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Factors Shaping Thai Millennials' Low-Carbon Behavior: Insights from Extended Theory of Planned Behavior

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Abstract

Objective: This research serves a dual purpose: To construct a predictive model for low-carbon behavior among Thai millennials and to analyze the interplay between socio-demographic variables and eco-conscious actions. *Methods/Analysis*: By employing PLS-SEM and surveying 150 Thai millennials through purposive sampling, this study reaffirms the influence of persuasive technology and incentives on low-carbon behaviors. It highlights the significance of perceived behavioral control within the TPB framework and reveals intricate pathways by which persuasive technology and incentives shape attitudes, perceived control, and social norms, thereby driving eco-friendly actions. *Findings*: Among Thai millennials, positive attitudes and perceived control drive low-carbon behavior, while social norms and accessible low-carbon infrastructure also impact eco-conscious actions. Persuasive technology shows promise for attitude adjustment, but incentives' relationship with low-carbon behavior is complex. Interestingly, mature women exhibit more low-carbon behavior, whereas education and income show an inverse relationship. *Novelty/Improvement*: This study contributes novel and substantial insights into the drivers of low-carbon behavior among Thai millennials by integrating diverse theoretical frameworks. It enriches our understanding of the mediating role of TPB factors and socio-demographic dimensions, offering invaluable guidance for stakeholders in crafting effective interventions while aligning seamlessly with Sustainable Development Goals 7, 9, 12, and 13.

Keywords: Persuasive Technology; Motivating Variable; Climate-Change Mitigation; Sustainability; Structural Equation Modeling.

1. Introduction

As COP27 approached, there was a solid call to limit global temperature rise to +1.5 °C to mitigate the severe impacts of climate change. Extensive scientific evidence has established that human-induced CO_2 emissions play a dominant role in driving global climate change. Anthropogenic activities are primarily responsible for the substantial annual increase in atmospheric CO_2 levels [1]. The transformation of human behavior and lifestyles is critical in facilitating and implementing mitigation measures to achieve transitions consistent with a 1.5°C pathway [2]. Recognizing the significance of this aspect, the strategic vision for achieving a climate-neutral economy in Europe highlights that transitioning to a greenhouse gas-free economy relies not only on technological progress and job opportunities but also on transforming individual and organizational behaviors.

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Climate change has emerged as a pressing global issue that demands immediate attention from individuals, organizations, and governments. Increased awareness of the negative effects of climate change has led to the implementation of various strategies to mitigate greenhouse gas emissions, including the promotion of low-carbon behavior. Low-carbon behavior encompasses actions that positively impact resource and energy efficiency, leading to beneficial transformations in ecosystems and the overall biosphere. Specifically, low-carbon behavior refers to individual activities aimed at reducing greenhouse gas emissions and mitigating the consequences of climate change. Such behaviors can encompass a wide range of actions, such as reducing energy consumption, utilizing public transportation, opting for walking or cycling instead of driving, practicing recycling and composting, and making eco-friendly purchases [3]. Additionally, within this context, the term "hot-spot activities" refers to specific elements of lifestyle characterized by high consumption levels, high carbon intensity in production, or both [4].

Promoting low-carbon behavior is pivotal for sustainable development and aligns directly with SDG 13, which seeks to combat climate change through the identification of sustainable practices. It also aligns with SDG 12 to find the determinants influencing individual consumption patterns, potentially informing responsible consumption and production strategies. It also indirectly supports SDG 7 by exploring factors related to energy usage, aligning with the transition to clean and sustainable energy sources. Furthermore, this also contributes to SDG 9, it can foster innovative approaches to environmental challenges and promote eco-friendly practices through infrastructure development. In essence, it aids in achieving multiple SDGs by shedding light on the factors shaping low-carbon behavior among millennials and supporting climate change mitigation, responsible consumption, and sustainability efforts [3].

In studying low-carbon consumption behavior among residents, a common approach is to differentiate between urban and rural residents due to variations in living conditions, economic circumstances, policy environments, cultural settings, and social control [4]. Urban areas typically exhibit different patterns of low-carbon behavior than rural regions, making it essential to understand these distinctions. Western research often concentrates on towns and cities, while in China, urban residents significantly contribute to national energy consumption [5]. Therefore, this study focuses on urban residents, simply called "residents." Drawing from prior research, this article categorizes the factors influencing residents' low-carbon consumption behavior into three broad groups: self-factors (psychological and demographic), family factors, and situational factors. Self-factors encompass elements such as environmental values, personal norms, attitudes, and knowledge, while demographic factors include variables like gender, age, education, and income. Family factors consider aspects such as family structure and ownership, and situational factors encompass policy, social norms, and geographic or climate-related factors.

Research methods employed to investigate these influencing factors are typically classified into three categories: quantitative research, qualitative research, and mixed-method research. Quantitative research examines relationships among variables through numerical data analysis, while qualitative research explores the meaning individuals or groups attribute to social or human issues. Mixed-method research combines both quantitative and qualitative data for comprehensive analysis. Several recent studies shed light on specific aspects of low-carbon behavior and consumption. Halder et al. [6] examine the impact of collectivism and long-term planning on green consumption values. Valor and Martínez-de-Ibarreta [7] explore the relationship between sustainable personal projects, sustainable consumption, and self-transcendence values. Yan et al. [8] investigate the influence of power and green consumption values on preferences for green products. Khan et al. [9] analyse the effects of green supply chain management and green marketing orientation on green consumption intention, with environmental concerns mediating. Xie et al. [10] explores the impact of environmental cognition and regional economic development on green consumption attitudes, subjective norms, and perceived behavior control. Li et al. [11] examines the influence of climate change information framing, environmental self-efficacy, and global-local identity on household low-carbon behavior. Wei et al. [12] assesses low-carbon consumption behavior in terms of purchasing, daily use, garbage disposal, and public participation behavior, emphasizing information incentives and social influence as key predictors. Finally, Zhong & Chen [13] employ game theory to analyse the relationship between environmental beliefs and willingness to pay a green premium for low-carbon rice, while Luo et al. [14] employ the S-O-R model to explore the impact of green advertising on social media on green purchase intention through perceived information utility.

These studies collectively enrich our comprehension of the intricate dimensions of low-carbon behavior and consumption, underscoring the relevance of a multitude of factors, from individual convictions and values to external incentives and social influence. Nevertheless, to gain a more nuanced understanding of this intricate phenomenon, there is a pressing need for a comprehensive and holistic framework that integrates these multifaceted elements. In response to these identified gaps in the literature, our study takes a focused approach by centering on Thai millennials, specifically scrutinizing their low-carbon behavior, particularly in activities with notable carbon footprints. Despite numerous investigations into the determinants of sustainable behavior, empirical research targeted at Thai millennials within the context of a middle-income country such as Thailand, remains limited. Our research aims to bridge this gap by employing the Partial Least Squares Structural Equation Modelling (PLS-SEM) methodology, coupled with survey data gathered from Thai millennials. Our objectives encompass the construction of a predictive model of low-carbon behavior within this demographic and exploring the intricate interplay between socio-demographic factors and environmentally conscious actions.

A noteworthy innovation in our study lies in amalgamating motivating factors, such as persuasive technology and incentives, within the extended Theory of Planned Behavior (TPB) framework. By concurrently examining these elements in conjunction with socio-demographic considerations, we aspire to provide a more comprehensive and nuanced understanding of the multifaceted drivers propelling low-carbon behavior among Thai millennials. This holistic approach distinguishes our research from previous studies, which oftentimes overlook the impact of these variables on eco-conscious actions. In summary, our research significantly contributes to the existing body of knowledge by furnishing a deeper insight into low-carbon behavior, particularly among Thai millennials. By illuminating the intricate interplay between various determinants and motivating factors, our study offers invaluable insights that can inform the design of precisely targeted interventions and initiatives to nurture a more sustainable future within this demographic.

Millennials, characterized by their distinctive attitudes and behaviors, have garnered substantial attention concerning sustainable practices and environmental behaviors. Research has delved into various facets of millennials' involvement in sustainability, illuminating their socio-demographic profiles, motivations, barriers, and potential contributions to environmental preservation. On a global scale, studies have underscored millennials' heightened environmental awareness and their aspiration to contribute to sustainability endeavours. As highlighted by Shukla [15], millennials consistently exhibit more pronounced levels of environmental consciousness compared to older generations, signifying their potential as catalysts for change. This assertion underscores that attitudes, subjective norms, and perceived behavioral control substantially influence millennials' intentions to engage in sustainable practices [16]. Thai millennials, born between 1981 and 1996, constitute a pivotal demographic for promoting low-carbon behavior within Thailand [17]. As digital natives, they enjoy access to various technologies that can facilitate their embrace of low-carbon practices [18].

Despite extensive examinations of intentions to engage in environmentally friendly behavior, the leap from intent to action remains a complex puzzle. Notably, despite the surging interest in sustainable behavior and the sway of diverse factors on individual choices, empirical inquiries centred on the low-carbon behavior of Thai millennials remain conspicuously scarce. Thai millennial is approximately 22% of the total population in Thailand, they are a digitally connected generation with tech-savvy characteristic, and 82% of them own smartphones. 72% of them have expressed concern about climate change and this growing awareness highlights their potential as change agents in driving eco-friendly practices [19]. While some studies have probed sustainable practices in specific niches [20] and investigated environmental attitudes in a broader sense [20], the millennial generation in a medium-income nation like Thailand has seldom been the focal point of research.

Consequently, our study aims to bridge this gap by inspecting the determinants and motivating variables that influence and drive low-carbon behavior, particularly among Thai millennials. This demographic grapples with navigating a swiftly evolving socio-economic landscape, thereby necessitating an examination of the unique determinants and motivations that drive their low-carbon behavior. Moreover, while low-carbon behavior is undeniably pivotal, previous research has often underestimated its effects, resulting in gaps in our comprehension.

This research embarks on a comprehensive exploration of the determinants and motivating factors underpinning the low-carbon behavior of Thai millennials. Its primary objectives encompass a two-fold approach: first, to craft a causal-predictive analysis of low-carbon behavior among Thai millennials, entailing a dissection of the psychological, technological, and motivational factors that exert influence on their sustainable practices, and second, to scrutinize the relationship between socio-demographic characteristics and the low-carbon behavior of this demographic. By delving into these determinants, the study probes potential links between motivating variables, low-carbon behavior, and the determinant factors characterizing Thai Millennials. The goal is to uncover the effectiveness of existing strategies and provide insights that can inform the development of targeted interventions or innovations to effectively engage and empower this demographic group.

2. Literature Reviews and Hypotheses Development

The escalating global urgency to combat climate change has elevated the scrutiny of individuals, particularly millennials, as pivotal actors in adopting low-carbon behavior. This pressing concern has spurred extensive research into the underlying factors that shape millennials' environmental conduct. This review seeks to join and scrutinize pivotal studies on the determinants of low-carbon behavior among Thai millennials. In existing studies, the connotation of low-carbon behavior is explored. The influencing factors of low-carbon behavior are mainly psychological, socio-demographic, and external or motivating factors. This investigation extends its scope to encompass the Theory of Planned Behavior (TPB) while exploring the interplay of related constructs such as Self-Determination Theory (SDT), allied constructs, and pertinent theoretical frameworks.

2.1. Low-carbon Behavior and Hot-Spot Activity

According to Stern [21], Low-carbon behaviors refer to actions that positively affect the efficient use of resources and energy, leading to beneficial transformations in the ecosystems and the overall biosphere. Low-carbon behavior refers to individual activities intended to reduce greenhouse gas emissions and lessen the impacts of climate change. These behaviors can take many forms, including reducing energy consumption, using public transportation, walking or cycling instead of driving, recycling, composting, and purchasing eco-friendly products. In addition to these factors,

some studies have identified specific indicators of low-carbon behavior. For example, a study by Abrahamse et al. [22] identified indicators such as the frequency of using public transportation, the frequency of recycling, and the frequency of reducing energy consumption. Other studies have identified indicators such as purchasing eco-friendly products and participating in community sustainability initiatives. Contextually, the term "hot-spot activities" refers to specific lifestyle elements that involve either consumption level, high carbon intensity in production, or both [23].

2.2. Determinant Factors of Low-Carbon Behavior and Extended Theory of Planned Behavior (TPB)

Regarding psychological factors, central to the Theory of Planned Behavior (TPB), as postulated by Fishbein and Ajzen [24], is the foundational idea that attitudes, subjective norms, and perceived behavioral control intricately converge to mold behavioral intentions. Many studies have delved into the diverse determinants that influence adopting low-carbon behaviors. Among these, environmental awareness and knowledge emerge as pivotal factor. For instance, in a studies conducted by Iyengar [25] and Gong et al. [26], individuals who possessed a more profound understanding of climate change's repercussions were considerably more predisposed to engaging in low-carbon behaviors. Notably, the sway of social norms plays a significant role in shaping an individual's involvement in low-carbon behavior. Extensive research has demonstrated that individuals are more inclined to embrace low-carbon behaviors when they perceive them as socially commendable and aligned with established societal norms [27]. Furthermore, extensive research indicates that individuals who perceive themselves as having a high degree of control over their behavior are more inclined to adopt low-carbon behaviors [28]. This suggests that the perceived ability to control one's actions significantly influences the likelihood of engaging in environmentally friendly practices. Overall, the literature suggests that a combination of attitude, awareness and knowledge, social norms, perceived behavior control, and specific indicators can influence low-carbon behavior.

Subsequent research endeavors should continue exploring these factors and their intricate interplay in promoting low-carbon behavior. In addition to delving into the psychological aspects, it is crucial to recognize that millennials' low-carbon behavior is significantly shaped by diverse social and demographic characteristics spanning gender, age, income, and educational attainment. Notably, the work of Grønhøj & Thøgersen [29] unveils that, within their daily routines, women exhibit a heightened proclivity towards energy-saving practices compared to men. Moreover, the research conducted by Chen & Li [30], illuminates that women and urban residents equipped with bachelor's degrees manifest a heightened inclination toward embracing low-carbon behaviors. Similarly, Girod & Tofigh [31] observed that well-educated young men boasting substantial incomes and robust technical backgrounds are more disposed to opt for electric vehicles. Furthermore, findings by Ignatow [32] underscore that advanced age is a key determinant, with older individuals demonstrating a greater propensity for energy conservation practices. Geng et al. [33] revealed that willingness to pay for low-carbon vegetables significantly differs across their demographic factors. Stern [21] noted that the gender factor embraces low-carbon consumption as a social responsibility. Moreover, individuals with higher income and elevated education are likelier to consume low-carbon [34]. The key drivers of consumers' eco-friendly choices often encompass more direct variables.

Another study conducted by Andre et al. [35] investigated the influence of misperceived social norms on individuals' willingness to take action against climate change. Social norms, a crucial component of the TPB, play a significant role in shaping individuals' behaviors. The study suggests that correcting misperceptions about social norms can lead to changes in behavior. Fang et al. [36] delve into the intricate interplay of energy conservation, mirroring TPB's emphasis on perceived behavioral control. This synergy of interventions amplifies individuals' mastery over their behavior, congruent with TPB's core tenet of perceived control. Imai et al. [37] accentuates the transformative potential of rectifying consumer misperceptions, mirroring TPB's focus on attitudes and beliefs. Addressing fallacious notions regarding carbon emissions holds the potential to catalyse affirmative attitudes and intentions toward low-carbon actions.

This underscores the instrumental role of accurate information in catalysing shifts in behavior, resonating deeply with TPB's conceptual underpinnings. Kaufmann & Koszegi [38] spotlight the potent influence of values on consumer behavior, aligning harmoniously with TPB's subjective norms shaped by values and convictions. Exploration of carbon footprint labels' impact on dietary preferences closely resonates with TPB's accentuation on perceived behavioral control and attitudes [25], thereby nurturing their perceived control and positive attitudes toward low-carbon behavior. Infrastructure is also pivotal in connecting behavioral intentions with real-life actions, as highlighted by the Attitude-Behavior-External Condition model [27].

2.3. External Factors as Motivating Variables

Numerous researchers have emphasized the potential enhancement of the TPB model's predictive capacity by including external variables. These variables, such as the perceived policy effectiveness, economic incentives, knowledge, technological factors, and community awareness, have been suggested to augment the TPB framework [28, 39-41]. Based on the literature review and local background, the external variables as motivating variables are added in this article: incentives and persuasive technology to better form an extended theoretical model of planned behaviour.

Moreover, Allcott & Rogers [41] highlight behavioral interventions' impact on energy conservation. Their discoveries indicate that these interventions' immediate and prolonged consequences can induce behavioral modifications. Fogg's Behavior Model (FBM), which elucidates the determinants influencing the efficacy of a persuasive system, posits that human actions are shaped by motivation, capability, and triggers [16]. Persuasion involves deliberately influencing behaviors, emotions, or thoughts regarding a particular issue, object, or action. Persuasive Technology is a broad range of technologies designed to modify user behaviors or underlying attitudes [42] by employing behavior change techniques. Numerous persuasive tactics, such as competition, self-tracking with feedback, goal establishment with recommendations, customization, and social contrasts, yield diverse outcomes contingent on the precise context and may fluctuate depending on the user's emotional state and individual characteristics [43]. Using persuasive technology extends to advancing eco-friendly ideals and enhancing the determinants influencing students' environmentally conscious actions.

Research also indicates a strong correlation between positive external incentives and specific behavioral outcomes [44]. Nevertheless, it is important to acknowledge that negative incentives may also exist, although they are often concealed. The establishment of challenges and goals can lead to diverse outcomes, with positive results when individuals succeed and negative consequences if they fail to achieve them. In a study conducted by Schneider et al. [45] the effects of financial incentives on vaccination behavior were investigated, highlighting the significance of incentives in driving behavior. This insight underscores the latent efficacy of financial incentives in driving potential eco-conscious actions. The components of attitudes, subjective norms, and perceived behavioral control in the Theory of Planned Behavior (TPB) align with the motivation and ability factors in the Fogg Behavior Model (FBM). The use of persuasive technology and incentives, acting as triggers, helps bridge the gap between these two models.

Moreover, the Self-Determination Theory (SDT) can also be integrated to explain the intrinsic motivation underlying millennials' engagement in low-carbon behavior. SDT highlights the importance of autonomy, competence, and relatedness in driving behavior. Aligning persuasive technology and incentives with these factors can enhance millennials' intrinsic motivation to adopt sustainable practices [46]. Moreover, Zhao [47] is systematically reviewed the recent studies of low-carbon consumption [12, 48] and low-carbon customization [49].

Despite the growing literature exploring sustainable behavior and its determinants, a notable gap exists in the context of Thai millennials' low-carbon behavior within middle-income countries like Thailand. Existing research has primarily focused on Western contexts, leaving a knowledge void regarding the unique factors influencing eco-conscious actions in this demographic and geographic context. This study seeks to rectify this gap by carefully examining the determinants and motivating variables underlying Thai millennials' low-carbon behavior. What sets this research apart is its holistic framework, which ingeniously integrates the motivating variables of persuasive technology and incentives into the established Extended Theory of Planned Behavior (TPB) model. This novel conceptual framework, as depicted in Figure 1, refines the TPB by encompassing external motivating factors (persuasive technology and incentives) that subsequently influence the core components of the TPB model, including attitudes, subjective norms, perceived behavioral control, and infrastructure, ultimately shaping low-carbon behavior. This innovative approach differentiates this study from prior research, which often needs to account for the multifaceted interplay of these variables in the low-carbon behavior of Thai millennials.

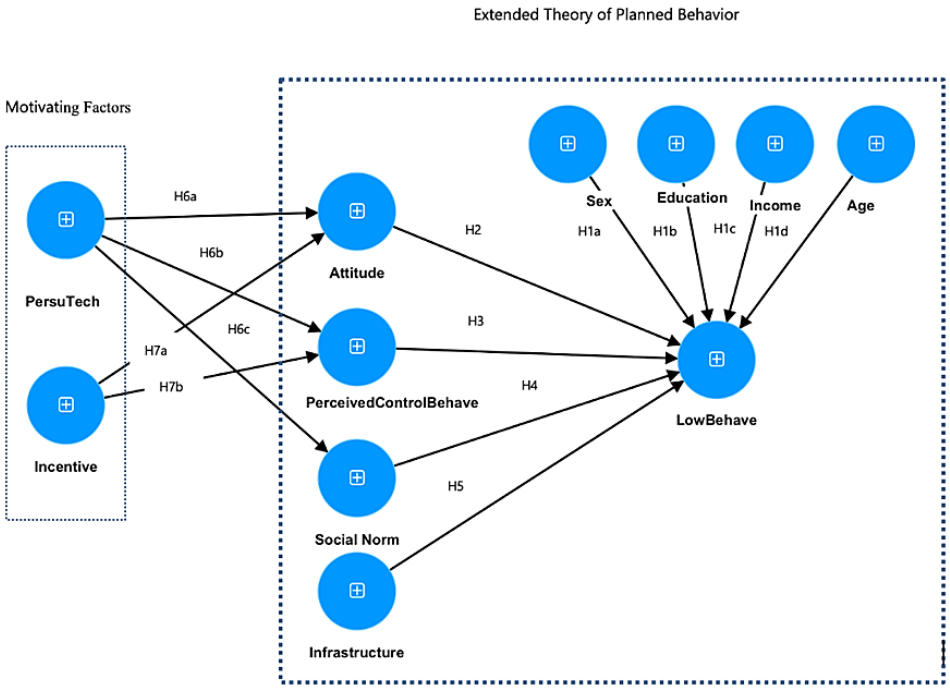

Figure 1. Conceptual Framework

2.4. Hypotheses Development

2.4.1. Socio-Demographic Factors

According to the previous literature [29], this study presents the following hypotheses to investigate the interplay between socio-demographic factors.

Hypothesis 1:

H1a**.** Gender has a significant relationship with millennials' low-carbon behavior**.**

H1b**.** The education level has a significant relationship with millennials' low-carbon behavior**.**

H1c**.** The income earned has a significant relationship with millennials' low-carbon behavior**.**

H1d**.** Age has a significant relationship with millennials' low-carbon behavior.

2.4.2. Attitude

Attitude refers to an individual's emotional inclination toward positive or negative behaviors **.**Factors shaping attitude include values, beliefs, knowledge, and environmental awareness [50] **.**Attitude plays a key role in the TPB models [50], and eenvironmental awareness and understanding are linked to making pro-environmental decisions [51] **.**Based on these insights, the following hypothesis is proposed:

Hypothesis 2:

H2: Attitude and awareness have a positively significant relationship with low-carbon behaviors.

2.4.3. Perceived Behavior Control

Perceived behavior control includes an individual's perception regarding the extent of their command over their actions and their unwavering belief in their capacity to execute promised actions [52] **.**It encompasses a range of factors, including but not limited to time, knowledge, energy, skills, resources, and opportunities. Individuals perceive these factors as assets that can help overcome perceived hindrances when engaging in a specific behavior [53] .Based on this well-established premise, the ensuing hypothesis undergoes rigorous empirical scrutiny.

Hypothesis 3:

H3 **:**Perceived behavior control has a positively significant relationship with low-carbon behaviors.

2.4.4. Social Norms

Social norms represent the influence of social pressure on individuals, acting as a form of social regulation [54] . Substantial evidence indicates that social norms significantly influence various environmental choices and behaviors [55]. Studies have found that social pressure put forth through social norms considerably impacts energy use behaviors and personal low-carbon practices [56] .As individuals do not act in isolation, they are likely influenced by normative pressures and contextual factors [57] **.**Therefore, the following hypothesis is examined:

Hypothesis 4:

H4 **:**Social norms have a positively significant relationship with low-carbon behaviors.

2.4.5. Infrastructure

The availability and convenience of infrastructure can potentially affect individuals' motivations and either promote or discourage environmentally-friendly behaviors [27]**.** Essential elements such as recycling facilities, efficient public transportation systems, and the accessibility of low-carbon products in the market significantly influence individuals' intentions and behaviors about low-carbon practices.

Hypothesis 5:

H5: Infrastructure has a positively significant relationship with low-carbon behavior.

2.4.6. Persuasive Technology

Supported by studies Allcott and Rogers [41], which highlight the effectiveness of behavioral interventions in altering attitudes and intentions. Lin [[٥٨ persuasive technology significantly improves the student sample's carbon footprint awareness and perceived behavioral control and promotes subjective norms .Persuasive Technology also facilitates the flow of relevant information and can help optimize individuals' decision-making and perceptions regarding consumption [59, 60] .Thus, it is assumed that millennials with higher supportive persuasive technology will have more favorable attitudes and perceived behavior control and social norm.

Hypothesis 6.

H6a**.** Persuasive Technology has a positively significant correlation to attitudes toward low-carbon behavior**.**

H6b**.** Persuasive Technology has a positively significant relationship with the perceived behavior control towards low-carbon behavior**.**

H6c**.** Persuasive Technology has a positively significant relationship with the social norm towards low-carbon behavior.

2.4.7. Incentive

The studies from Schneider et al. [45] and Ahshanul Mamun [46] highlight the potential of incentives in driving behavior .Moreover, Kaufmann & Koszegi [38] emphasize the role of consumer values in decision-making, indicating that aligning incentives with millennials' values can positively influence their attitudes and perceived control behavior . According to Ahshanul Mamun's [46] findings, different types of incentives affect pro-environmental behavior differently .However, it is important to note that while financial incentives may initially boost pro-environmental behaviors, they may decline once they are no longer available .Considering the significance of motivation in this context, we propose the following hypothesis:

Hypothesis 7.

H7a**.** The incentive has a significant relationship with the attitude toward low-carbon behavior**.**

H7b**.** The incentive has a significant relationship with the perceived behavior control towards low-carbon behavior**.**

Consequently, the overall hypothesis & conceptual framework are shown in Figure 1.

3. Methodology

This research used a quantitative research approach. The steps according to the research methodology are as follows in Figure 2.

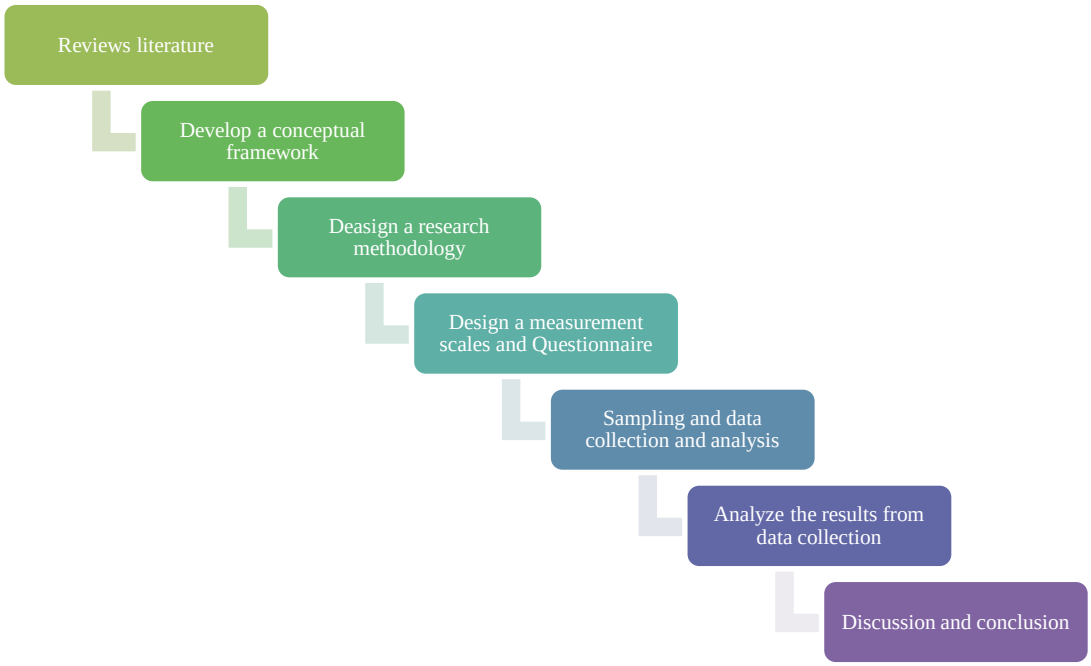

Figure 2. Research methodology process

3.1. Research Design and Procedure

The study adopted a quantitative research framework, employing an online survey as the data collection method. Hypotheses were subsequently examined utilizing the structural equation modeling (SEM) approach, facilitated by Smart PLS 4. To ensure a comprehensive and diverse participant pool, the researchers employed a purposive sampling technique, strategically selecting Thai millennials from various geographical regions. Great efforts were made to include a diverse range of participants from different socio-economic backgrounds, education levels, and income levels. The survey was carefully conducted online, with clear instructions for participants. Ethical considerations were followed,

including obtaining approval from the Institutional Review Board (IRB) and obtaining informed consent from all participants before conducting the survey. The data collection phase was carefully planned and executed over a specific duration to ensure a substantial sample size for analysis. This process followed established best practices and was complemented by G*Power software calculations.

3.2. Measurement scales and Questionnaire design

3.2.1. Measurement Scales

This study chose measurement scales that were valid and aligned with the research goals. The conceptual model included six ideas, and existing scales from past research were used to measure them. Four criteria were used to evaluate the extended Theory of Planned Behavior (TPB) ideas: attitudes, subjective norms, perceived behavioral control, and infrastructure for promoting low-carbon behavior. The motivation variables were assessed by looking at incentives and persuasive technology using items from academic sources.

Five items were adapted to assess attitudes (AA) with some modifications from Ajzen [61], Ajzen & Fishbein [62], and Han & Stoel [63]. Subjective norms (SN) were evaluated using three items from the aforementioned studies with minor adjustments. Perceived behavioral control (PC) was measured using five items from Ajzen [61], Chen and Peng [64], and Dean et al. [65]. Three items assessing infrastructure were adopted with slight adaptations from Chen and Chang [66] and Pavlou [67].

The four items for the incentive (IN) were derived from Thaler and Ganser [68] while the five items for persuasive technology (PT) were taken from Du et al. [59]. A summary of the assessment items and their respective references can be found in Table 1.

Table 1. Questionnaire constructs

Constructs	Items	Contents	Sources
Attitude & Awareness	AA1	I am worried about high-carbon issues because I want to keep myself and my family safe from climate change disasters.	Ajzen [61], Ajzen & Fishbein [62], and Han & Stoel [63]
	AA2	I am realized that the current situation of greenhouse gas emission has reached a very serious level.	
	AA3	I have agreed that waste separation should be an own duty of each household.	
	AA4	I think using mass transportation much better to our environment than using private cars or taxi.	
	AA5	I think having local and seasonal fruits & vegetables and avoiding food waste can lower climate-change issues.	
Perceived Control Behavior (PC)	PC1	I have confidence in my skills to live a low-carbon lifestyle.	Ajzen [61], Chen & Peng [64], and Dean et al. [65]
	PC2	I can give up some of my habit to live a low-carbon lifestyle	
	PC3	I can pay more to buy low-carbon goods and services	
Social Norm	SN1	People around me contribute to my low-carbon behavior.	Yu et al. [54]
	SN2	I want to participate in an event about saving the planet with friends or acquaintances.	
	SN3	My experience in preserving the environment in my household/community has contributed to my low-carbon behavior.	
Incentive	IN1	I need special financial packages to use renewable energy such as low-interest loans, a long installment term for solar cell or electric car purchase.	Thaler & Ganser [68]
	IN2	I want an obvious discount when buying green products.	
	IN3	I want to earn points when purchasing green products to redeem for essential goods.	
	IN4	I think tax-subsidy should be imposed on low-carbon goods.	
Persuasive Technology	PT1	I believe that having a system inform the carbon footprint of the chosen activities to do will help me for better decisions.	Du et al. [59]
	PT2	I believe that having a system to help you know the carbon emission of the products chosen will help me for better decisions.	
	PT3	I believe that if there is a system to help inform my carbon emission compared to my friends will improve my low-carbon behaviors.	
	PT4	I believe that an accumulated reward system upto my behavior will improve my low-carbon behavior?	
	PT5	I believe that if there is a system evaluation with compliment to my daily activity will improve my low-carbon behavior.	
Infrastructure (INF)	INF1	I think that the basic infrastructure around my residence do not allow for low-carbon living, such as without a waste separation system.	Chen & Chang [66] and Pavlou & Chai [67]
	INF2	There are very few or no trees or gardens in my house and offices nearby.	
	INF3	The surrounding transportation system has no electric mass transportation.	

Low-Carbon Behavior (LCB)	LCB1	I usually adjust the air conditioner not lower than 25 degrees Celsius	Stern [21]
	LCB2	I regularly separate garbage at home and avoid food waste.	
	LCB3	In my daily mobility, I use public transportation such as the Skytrain rather than a private car.	
	LCB4	I bring my own bottle of water to get my drink at my favourite coffee shop.	
	LCB5	I prefer to travel green or stay in a green hotel.	
	LCB6	I usually choose environmentally friendly products by looking at labels such as carbon label or eco-energy.	
	LCB7	I like to buy second-hand or recycled.	
	LCB8	I plan to buy an EV car or place solar panels on the rooftop in the next three months?	
	LCB9	I like to plant gardening or tree around the house for coolness.	
	LCB10	I often persuade my family, peers, or participate in activities to create low-carbon behaviors together to protect the environment.	

By selecting these measurement scales, the study ensures the reliability and validity of the collected data, allowing for a strong analysis of the relationships between the constructs in the research model.

3.2.2. Survey Instrument

The survey instrument used in this study consisted of three main sections. Section A focused on gathering socio-demographic information and details of respondents' current energy consumption. It consisted of 12 questions about age, gender, income, education level, and energy usage patterns.

Section B comprised 24 items, which aimed to evaluate six latent variables: five for Attitude & Awareness (AA), three for Perceived Behavior Control (PC), three for Social Norms (SN), three for Infrastructure (INF), six for Persuasive Technology (PT), and four for Incentive (IN). These variables were explicitly chosen to measure the influence of the extended Theory of Planned Behavior (TPB) factors and motivating factors on participants' engagement in low-carbon behavior. The items in this section were derived from existing research and validated questionnaires, including the International Social Survey Program (ISSP) [69] and the New Ecological Paradigm (NEP) [70].

Section C encompassed 10 items to explore self-reported low-carbon behaviors among millennial participants. Due to their efficiency and cost-effectiveness, these self-reported behaviors were employed as proxies for actual human activities. The questionnaire employed a five-point Likert scale to measure the respondents' level of agreement or disagreement with each statement. For items related to AA, PC, SN, INF, PT, and IN, the scale ranged from 1 to 5, with options indicating strongly disagree, disagree, neither agree nor disagree, coordinate, and strongly agree. Regarding items associated with low-carbon behavior (LCB), the scale ranged from never, rarely, sometimes, often to very often.

Several preliminary research tasks and a pilot study were conducted to ensure the questionnaire's reliability and validity. The pilot study involved 30 millennial volunteers in Bangkok, one of the targeted study areas, and their feedback was used to address any unclear or problematic questions. Additionally, three experts in environment and statistics reviewed the questionnaire to ensure its content validity.

The questionnaire underwent a series of verification and validation procedures to ensure systematic data collection. Focus group discussions were held to review the set of questions, and subsequently, a statistical analysis using SPSS software version 25.0 was conducted. Cronbach's alpha values were utilized to evaluate each variable group's internal consistency and reliability. Generally, Cronbach's alpha values within the range of 0.6 to 0.7 are considered acceptable, while values above this range are regarded as good or excellent reliability indicators [71]. Table 1 displays Cronbach's alpha values for AA, PC, SN, INF, PT, IN, and LCB based on the pilot study data. All items within each variable group fell within the acceptable range, so the questionnaire was deemed ready for distribution.

3.3. Sampling and Data Collection

Data for this research were gathered through an online survey conducted on Google Forms, which served as the data collection platform. Initially, potential participants were contacted over the phone, and upon their consent to participate, they received the survey link. The data collection period spanned from February to April 2023. G*Power software is entered utilized by inputting certain; the number of latent constructs, the test's power, and the effect size [72, 73]. Therefore, the calculated minimum sample should be 122 cases, but the study’s sample aims for 150 respondents for more consistency.

The purposive random sampling method was used to carefully select participants in order to ensure that the sample adequately represented the characteristics and diversity of the target population. This method allowed for the inclusion of participants with diverse socio-demographic backgrounds and ensured a more comprehensive representation of the Thai millennial.

The research aimed to gather comprehensive and reliable data for subsequent analysis by leveraging online survey technology and employing rigorous sampling techniques.

3.4. Data Analysis

For the data analysis in this research, Partial Least Squares Structural Equation Modeling (PLS-SEM) was applied.

This choice was made due to the method's well-documented advanced predictive and explanatory capabilities, as supported by prior scholarly investigations [73]. Given the specific research objective of scrutinizing the influence of motivational factors, namely persuasive technology, and incentives, on various dimensions, including millennials' attitudes, subjective norms, perceived behavioral control, and infrastructure, all with the goal of promoting low-carbon behavior, the primary focus resided in evaluating a series of predictive relationships rather than embarking on theory testing or confirmation, aligning with the study's distinct analytical requirements.

4. Results

4.1. Descriptive Statistics

A total of 160 questionnaires were received, but ten responses were excluded from the analysis due to either being incomplete or containing identical data. This resulted in 150 valid responses, indicating an impressive response rate of 98%. As outlined in Table 2, the gender distribution showed a higher representation of females (60.2%) compared to males (39.8%), with the largest proportion falling within the age brackets of 23 to 28 years old (43%) and 29 to 34 years old (28%). Most respondents held a university degree (73%) regarding educational attainment. The respondents' residents were distributed as follows: 81 individuals (54%) hailed from Bangkok, 54 (36%) resided in the surrounding areas, and 15 (10%) were from other regions in terms of monthly income, the majority reported earnings in the range of THB15,001 to THB50,000 (65%), followed by those earning ≤THB15,000 (22%). Employment status varied; approximately 63% of participants reported being employed, while 11% identified as self-employed. For a visual representation of these demographic statistics, please refer to Table 3.

Table 2. The summary of demographic statistics

Factors	Item	Percentage
Gender	Male	37% (55)
	Female	63% (95)
Age	23-28	43% (65)
	29–34	28% (42)
	35–40	18% (27)
	41–43	11% (16)
Education	Master Degree	21% (31)
	Bachelor Degree	73% (109)
	Undergraduate	7% (10)
Residence	Bangkok	54% (81)
	Vicinity	36% (54)
	Others	10% (15)
Income (THB)	<15,000.-	22% (33)
	15,001–50,000	65% (97)
	50,001–100,000	11% (16)
	>=100,001.-	3% (4)
Occupation	Employee	63% (94)
	Self-employed	11% (17)
	Student	10% (15)
	Government Officer	7% (10)
	Farmer	1% (2)
	Unemployed	3% (5)

Table 3. The summary of the carbon-behavior profile

Factors	Items	Percentage
Monthly electricity bill (THB per household)	>=3,001.-	12% (18)
	2,001-3,000	15% (23)
	1,001-2000	36% (53)
	501-1,000	27% (41)
	≤500.-	10% (45)
	>=3,001.-	20% (30)
Monthly transportation fee (THB)	2,001-3,000	9% (14)
	1,001-2000	35% (52)
	501-1,000	25% (37)
	≤500.-	11% (17)
Hot Spot Activity in Mobility	Electric Mass Transportation	37% (56)
	Walk or Bicycle	27% (41)
	Work from Home	27% (41)
	Others	9% (12)
Transportation Type	Mass Transportation	29% (43)
	Taxi or Own car	69% (104)
	Others	2% (3)
Hot Spot Activity in Entertainment	Yakiniku Buffet	69% (104)
	Green Trip	21% (31)
	Less Online Game	10% (15)
Hot Spot Activity in Goods & Services	Mobile Banking	65% (98)
	Mobile Banking	65% (98)
	Less Imported Cosmetics	8% (13)
	Invest green fund	5% (7)
Hot Spot Activity at Home	Reduce electricity usage	65% (98)
	Waste Manage	19% (32)
	Saving water usage	12% (13)
	Set-up Solar-Cell	3% (7)

Note: frequency in parentheses.

For their carbon-behavior profile, as shown in Table 3, the majority of respondents, comprising 36%, reported paying monthly electricity bills ranging from THB1,001 to THB2,000. Additionally, 27% of participants stated that their monthly electricity expenses fell from THB501 to THB1,000. Concerning transportation costs, 35% of respondents indicated that they spend between THB1,001 and THB2,000 per month, while 25% stated that their monthly transportation expenses amount to THB501 to THB1,000.

Regarding activities with significant carbon emissions in the entertainment sector, many millennials expressed their intention to address these issues. Specifically, 69% of respondents mentioned their desire to reduce their carbon footprint when participating in grilled-pork buffets. In the goods and services category, 65% of participants expressed a strong inclination to reduce their electricity consumption at home. In the home segment, respondents showed considerable interest in managing their carbon emissions by opting for electricity from renewable sources (37%). Furthermore, 27% of millennials expressed their intention to either walk or use a bicycle to reduce carbon emissions in the mobility segment.

4.2. Structural Equation Modeling Analysis

The analysis of the measurement and structural models was conducted using the PLS approach, with the interpretation of results relying on standardized path coefficients and coefficients of determination. To enhance the analysis's reliability, 5000 bootstrap samples were employed [73]. The subsequent sections present the findings derived from the measurement and structural models, respectively.

4.2.1. Measurement Model Analysis

For the measurement model analysis, SmartPLS 4.0 software was deployed to conduct confirmatory factor analysis and evaluate various aspects such as convergent validity, internal consistency, reliability, and discriminant validity of

the questionnaire—the assessment procedure aligned with the recommended approach [74]. Certain items (AA3, LCB2, IN4, and PC4) were excluded from the analysis to enhance reliability. The remaining items demonstrated robust outer loadings, ranging from 0.314 to 0.936. Crucially, key metrics, including Cronbach's α (>0.7), composite reliability (>0.7), and outer loadings (>0.3), consistently surpassed the prescribed thresholds, underscoring the questionnaire's high reliability, validity, and internal consistency [73]. Moreover, the average variance extracted (AVE) comfortably exceeded 0.3, signifying acceptable convergent validity [74]. Discriminant validity, in line with the suggestion of Henseler et al. [75] was assessed using the Heterotrait-Monotrait ratio of correlations (HTMT). As presented in Table 4, the results incorporated the square root of AVE values on the diagonal and correlation coefficients between constructs. Importantly, these findings indicated that none of the items exhibited higher cross-loadings on other constructs than on their own, providing compelling evidence of the questionnaire's satisfactory discriminant validity [76].

Table 4. Composite Reliability and Validity

Construct	Item	Loading	Cronbach's alpha	Composite reliability (CR, rho_c)	Average variance extracted (AVE)
Attitude & Awareness (AA)	AA1	0.646***	0.661	0.652	0.324
	AA2	0.505***			
	AA4	0.648 ***			
	AA5	0.451***			
Perceived Control Behavior (PC)	PC1	0.778***	0.869	0.872	0.6
	PC2	0.919***			
	PC3	0.798***			
Low-Carbon Behavior (LCB)	LCB1	0.636***	0.861	0.859	0.405
	LCB3	0.746 ***			
	LCB4	0.692 ***			
	LCB5	0.704 ***			
	LCB6	0.730 ***			
	LCB7	0.662***			
	LCB8	0.564***			
	LCB9	0.641***			
	LCB10	0.576***			
Persuasive Technology (PT)	PT1	0.730***	0.888	0.886	0.568
	PT2	0.639***			
	PT3	0.679***			
	PT4	0.677***			
	PT5	0.878***			
	PT6	0.881***			
Social Norms (SN)	SN1	0.570***	0.721	0.710	0.456
	SN2	0.824***			
	SN3	0.604***			
Incentive (IN)	IN1	0.698***	0.651	0.650	0.387
	IN2	0.505***			
	IN3	0.647***			
Infrastructure (INF)	INF1	0.525***	0.610	0.643	0.417
	INF2	0.936***			
	INF3	0.314***			

*** $p < 0.001$

It is crucial to examine the potential for Common Method Bias (CMB) and multicollinearity among predictive variables. CMB occurs when variations in responses are due to the measurement tool itself rather than the true inclinations of the respondents that the tool aims to reveal. To evaluate multicollinearity, we employed a comprehensive test introduced by Kock & Lynn [77] recommended for assessing the prediction of the collinearity test. As displayed in Table 5, the results indicate that all inner Variance Inflation Factors (VIFs) among the latent constructs range from 1.000 to 1.631. These values are below the threshold of 3.3 suggested by Kock [78], signifying that the full collinearity test yielded satisfactory VIFs. Consequently, the model can be deemed free from Common Method Bias.

Table 5. Discriminant Validity

	AA	IN	INF	LCB	PC	PT	SN
AA	0.569						
IN	0.566	0.622					
INF	0.379	0.606	0.646				
LCB	0.498	0.464	0.43	0.636			
PC	0.497	0.319	0.266	0.624	0.834		
PT	0.545	0.728	0.496	0.485	0.519	0.754	
SN	0.432	0.431	0.461	0.625	0.618	0.477	0.675

Note: All the correlations were significant at $p < 0.01$. Values in the crosswise are the square roots of the average variance extracted from the constructs.

4.2.2. Evaluation and Structural Model Analysis

The bootstrap method was employed to examine the causal relationships among the latent variables in the structural model. 5,000 bootstrap samples were generated to calculate the standard error at a 95% confidence level. The significance and strength of the paths and causal relationships between the latent variables were assessed based on the β values (path coefficients) [73]. The findings, depicted in Figure 3, confirmed that all socio-demographic factors (Sex, Education, Income, and Age) had a substantial impact on low-carbon behavior (LCB) as indicated by the following β values: (Sex → LCB, Education → LCB, Income → LCB, and Age → LCB): β = 0.064, $p < 0.001$; β = -0.033, $p < 0.001$; β = -0.200, $p < 0.001$; β = 0.024, $p < 0.001$. Therefore, H1a, H1b, H1c, and H1d were supported.

Furthermore, the extended Theory of Planned Behavior (TPB) factors, including Attitude & Awareness (AA), Perceived Control Behavior (PC), Social Norm (SN), and Infrastructure (INF), exhibited a positive relationship on low-carbon behavior (LCB) as evidenced by the following β values: (AA → LCB, PC → LCB, SN → LCB, and INF → LC): β = 0.169, $p < 0.001$; β = 0.353, $p < 0.001$; β = 0.231, $p < 0.001$; β = 0.024, $p < 0.001$. Therefore, H2, H3, H4, and H5 were supported.

In addition, the motivating variables, namely Persuasive Technology and Incentive, has a significant relationship with millennials' TPB factors with the following β values: (Persuasive Technology → AA, Persuasive Technology → PC, Persuasive Technology → SN, Incentive → AA, and Incentive → PC): β = 0.306, $p < 0.001$; β = 0.590, $p < 0.001$; β = 0.496, $p < 0.001$; β = 0.342, $p < 0.001$; β = -0.095, $p < 0.001$. Therefore, H6a, H6b, H6c, H7a, and H7b were supported.

Table 6 and Figure 3 comprehensively summarize the results for all the hypotheses.

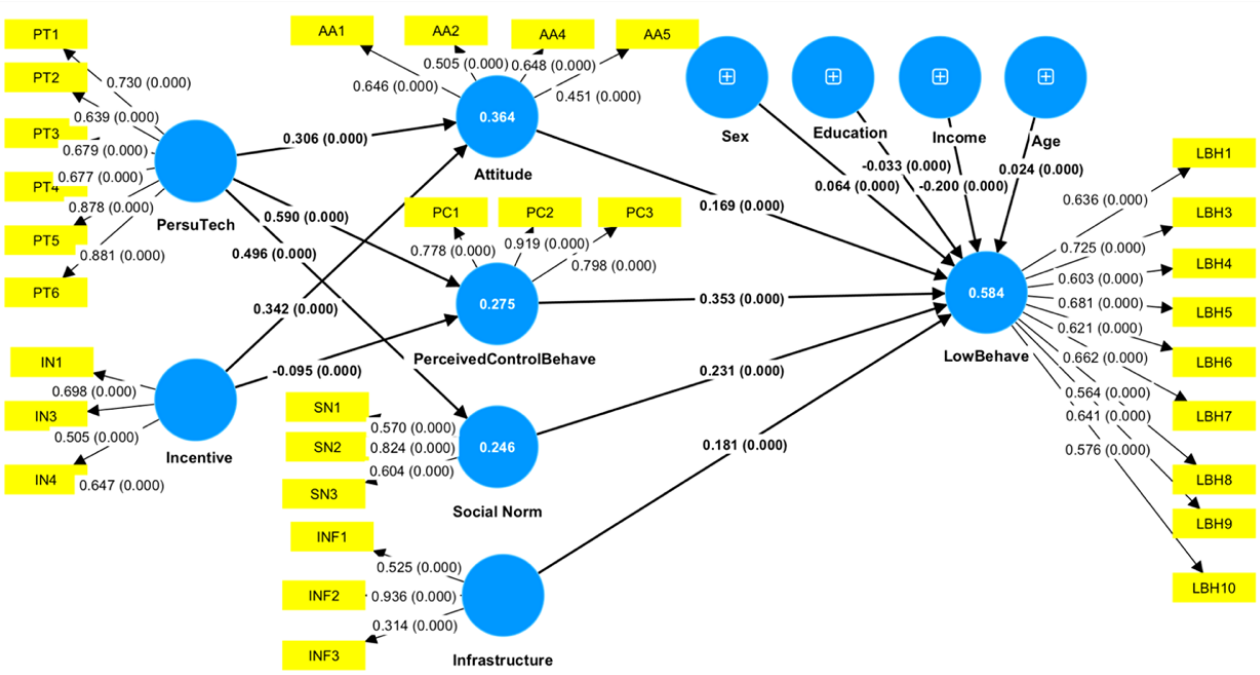

Figure 3. Results of the Low-Carbon Behavior Model

Table 6. Hypothesis Test Results

Hypothesis	Path	*Path Coef.*	*p*-value	Results
H1a	Sex→ Low-Carbon Behavior	0.064	0.000	Supported
H1b	Education→ Low-Carbon Behavior	-0.033	0.000	Supported
H1c	Income→ Low-Carbon Behavior	-0.200	0.000	Supported
H1d	Age→ Low-Carbon Behavior	0.024	0.000	Supported
H2	Attitude→ Low-Carbon Behavior	0.169	0.000	Supported
H3	Perceived Control Behavior→ Low-Carbon Behavior	0.353	0.000	Supported
H4	Social Norm→ Low-Carbon Behavior	0.231	0.000	Supported
H5	Infrastructure→ Low-Carbon Behavior	0.024	0.000	Supported
H6a	Persuasive Technology → Attitude	0.306	0.000	Supported
H6b	Persuasive Technology→ Perceived Control Behavior	0.590	0.000	Supported
H6c	Persuasive Technology→ Social Norm	0.496	0.000	Supported
H7a	Incentive →Attitude	0.342	0.000	Supported
H7b	Incentive→ Perceived Control Behavior	-0.095	0.000	Supported
R^2 Attitude Toward Low-Carbon Behavior = 16.9%				
Perceived Behavior Control Toward Low-Carbon Behavior = 35.9%				
Social Norm Toward Low-Carbon Behavior = 22.3%				
Infrastructure Toward Low-Carbon Behavior = 18.1%				
Low-Carbon Behavior = 58.4%				

Table 6 shows that all thirteen estimated paths were statistically significant. The motivating variables significantly and indirectly affect Thai millennials' low-carbon behavior through their TPB factors. Moreover, attitudes & awareness, subjective norms, perceived behavior control, and infrastructure exhibited a substantial explanatory power, with an R-square value of 58.4% for low-carbon behavior. An R-square value exceeding 0.5 (r > 0.5) is commonly regarded as indicating an explanation power [79]. Attitude & Awareness, influenced by Persuasive Technology and Incentive, displayed more predictive strength **(**36**.**4**%)** than Perceived Control Behavior influenced by Persuasive Technology and Incentive **(**27**.**5**%)** and Social Norms influenced by Persuasive Technology) 24.6 .(%This supported the earlier argument that persuasive technology positively related to millennials' attitudes, social norms, and perceived control behavior, and incentive positively affects only attitudes promoting low-carbon behavior. However, incentive negatively affects their perceived control behavior.

4.2.3. SEM Analysis using Mediating Variables

This study employed the bootstrapping method Preacher and Hayes **[**73**]** suggested to test the mediating effects**.** Table 7 shows that Persuasive Technology had a positive indirect effect on Low Carbon Behavior through TPB Factors of Attitude **(**ß = 0**.**052, p < 0**.**001**)**, Perceived Behavioral Control **(**ß = 0**.**208, p < 0**.**001**)**, and Social Norm **(**ß = 0**.**114, p < 0**.**001**)**, and Incentive also had a positive indirect effect on Low Carbon Behavior through TPB Factors of Attitude **(**ß = 0**.**058, p < 0**.**001**)**; however, Incentive had a negative indirect effect on Low Carbon Behavior through Perceived Behavioral Control **(**ß = **-**0**.**034, p < 0**.**001**)**.

Table 6. Special indirect effect

Path	*a*	*b*	Specific Indirect effect ß =(**a** × **b**)	*P Value*
Persuasive Technology → Attitude → Low-Carbon Behavior	0.306	0.169	0.052	0.0000
Persuasive Technology → Perceived Control Behavior → Low-Carbon Behavior	0.59	0.353	0.208	0.0000
Persuasive Technology → Social Norm → Low-Carbon Behavior	0.496	0.231	0.114	0.0000
Incentive →Attitude → Low-Carbon Behavior	0.342	0.169	0.058	0.0000
Incentive → Perceived Control Behavior → Low-Carbon Behavior	-0.095	0.353	-0.034	0.0000

One method for gaining further insight into the mediated component involves calculating the ratio of the indirect-to-total effect, commonly referred to as the Variance Accounted For (VAF) value. Following the guidance of Hair et al. [73], a VAF value below 20% signifies no mediation, while a value ranging from 20% to 80% indicates partial mediation and a value exceeding 80% suggests full mediation.

This investigation determined the VAF value using the formula: VAF = Indirect effect/total effect. The VAF analysis indicated that in the relationship between Persuasive Technology and Low-Carbon Behavior, the mediation effect of Perceived Behavioral Control had a VAF value of 56%, indicating partial mediation. Similarly, the mediation effect of Social Norm had a VAF value of 30%, also suggesting partial mediation. However, none of the TPB factors were found to mediate the relationship between Incentive and Low-Carbon Behavior.

5. Discussions

The primary objective of the study was to develop a comprehensive causal-predictive analysis of low-carbon behavior among Thai millennials. This involved a detailed investigation of various influencing factors, including psychological, infrastructural, technological, and motivational aspects. The results (H2) provided insights into the psychological factors, indicating a significant link between positive attitudes towards environmental concerns and the propensity of Thai millennials to adopt low-carbon behavior. This discovery aligns with previous research conducted by Ajzen and Fishbein [80] and Pothitou et al. [55], reinforcing the notion that favourable attitudes are conducive to adopting low-carbon behavior. It suggests that Thai millennials possess a pro-sustainability mindset, naturally driving them towards eco-friendly activities in their daily lives. Additionally, the study (H3) affirmed a substantial relationship between perceived behavioral control and low-carbon behavior, in line with empirical research that have demonstrated that people's intention/behavior is positively influenced by their self-confidence in their ability to perform the behavior [81, 82] that links consumers' intent to purchase energy-efficient household appliances with their perceived control over such behavior. Furthermore, the study supported the hypothesis (H4) that a positive relationship exists between social norms and low-carbon behavior, implying that increasing social acceptance of these norms may foster a greater willingness among Thai millennials to embrace low-carbon practices which corresponds to the study by Steg & Vlek [83].

In the realm of infrastructure, the study's findings corroborated the hypothesis (H5) that the presence of low-carbon infrastructure plays a vital role in motivating Thai millennials to change their low-carbon behaviour. This is in line with research by Zand Hessami & Yousefi [84] and Li et al. [85] which emphasize the impact of external conditions, such as infrastructure and technology support, on the adoption of low-carbon behavior. The study (H6a) also explored the role of persuasive technology as a motivating variable and found that it can be employed to influence Thai millennials' attitudes indirectly, thereby encouraging low-carbon behavior without coercion. This finding aligns with the idea of persuasive technology and its ability to encourage people to change their attitudes towards environmentally friendly actions [86].

Moreover, concerning technological aspects, the study's (H6c) outcomes indicated that persuasive technology can be linked to changes in social norms and indirectly contribute to fostering responsibility for environmentally friendly behaviors among Thai millennials, aligning with the study by Bardhan et al. [87]. Additionally, the study found a positive relationship between persuasive technology and perceived behavioral control, echoing the research by Lin [58] which demonstrated that persuasive technology significantly enhances students' awareness of their carbon footprint and perceived behavioral control. On the motivation front, the study's results revealed that incentives have a positive impact on adjusting favorable attitudes toward low-carbon behavior change, consistent with research conducted by Owusu et al. [88]. Surprisingly, the study also found an indirect negative relationship between incentives and Thai millennials' low-carbon behavior through perceived behavioral control, which presents an intriguing contrast to findings from China [89]. This suggests that incentives alone may not ensure the sustained control of low-carbon behavior among Thai millennials. However, Zhao [47] recommended that low-carbon customization has been gradually derived differently from traditional low-carbon behavior and may carry out the new low-carbon consumption behavior model supported by the booming development of emerging technologies such as artificial intelligence and big data.

The research focused on objective 2, which aimed to examine how socio-demographic factors influence the low-carbon behavior of a specific group of people. The investigation looked into the connection between socio-demographic factors and low-carbon behavior, as suggested by the initial hypotheses (H1a, H1b, H1c, H1d). The study produced important and meaningful results that supported these hypotheses. In this Thai context, the results reveal that mature women tend to exhibit low-carbon behavior, aligning with the observations made by Chen and Li [30] who noted that women and urban residents with bachelor's degrees were more inclined toward low-carbon behaviors. Furthermore, this outcome echoes the research of Ignatow [32] and Urban & Ščasný [90] who found that older individuals were more likely to engage in energy conservation practices. However, the results show that education and income both show a negative relationship to low-carbon behavior consistent with a high-growth country like China, Liu et al. [91] and Han et al. [57] claimed that household income was inextricably associated with increasing CO2 emissions due to the demand for more products and services .This opposes the studies of De Groot et al. [92] and Hatfield-Dodds et al. [93], who claimed that well-educated, higher-income are more willing to select pro-environmental vehicles .However, Liu et al. [94] recommend further studies to reduce the impact of cultural difference and the proportion of the sample's education and income level for more accurate results.

In summary, the present study tested the appropriateness of TPB in explaining Thai millennials' formation to choose low-carbon behavior. We successfully achieved our study objectives and found support for all seven hypotheses in the

modified TPB model. Overall, the results of this study confirm that our study constructs play a significant role in motivating Thai millennials to engage in low-carbon behavior.

The findings of our study specifically contribute to our understanding of how Thai millennials are willing to adopt low-carbon behavior. The study highlights the roles of persuasive technology and incentives in empowering Thai millennials, mediated by their TPB factors. These factors are specifically designed to adequately explain their decision-making process when it comes to being environmentally friendly. To the best of our knowledge, this study was the first attempt to employ TPB to examine influencing factors on low-carbon behavior formation in the Thai Millennial context. The comprehensive analysis and robust interpretations provided in our study can enhance the scientific discourse on low-carbon behavior in the context of Thai millennials. These insights can inform targeted interventions and guide future research efforts in this field, ultimately advancing our understanding of this topic.

6. Conclusions and Implications

6.1. Conclusion

Our study has revealed significant insights regarding the factors that influence low-carbon behavior among Thai millennials. We have found that psychological and socio-demographic factors play a crucial role, social norms have an impact, infrastructure is an important consideration, persuasive technology shows promise, and incentives have complex effects. The studies help the academic discourse better understand the determinants and motivating variables that predict low-carbon behavior among Thai millennials.

The integration of multiple theoretical frameworks in this study enriches the conceptual framework. Additionally, the exploration of TPB factors as mediators sheds light on the interaction of psychological, social, and technological factors. To test the model, 150 Thai millennials were involved, and a structural equation model was employed.

The findings of the study indicate that among all the paths influencing low-carbon behavior, the effects of perceived control behavior were notably the strongest, both directly and indirectly. This suggests that implementing strategies that enhance millennials' perceived control behavior may effectively promote their transition towards low-carbon practices**.**

Moreover, Thai millennials' TPB factors can mediate all five links between the external factors as motivating variables of persuasive technology and incentive with their low-carbon behavior**.** The findings suggest that persuasive technology and incentives play a role in determining Thai millennials' attitudes toward low-carbon behavior, with some exceptions**.**

The results also suggest that the relationship between incentives and perceived behavioral control may negatively promote low-carbon behavior. The practical implications of this study extend to the development of targeted interventions that take into consideration the socio-cultural context of Thailand and aim to empower millennials to make sustainable choices.

Additionally, our exploration of socio-demographic factors uncovered that mature women exhibited a higher propensity for low-carbon behavior, while education and income displayed nuanced relationships, varying based on cultural and contextual factors. Nonetheless, the study maintains a cautious approach, recognizing the complexity of behavior change and the need for multifaceted strategies. This study also makes a significant contribution towards the advancement of SDG 13 (Climate Action), SDG 12 (Responsible Consumption and Production), SDG 9 (Industry, Innovation, and Infrastructure) and SDG 7 (Affordable and Clean Energy).

6.2. Theoretical Implications

From a theoretical perspective, this study makes a significant contribution by integrating multiple theoretical frameworks, resulting in a more comprehensive understanding of the intricate factors that influence low-carbon behavior. The incorporation of the extended Theory of Planned Behavior (TPB), Fogg's Behavior Model (FBM), and Self-Determination Theory (SDT) enriches the conceptual framework by encompassing psychological, social, and technological dimensions. This amalgamation aligns with contemporary research advocating for a holistic approach to comprehending complex behaviors like environmental consciousness and eco-friendly actions. The study provides an intricate view of the underlying mechanisms guiding millennials' sustainable choices by establishing the mediating roles of TPB factors within the relationship between persuasive technology, incentives, and low-carbon behavior.

Furthermore, the finding that the indirect impact of persuasive technology on low-carbon behavior is more pronounced when mediated by perceived control behavior (0.208) and social norms (0.114) compared to attitude (0.052) holds potential for enhancing the theoretical understanding of behavior change and technology-mediated interventions. This outcome underscores the critical significance of perceived control behavior and social norms in shaping low-carbon behavior, suggesting their potentially greater influence over individual attitudes alone. To capitalize on this, strategies emphasizing strengthening social norms could leverage persuasive technology to cultivate social influence and establish a collective sense of responsibility for low-carbon behavior.

The study's identification that the effects of incentives on low-carbon behavior are particularly potent when mediated by perceived control behavior (-0.034) as opposed to attitude (0.058) brings novel insights to the theoretical realm. This discovery sheds light on the role of perceived control behavior in mediating the relationship between incentives and low-carbon behavior. Notably, the negative correlation raises intriguing implications. It suggests that individuals with high control over their behavior might exhibit decreased responsiveness to external incentives intended to encourage low-carbon behavior. One plausible interpretation is that those with a robust sense of control may deem external incentives redundant or counterproductive to their intrinsic motivation. Consequently, the effectiveness of incentives for low-carbon behavior could diminish or even become adverse.

In conclusion, this study has made significant theoretical contributions in various areas. The intricate integration of multiple theoretical perspectives expands our understanding of low-carbon behavior's complexities. TPB factors observed mediating roles, indirect effects' varying strengths, and the nuanced interplay between incentives and perceived control behavior offer valuable insights into the theoretical foundations of behavior change and technology-driven interventions. While these findings provide fertile ground for advancing theoretical frameworks, it's essential to acknowledge the study's limitations and encourage further research to validate and refine these emerging insights.

6.3. Practical Implications

The study's practical implications are significant, offering valuable insights that can shape targeted interventions to promote low-carbon behavior among Thai millennials. The findings emphasize the pivotal role of attitudes, subjective norms, and perceived behavioral control as mediating factors in the relationship between persuasive technology, incentives, and low-carbon behavior. This revelation gives practitioners a clear roadmap for crafting strategies that effectively address these influential factors.

Campaigns and initiatives that aim to promote positive attitudes towards sustainable actions among millennials can effectively use persuasive technology. The study's results indicate that interventions focused on bolstering individuals' perceived control over their low-carbon behavior can yield more substantial results. To this end, persuasive technology can be harnessed to create tools, resources, and feedback mechanisms that empower users to monitor and manage their carbon footprint. Interactive features that facilitate goal-setting, progress tracking, and timely reminders for eco-friendly actions can be integrated.

The study also highlights the potential of incorporating social comparison and networking components into persuasive technology interventions. These features can foster a sense of community, enable information sharing, and encourage peer support for sustainable actions. While attitude may have a weaker direct impact on low-carbon behavior, the study suggests that integrating persuasive elements that shape attitude formation can still benefit. Providing educational information, testimonials, or compelling narratives about the environmental benefits of low-carbon behavior through technology can align users' attitudes with desired actions.

The study's contribution extends to technology-based interventions, offering insights into how persuasive technology effectively promotes sustainable behaviors. Notably, the significant mediation effects of Perceived Behavioral Control and Social norm in the relationship between Persuasive Technology and Low-Carbon Behavior emerges as a crucial finding. This underscores the importance of empowering individuals and enhancing their control over environmental actions. The study emphasizes that efforts should cultivate self-efficacy, autonomy, and a sense of control. Furthermore, social norms' significance in mediating persuasive technology's effects on low-carbon behavior underscores the need for interventions that foster supportive norms. Initiatives such as social marketing campaigns, community engagement strategies, and platforms for social interaction can be pivotal in shaping norms that encourage sustainable practices. The absence of mediation effects of Attitude and Perceived Behavioral Control in the relationship between Incentive and Low-Carbon Behavior offers valuable insights. Simple incentive schemes might not be sufficient to drive low-carbon behavior in this demographic. Policymakers, startups, or businesses focusing on sustainability can use this information to design more effective marketing and incentive strategies. may need to consider alternative approaches, such as combining incentives with persuasive technology or social influence, to create a more compelling case for eco-friendly actions.

The study's practical relevance is further enhanced by its exploration of Thailand's socio-cultural context. By acknowledging the diversity within the demographic of Thai millennials, the findings provide a basis for culturally sensitive interventions that align with local values and norms. Policymakers, environmental organizations, and startups can utilize these insights to develop contextually relevant strategies that resonate with the aspirations and preferences of Thai millennials. However, it's crucial to acknowledge the study's limitations. Behavior change is a multifaceted process influenced by various factors beyond this study's scope. Individual responses to persuasive technology and incentives can vary widely based on personal circumstances. Therefore, while the study offers valuable practical implications, its contributions should be seen as a step toward informed and contextually sensitive interventions rather than definitive solutions.

6.4. Limitations

Although this study has provided valuable insights, it is important to consider several limitations. Firstly, the research relied on self-reported data, which could be subject to social desirability bias. Participants might have provided responses they perceived as more socially acceptable, potentially leading to overestimating the relationships between variables. Employing additional methods, such as behavioral observations or longitudinal studies, could lessen this bias. Secondly, the study's cross-sectional nature limits the ability to establish causality definitively. While the proposed conceptual framework provides a comprehensive perspective on the relationships, it is worth noting that the direction of causality could potentially be bidirectional or influenced by other unexplored variables. Future research using longitudinal designs could provide more robust insights into the temporal dynamics of the variables.

Furthermore, the study focused exclusively on Thai millennials, which restricts the generalizability of findings to this demographic. Cultural, contextual, and generational factors specific to Thailand might not apply to other populations or age groups. Conducting similar studies in diverse cultural settings and among different age cohorts could provide a more comprehensive understanding of the factors influencing low-carbon behavior.

6.5. Future Research

Based on the study's findings, there are several potential directions for future research. Firstly, investigating the mechanisms that underlie the observed relationship between persuasive technology and incentives to perceived control behavior could provide a deeper understanding of how external motivators interact with internal determinants of behavior—exploring whether this relationship holds across different contexts and their socio-demographic differences could offer valuable insights into the intricate dynamics between incentives, persuasive technology, and perceived control. Moreover, conducting longitudinal studies and cross-cultural comparisons could further enhance our understanding. Such research could provide valuable insights for policymakers and businesses to develop more effective strategies in promoting sustainable behaviors and fostering a greener future. Exploring the role of cultural factors in influencing the relationships among persuasive technology, incentives, and low-carbon behavior is a promising direction. Cultural distinctions might impact the effectiveness of persuasive strategies and the perception of incentives, thus shaping the mediating roles of TPB factors differently. Comparative studies across various cultures could uncover cultural factors that moderate the relationships.

Furthermore, extending the research to examine the long-term sustainability of low-carbon behavior interventions is essential. Investigating whether the effects of persuasive technology and incentives are enduring over time or fade after a certain period could provide insights into the sustainability of behavior change initiatives. Longitudinal studies tracking participants' behavior and attitudes over an extended period could shed light on the long-term impact of interventions. Lastly, exploring the interplay between individual and collective behaviors in driving low-carbon actions could offer a holistic perspective. Understanding how individual behaviors aggregate to shape broader societal norms and practices can inform strategies to promote eco-friendly actions on a larger scale. Investigating the social dynamics that lead to the formation and diffusion of pro-environmental behaviors within communities could pave the way for effective community-based interventions.

7. Declarations

7.1. 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 analysis, 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, A.T., K.S., and C.G.; funding acquisition, Y.Y. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

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

7.3. Funding

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7.5. Institutional Review Board Statement

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by The Research Ethics Review Committee for Research Involving Human Subjects: The Second Allied Academic Group in Social Sciences, Humanities and Fine and Applied Arts at Chulalongkorn University (13 March 2023/ COA 096/66).

7.6. Informed Consent Statement

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

7.7. Declaration of Competing Interest

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

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