainable lifestyle.

The study utilized a quantitative methodology, primarily collecting data through an online survey. To assess the hypotheses based on the technology acceptance model (TAM) framework, structural equation modeling (SEM) analysis was performed using SmartPLS 4. The acceptance test for the "Carbon Crush" app took place between May 2022 and May 2023, with data gathered from 30 respondents, including managers and millennials from various industries such as retail, banking, telecommunications, and startups.

Our study included 30 Thai millennials interested in green lifestyles and app usage. While this sample size is sufficient for an exploratory analysis, we acknowledge its limitations in terms of generalizability. The survey questionnaire comprised three sections: demographics, opinions, and recommendations, with responses recorded on a 5-point Likert scale. The reliability of the questionnaire was confirmed through reliability analysis using Cronbach's alpha coefficient, with all dimensions yielding values above 0.7.

To ensure diversity in the participant pool, purposive sampling techniques were employed to select Thai millennials from various geographic regions, socio-economic backgrounds, education levels, and income brackets. Ethical considerations were prioritized, with the Institutional Review Board (IRB) approval. The data collection process followed established practices and was supplemented by G*Power software to determine the required sample size. Participants were instructed to review the UX/UI presentation, app description, and explanatory video before completing the online survey, which included attention-check questions to confirm understanding. The app design and content details are available in the **Appendix A**.

4.2. Measurement Scales

We assessed the intention to use carbon footprint tracking apps as the dependent variable, employing measurement scales deemed appropriate and aligned with the study objectives. The conceptual model encompassed five constructs, using existing scales from previous studies and consultations with three experts in carbon mitigation and the carbon footprint tracking app (CFA) industry. Four constructs were used to gauge the extended Technology Acceptance Model (TAM) components: perceived usefulness and perceived ease of use to influence the intention to use. The external variables, trust and perceived enjoyment, were evaluated through items derived from academic literature.

For perceived usefulness (PU), three items were derived from Davis, Bagozzi and Warshaw[9] with some modifications, while four items were constructed for perceived ease of use, adapted from Venkatesh[29]. Three items assessing trust (TR) were derived from Moon and Kim[28], and three items measuring perceived enjoyment (PE) were taken from Agarwal and Prasad[46]. All indicators were rated on a five-point scale. The wording of the scales was documented,

and a summary of the calculation items, along with their references, is provided in **Table 1**.

4.3. Measurement Scales

The survey instrument employed in this research comprised four main sections:

Section A: This segment collected demographic statistics and details regarding participants' energy expenditure habits. Section B contains 12 questions covering age, gender, income, education level, and energy consumption patterns. This part focused on exploring participants' self-reported intention to use (IU) the prototype of the Carbon Footprint Monitoring Application (CFA) known as "Carbon Crush" among Thai Millennials to encourage low-carbon behaviors. It consisted of three items. Section C: This section evaluated four latent variables using a total of 14 items: three for perceived usefulness (PU), four for perceived ease of use (PEU), three for trust (TR), and three for perceived enjoyment (PE). These variables were selected to gauge participants' involvement in application adoption, considering both extended Technology Acceptance Model (TAM) factors and external factors.

Section D: This section included open-ended questions about the anticipated business model of the Carbon Crush app, such as fee structure and visit frequency, to provide additional context and ensure the reliability and validity of the quantitative responses. These variables were thoughtfully chosen to assess an intention to use the extended TAM factors and external factors in influencing participants' adoption of the application. Self-reported behaviors were indicators of actual human activities, considered efficient and cost-effective. The questionnaire used a five-point Likert scale ranging from 1 to 5 to gauge participants' levels of agreement or disagreement, with options such as strongly disagree, disagree, neutral, agree, and strongly agree. Preliminary research steps were taken before distribution to guarantee the questionnaire's reliability and validity by discussing with three environmental and statistics experts to review the questionnaire for content validity.

4.4. Sampling and Data

The data collection process for this study involved administering an online survey using Google Forms. Potential

Table 1. Survey construct.

Constructs	Items	Contents	Reference
Perceived Usefulness (PU)	PU1	Using "Carbon Crush" app has helped me adjust my behavior to be more low-carbon.	Davis, Bagozzi and Warshaw[9]
	PU2	Using "Carbon Crush" app saves energy cost.	
	PU3	Using "Carbon Crush" app has more benefit than disadvantages.	
Perceived Ease of Use (PEU)	PEU1	"Carbon Crush" is easy to use and easy to learn.	Venkatesh and Bala[10]
	PEU2	Using "Carbon Crush" is easy to understand.	
	PEU3	"Carbon Crush" is convenient to use anytime, anywhere.	
	PEU4	Using "Carbon Crush" is easy to link with banking apps or e-wallets.	
Perceived Enjoyment (PE)	PE1	I enjoy using "Carbon Crush" app.	Agarwal and Prasad[46]
	PE2	"Carbon Crush" app isn't boring.	
	PE3	I'm free time. I love opening "Carbon Crush" app for enjoyment.	
Intention to use (IU)	IU1	You want to download "Carbon Crush" app.	Davis, Bagozzi and Warshaw[9]
	IU2	Do you want to recommend "Carbon Crush" to your friends and acquaintances?	
	IU3	After you download "Carbon Crush" app, you still using it for more than six months..	
Trust (TR)	TR1	Information & data in "Carbon Crush" is reliable.	Moon and Kim[28]
	TR2	Information & data in "Carbon Crush" can gain credibility from other organizations.	
	TR3	I believe the technology in Zero Carbon app can adjust my behavior to be more low-carbon.	

participants were initially contacted via telephone; respondents received the survey link after consenting to participate. Upon their consent, data collection took place from April to May 2023. Purposive random sampling included participants from varied socio-demographic backgrounds, ensuring a thorough representation of the target group of Thai millennials.

4.5. Data Analysis

This study utilized Partial Least Squares Structural Equation Modeling (PLS-SEM) for data evaluation. This method was selected for its well-established predictive and explanatory capabilities, as evidenced by prior research. The study explored how external influences, including enjoyment and trust, affect millennials' perceptions of usefulness and ease of use within the Technology Acceptance Model (TAM) framework, all aimed at promoting CFA adoption. Rather than conducting theory testing or confirmation, the primary objective was to assess predictive relationships, aligning with the specific analytical requirements of the study.

5. Results

5.1. Descriptive Statistics

A total of 40 surveys were collected, of which 10 responses were excluded from analysis due to incompleteness or duplicate data. This affected 30 valid responses, representing a notable reply rate of approximately 80%. The gender distribution showed a predominance of females (80%) over males (20%), with the majority falling within the age brackets of 23 to 28 years (47%) and 29 to 34 years (50%). Regarding education, most respondents held a university degree (90%). In terms of residency, 14 individuals (47%) were from Bangkok, 16 (53%) were from the neighboring area, and 15 (10%) were from other regions. Concerning monthly salary, most reported income in the range of THB15,001 to THB50,000 (77%), followed by those earning THB15,000 (20%). All participants (100%) were employed. A visual depiction of these demographic statistics is provided in **Table 2**.

Table 2. Demographic profile overview.

Factors	Details	Percentage
Gender	Male	20% (6)
	Female	80% (24)
Age	23−28	47% (14)
	29–34	50% (15)
	35–40	0% (0)
	41–43	3% (1)
Education	Master degree	3% (1)
	Bachelor degree	90% (27)
	Undergraduate	7% (2)
	Bangkok	47% (14)
Residence	Vicinity	53% (16)
	Others	0% (0)
	≤15,000–	20% (6)
Salary (THB)	15,001–50,000	77% (23)
	50,001–100,000	0% (0)
	>=100,001–	3% (1)
	Employee	100% (30)
	Entrepreneur	0% (0)
Employment	Pupil	0% (0)
	Government Officer	0% (0)
	Farmer	0% (0)
	Unemployed	0% (0)

Regarding carbon footprint behaviors, as depicted in **Table 3**, the most significant proportion of respondents (37%) reported monthly electricity expenses ranging from THB 1,001 to THB 2,000. Furthermore, 20% indicated monthly electricity costs between THB 501 and THB 1,000. For transportation expenses, 40% reported spending around THB 1,001 and THB 2,000, while 27% mentioned monthly transportation costs of THB 501 to THB 1,000. In the entertainment area, many millennials stated they would address carbon emissions, with 69% mentioning intentions to decrease their carbon footprint at grilled pork buffets. In the goods & services, 65% showed a strong inclination to utilize Mobile Banking services. Concerning the home segment, respondents demonstrated significant interest in handling carbon emissions by selecting electricity from renewable sources (80%). Additionally, 27% conveyed intentions to utilize electric mass transportation to reduce carbon emissions in motion.

Regarding feedback and recommendations from the experts and lead users, 93% of the respondents indicated that they would revisit and expected to access the Carbon Crush app approximately 4−5 times per month. Among the target retail users, 100% were unwilling to pay for the app but were open to receiving advertisements for sustainable products and services. At the managerial level, there is a willingness to procure the program for an unlimited number of user licenses, with an annual fee not exceeding 5,000 baht per year.

5.2. Structural Equation Modeling Analysis

The measurement and structural models underwent analysis using the PLS approach, with outcomes interpreted using standardized path coefficients and coefficients of determination. To ensure the analysis's reliability, 5,000 bootstrap samples were utilized[48].

5.2.1. Measurement Model Analysis

To evaluate the measurement model, we employed Smart PLS 4.0 software for confirmatory factor analysis, assessing various questionnaire facets, for example, convergent validity, internal consistency, reliability, and discriminant validity, following established guidelines[49]. Specific items (PEU4) were removed to enhance reliability, resulting in strong outer loadings ranging from 0.808 to 0.964. Validation of survey instrument: Vital metrics, including Cronbach's α (>0.7), composite reliability (>0.7), and outer loadings (>0.3), constantly exceeded recommended limits, confirming the questionnaire's high reliability, validity, and internal consistency[49]. Moreover, the average variance extracted (AVE) surpassed 0.3, indicating acceptable convergent validity. Discriminant validity was assessed using the Heterotrait-Monotrait ratio of correlations (HTMT), as suggested by Henseler, Ringle and Sarstedt[50]. As given in **Table 4**, the results included the square root of AVE values on the oblique alongside correlation coefficients between constructs. These outcomes provided compelling evidence that no items demonstrated greater factor loadings on unrelated constructs compared to their intended construct, supporting the survey's satisfactory discriminant validity.

5.2.2. Evaluation & Structural Model Analysis

The structural model's causal relationships among latent variables were evaluated using the bootstrap method. 5,000 bootstrap samples were generated to calculate standard errors at a 95% confidence interval. Path coefficients (β values)[48] were used to assess the strength and significance of relationships between latent variables[33]. Results,

Table 3. The summation of the energy-consuming profile.

Factors	Details	Percentage	Factors	Details	Percentage
Monthly electrical fee (THB per household)	>= 3,001–	17% (5)	Mobility type	Mass transport	53% (16)
	2,001−3,000	10%(3)		Car	43% (13)
	1,001−2000	37%(11)		Others	3% (1)
	501−1,000	20%(6)	Hot spot activities in leisure	Grilled buffet	73% (22)
	≤500–	17% (5)		Green trip	13% (4)
Monthly transportation fee	>= 3,001–	20% (6)		Online game	13% (4)
	2,001−3,000	7% (2)	Hot spot activities in goods & services	Mobile banking	63% (19)
	1,001−2,000	40% (12)		Second-hand shopping	10% (3)
	501−1,000	27% (8)		Imported cosmetics	17% (5)
	≤500–	6% (2)		Invest green fund	10% (3)
Hot spot activity in mobility	Electric mass vehicle	50% (15)	Hot spot activities at home	Electricity usage	80% (24)
	Walk or bicycle	33% (10)		Waste manage	13% (4)
	Work from home	10% (3)		Water usage	0% (0)
	Others	6% (2)		Set-up solar-cell	7% (2)

Note: Frequency in parentheses.

shown in **Figure 2** and **Table 6**, revealed that within the TAM model, only perceived ease of use significantly correlated with intention to use (PEU → IU: β = 0.633, p < 0.001), supporting H1. Trust and perceived enjoyment, as external factors, showed positive associations with both perceived usefulness and perceived ease of use, respectively, as indicated by the following β values: (TR → PU): β = 0.782, p < 0.001, (PE → PEU): β = 0.924, p < 0.001. Hence, H3a and H4a were confirmed. Furthermore, the external variable of perceived enjoyment displayed a significant relationship with Thai millennials' perceived ease of use TAM factor, which indirectly influenced intention to use (IU) in the CFA with the following β value: (PE → PEU): β = 0.585, p < 0.001. Consequently, H4b was upheld.

Figure 2. Results of the extended TAM model.

Table 6 illustrates that four estimated paths reached statistical significance. Notably, only the perceived enjoyment of external variables has a statistically significant and indirect impact on CFA adoption through the TAM factor.

Moreover, the combined factors of perceived ease of use, perceived usefulness, trust, and perceived enjoyment exhibited substantial predictive capability for CFA adoption intention, accounting for 85.4% of its variance ($R^2 = 0.854$). This R^2 value surpasses the typically accepted threshold of 0.5, indicating a robust explanatory model (r > 0.5) that indicates significant explanatory power[51]. Perceived ease of use, influenced by perceived enjoyment, exhibited greater predictive strength (85.4%) than perceived usefulness influenced by trust (61.2%). This finding further supports the previous arguments suggesting that trust positively influences millennials' perceived usefulness and perceived enjoyment, which influences perceived ease of use, thus indirectly facilitating CFA adoption. However, perceived usefulness does not directly correlate with adoption intention. Additionally, perceived usefulness adjusted by trust does not support CFA adoption for Thai millennials. The strong influence of perceived enjoyment on perceived ease of use and the lack of direct correlation between perceived usefulness and adoption intention may reflect cultural nuances specific to our Thai millennial sample. However, further research would be needed to confirm whether these patterns are characteristic of the broader Thai millennial population.
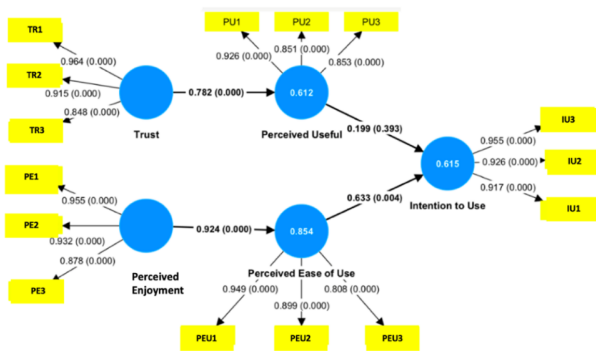
6. Discussion, Implications, and Conclusions

This study aimed to comprehensively examine the factors influencing Thai millennials' adoption of carbon footprint tracking apps (CFAs) using the extended Technology

Table 4. The convergence validity of constructs.

Construct	Item	Outer Loading	*p* Value
Perceived Enjoyment (Reflective)			
CR = 0.945	PE1	0.955***	0.0000
AVE = 0.851	PE2	0.932***	0.0000
Cronbach's α = 0.912	PE3	0.878 ***	0.0000
Perceived Ease of Use (Reflective)			
CR = 0.917	PEU1	0.949***	0.0000
AVE = 0.787	PEU2	0.899***	0.0000
Cronbach's α = 0.862	PEU3	0.808***	0.0000
Intention to Use (Reflective)			
CR = 0.953	IU1	0.917***	0.0000
AVE = 0.870	IU2	0.955 ***	0.0000
Cronbach's α = 0.926	IU3	0.926 ***	0.0000
Perceived Usefulness (Reflective)			
CR = 0.909	PU1	0.926***	0.0000
AVE = 0.770	PU2	0.851***	0.0000
Cronbach's α = 0.850	PU3	0.853***	0.0000
Trust (Reflective)			
CR = 0.936	TR1	0.964***	0.0000
AVE = 0.829	TR2	0.915***	0.0000
Cronbach's α = 0.896	TR3	0.848***	0.0000

Note: CR is the composite reliability, and AVE is the average variance extracted *** p < 0.001.

Table 5. Correlations and discriminant validity.

	EN	IN	PE	PU	TR
EN	0.922				
IN	0.699	0.933			
PE	0.924	0.771	0.887		
PU	0.65	0.639	0.695	0.877	
TR	0.836	0.794	0.867	0.782	0.911

Note: All correlations were statistically significant (p < 0.01). Diagonal values represent the square roots of the average variance extracted (AVE) for each construct.

Acceptance Model (TAM). Our findings address the three primary research objectives and contribute several insights into understanding CFA adoption in the Thai context.

Underlying motivations driving sustained CFA use, our research reveals that hedonic elements, particularly perceived enjoyment, are crucial in motivating Thai millennials to adopt and continue using CFAs. This finding aligns with Chen[52] work on the impact of perceived app enjoyment on sustainable user loyalty. The importance of 'Sanuk' (fun) in Thai culture significantly influences the adoption and sustained use of CFAs, highlighting the need for engaging and enjoyable app features.

Our findings suggest a more nuanced role for trust and perceived usefulness in the CFA adoption process. Trust appears to positively influence millennials' perceived use-fulness of CFAs, aligning with previous research on the importance of trust in technology adoption[39]. However, this influence only translates directly into adoption intention. Interestingly, while trust positively influences perceived usefulness, this relationship does not increase CFA adoption among Thai millennials. This finding is particularly noteworthy as it suggests that even when users trust the app and perceive it as valid, these factors alone are insufficient to drive adoption.

A significant finding is the lack of a direct correlation between perceived usefulness and adoption intention, even when influenced by trust. It suggests that for Thai millennials, the practical benefits of CFAs, even when trusted, may be less motivating than other factors in driving adoption. This contrasts with findings in different technological contexts or cultural settings where perceived usefulness strongly

Table 6. Summary of hypothesis testing results.

Hypothesis	Path	*Path Coef.*	*p*-Value	Results
H1	Perceived Ease of Use -> Intention to Use	0.633	0.004	Supported
H2	Perceived Useful -> Intention to Use	0.199	0.393	Not-supported
H3a	Trust -> Perceived Useful	0.782	0.000	Supported
H3b	Trust -> Perceived Useful -> Intention to Use	0.156	0.406	Not-supported
H4a	Perceived Enjoyment -> Perceived Ease of Use	0.924	0.000	Supported
H4b	Perceived Enjoyment -> Perceived Ease of Use -> Intention to Use	0.585	0.003	Supported

R^2 Perceived Ease of Use toward Intention to Use = 85.4%

Perceived Useful toward Intention to Use = 61.2%

Intention to Use = 61.5%

predicts adoption[38].

Regarding barriers impeding CFA adoption, contrary to previous studies, particularly in electric scooter-sharing contexts[53], our research suggests that perceived usefulness and trust, while important, are not the primary drivers of CFA adoption among Thai millennials. Instead, our findings highlight the crucial role of hedonic elements, particularly perceived enjoyment, in influencing perceived ease of use and indirectly affecting adoption intention. This aligns with Chen's[52] findings on the significant impact of perceived app enjoyment on sustainable user loyalty.

While our study's sample size (n = 30) limits broad generalization, these exploratory findings provide valuable insights for future research with larger samples. They suggest that maintaining CFA adoption among Thai millennials may become problematic if the app isn't perceived as user-friendly and enjoyable.

To contextualize our findings on CFA adoption among Thai millennials, we examined three apps: our prototype Carbon Crush, Thailand's CERO Carbon Wallet, and the U.S.-based JouleBug. Carbon Crush, designed based on our research, prioritizes user-friendly interfaces and enjoyable features to encourage carbon footprint tracking. This approach directly applies our findings on the importance of perceived enjoyment and ease of use in driving adoption among Thai millennials. CERO Carbon Wallet, developed by Vekin[1] for the Thai market, offers a real-world validation of our findings. It successfully implements gamification through "CERO Points", provides an intuitive interface, and uses blockchain for transparency. CERO's innovative B2B2C model, partnering with eco-friendly businesses, demonstrates how CFAs can create value for users and sustainable enterprises in Thai-land. While focused on sustainability, JouleBug[2] takes a different approach as an employee engagement app for corporate sustainability goals. Its application of gamification in a workplace context illustrates how the principles we identified can be adapted to different settings. This comparison underscores the importance of tailoring sustainability apps to specific cultural and organizational contexts while maintaining core engagement strategies[54]. The success of the CERO Carbon Wallet in Thailand mainly validates our research findings, demonstrating their real-world applicability in the Thai market.

Based on our findings, we recommend that CFA developers prioritize user enjoyment and ease of use in their app design as an evidence-based recommendation for developers and policymakers. The success of the CERO Carbon Wallet in Thailand, with its gamification elements and intuitive interface, supports this recommendation. Additionally, it may suggest adopting a B2B2C business model, offering the app for free to customers while partnering with eco-friendly businesses. This approach, supported by Samadzad et al.'s[53] findings, can help bridge the gap between sustainable innovation and low-carbon consumption.

Moreover, the study presents several implications for policymakers, app designers, and marketers. While reinforcing the importance of well-established factors like perceived enjoyment and ease of use, the research also highlights the crucial role of trust in technologies that promote sustainable consumption. In the specific context of Thailand, application design should emphasize entertaining and gamifying low-carbon behaviors. The user interface and overall user experience must be carefully crafted to align with the needs and preferences of Thai millennial users. This approach

[1] https://www.vekin.co.th/en/cero

[2] https://joulebug.com/enterprise/

combines the proven effectiveness of enjoyment and usability with the necessary focus on building trust and tailoring the experience to the local market. Providers must also address trust issues related to carbon emission data and privacy concerns. Finally, adopting a B2B2C model and incorporating networking features can enhance user engagement and promote sharing among friends.

By incorporating multiple theoretical frameworks, our study has discovered significant insights into the factors influencing Thai millennials' intention to adopt carbon footprint monitoring applications (CFA). We have identified perceived ease of use and perceived enjoyment as critical drivers of adoption. These findings significantly contribute to the academic discourse by enhancing our understanding of the determinants and external variables that predict CFA adoption among Thai millennials. Our study expands the conceptual framework and examines the interaction between TAM factors, trust, and perceived enjoyment. To validate our model, we engaged thirty target users of Thai millennials and utilized a structural equation model. The results indicate that trust and perceived enjoyment notably affect CFA adoption, both directly and indirectly. This suggests that enhancing millennials' enjoyment of sustainable lifestyles effectively promotes their adoption of CFAs for low-carbon practices.

Our research highlights the importance of considering cultural context in technology adoption studies, particularly the role of 'Sanuk' (fun) in Thai millennials' decision-making processes. Furthermore, adopting a B2B2C model may help bridge the gap between sustainable innovation and low-carbon consumption, additionally aligning with SDGs 13 (Climate Action), 12 (Responsible Consumption and Production), and 9 (Industry, Innovation, and Infrastructure). Furthermore, adopting a B2B2C model may help bridge the gap between sustainable innovation and low-carbon consumption. Retail customers can utilize CFA at no cost to modify their behavior, while retail operators can cover the service charge to promote their sustainable brand. However, we maintain a thoughtful tactic, acknowledging the intricacy of behavior change and the need for multifaceted approaches. Our research makes a substantial contribution to advancing several Sustainable Development Goals (SDGs), specifically SDG 13 (Climate Action), SDG 12 (Responsible Consumption and Production), and SDG 9 (Industry, Innovation, and Infrastructure).

7. Limitations and Future Research

Our study's small sample size limits generalizability, and future research should employ more extensive, more diverse samples. The use of self-reported data may suffer from social desirability bias, suggesting future studies could incorporate objective measures of CFA usage. Our cross-sectional design provides only a snapshot of adoption intentions; longitudinal studies would offer insights into CFA adoption dynamics over time.

While we considered some Thai context, a more in-depth exploration of cultural influences on technology adoption is warranted. Future research could compare CFA adoption factors across Southeast Asian countries to identify regional trends and differences. Additionally, qualitative research methods such as in-depth interviews or focus groups could provide richer insights into consumer motivations and barriers to CFA adoption.

Limitations of our study on CFA adoption and the Technology Acceptance Model (TAM) factors among millennial consumers in Thailand may include sample limits, sample bias, reliance on self-reported data, cross-sectional design, qualitative research to explore consumer motivations and barriers, and lack of consideration for contextual factors. Sample bias may arise from urban-centric studies, limiting the generalizability of findings. Self-reported data may suffer from social desirability bias or memory recall issues, affecting the accuracy of responses. Cross-sectional designs offer only a snapshot of consumer behavior, while longitudinal studies would provide insights into CFA adoption dynamics over time. Additionally, many studies focus solely on TAM variables without considering other relevant factors like environmental attitudes or social norms. Moreover, contextual factors such as cultural norms and policy frameworks may need to be considered, warranting further investigation.

These limitations offer opportunities for future research to advance our understanding of CFA adoption among Thai millennials and in broader contexts, contributing to developing more effective strategies for promoting sustainable behaviors through technology.

Author Contributions

Conceptualization, A.T., and K.S.; methodology, A.T., K.S., and C.G.; software, A.T., K.S., and C.G.; formal anal-

ysis, A.T., and K.S.; resources, A.T., K.S., and C.G.; writing—original draft preparation, A.T., K.S., and C.G.; writing—review and editing, A.T., K.S., and C.G.; visualization, A.T., K.S., and C.G.; project administration. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

This study adhered to the principles outlined in the Declaration of Helsinki. Ethical approval was granted by the Research Ethics Review Committee for Human Subject Research: The Second Allied Academic Group in Social Sciences, Humanities, and Applied Arts at Chulalongkorn University (13 Mar 2023/ COA 096/66).

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data presented in this study are available in the article.

Acknowledgments

Conflicts of Interest

The authors declare no conflict of interest.

Appendix A

Description of the carbon footprint monitoring app—Carbon Crush

Instruction

Welcome to Carbon Crush, a gamification app that helps users reduce greenhouse gas emissions in carbon units. With Carbon Crush, users can track carbon emissions against targets to reduce environmental impact and earn reward points. Our app provides suggestions for low-carbon activities that enable users to assess the ecological footprint of their consumption habits. This environmental footprint is quantified using natural resources associated with consumption activities such as housing, transportation, food, and other consumables. Users can set targets for more sustainable consumption patterns and compare them with their current behavior. They can regularly update their consumption status in different areas and receive feedback on the environmental impact of their choices.

It's as easy as shown in **Figure A1**.

1) Log in and input user data.
2) Carbon tracking dashboards using photography as evidence.
3) Carbon footprint calculation, persona assessment, and campaign selection
4) Link to payment tools to track carbon emissions
5) Accumulation of points and redeem vouchers with partners.
6) Buying carbon credits/green investments to offset carbon to 0.
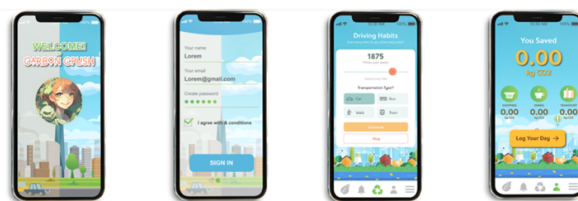7) Setting up and logging out

Figure A1. Screenshots of Carbon Crush's UX UI.

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