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Sensor-assisted Evaluation Framework for Mobile Cooling Devices Integrating Environmental Sensing and Multicriteria Decision-making

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In this study, we propose an integrated evaluation framework for mobile cooling products by combining environmental sensing, the analytic hierarchy process (AHP), and a fuzzy technique for order preference by similarity to ideal solution (Fuzzy-TOPSIS) to assess product performance and user experience under realistic usage conditions. Four representative product design types—turbo type, ice crystal type, folding type, and ice-crystal/folding hybrid type—were selected for empirical investigation. Environmental sensing was first employed to acquire microclimate parameters, including ambient temperature, relative humidity, and air velocity, enabling context-aware performance assessment. AHP was subsequently applied to determine the relative weights of two primary evaluation dimensions, namely, sensory attributes and sustainable design factors. Subjective sensory ratings and fuzzy linguistic evaluations collected from 60 participants were then integrated using Fuzzy-TOPSIS to obtain overall performance rankings across different usage scenarios. The results indicate comparable importance between sensory and sustainability dimensions (0.515 vs 0.485), reflecting users' simultaneous emphasis on thermal comfort and energy efficiency. The overall ranking was ice-crystal/folding hybrid type > ice-crystal type > turbo type > folding type. Regression analysis further reveals that tactile comfort and perceived airflow cooling significantly enhance emotional satisfaction, while noise negatively affects user experience in quiet environments. The proposed framework effectively integrates environmental sensing with multicriteria decision-making and sensory evaluation, offering a scalable approach for the design and assessment of portable and wearable climate-adaptive products.

1. Introduction

The increasing frequency of global extreme heat events has intensified the demand for personal cooling solutions in mobile and outdoor environments. In urban settings, microclimatic

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conditions characterized by high ambient temperature, low wind speed, and elevated radiative load frequently lead to thermal discomfort among commuters, outdoor workers, and people in recreational situations. Mobile cooling products have therefore emerged as an on-demand and infrastructure-independent solution for localized thermal relief. Despite their growing market presence, the evaluation of such products remains largely limited to isolated performance indicators, such as airflow velocity, battery endurance, and noise level, which cannot adequately represent the coupled effect of environmental conditions, device behavior, and user perception encountered in real-world usage scenarios. From an engineering and measurement perspective, two critical gaps persist in current research. First, device performance is rarely assessed in conjunction with environmental sensing data, meaning that cooling effectiveness is often evaluated without reference to actual microclimatic conditions.

As thermal sensation and airflow perception are strongly modulated by ambient temperature, humidity, wind, and radiation, performance metrics obtained under controlled laboratory conditions may lack contextual validity. Second, the user perception of mobile cooling products, including thermal sensation, tactile comfort, acoustic quality, and visual semantics, is inherently multidimensional and uncertain. Conventional linear rating scales struggle to capture such fuzzy subjective judgments, particularly when these perceptions must be integrated with sustainability-related design indicators such as energy efficiency, modularity, repairability, and lifecycle considerations. These limitations highlight the need for evaluation frameworks that explicitly link sensor-derived environmental data with human-centered experience assessment. To address these challenges, we propose an integrated evaluation framework combining environmental sensing, the analytic hierarchy process (AHP), and a fuzzy technique for order preference by similarity to ideal solution (Fuzzy-TOPSIS). Environmental sensing is employed to acquire key microclimatic parameters, enabling context-aware measurement rather than abstract performance comparison. AHP is applied to establish the relative importance of sensory attributes and sustainability indicators through expert-driven hierarchical weighting, ensuring transparency and consistency in the decision structure.

Fuzzy-TOPSIS is then used to manage uncertainty in subjective user evaluations by representing linguistic judgments with fuzzy numbers, allowing the robust comparison and ranking of alternative product designs. Four representative product design categories—turbo type, ice crystal type, folding type, and hybrid type—are selected as empirical case studies to enable cross-scenario and cross-dimensional analyses. The conceptual foundation of this work is grounded in sensory design and product experience research, which emphasizes that user responses emerge from the combined effects of multiple sensory stimuli, including thermally perceived airflow, acoustic characteristics, tactile interaction, and visual semantics, rather than from isolated functional performance indicators. This viewpoint motivates the adoption of an integrated evaluation framework that links sensor-measured physical parameters with user-centered experience assessment. Norman proposed that product experience is shaped through visceral, behavioral, and reflective levels.(1) Desmet and Hekkert(2) and Hekkert and Schifferstein(3) further conceptualized product experience as an integration of sensory perception, meaning attribution, and emotional response. In the context of mobile cooling products, this implies that perceived cooling effectiveness depends not only on measured airflow velocity or surface temperature but also on tactile feedback, acoustic behavior, and visual cues. Spence demonstrated that cross-modal correspondences among shape, sound, and color can significantly modulate users' expectations of coolness. However, many engineering-oriented studies still prioritize airflow or cooling efficiency measurements, with a limited incorporation of structured multisensory evaluation models grounded in sensing data.(4)

Recent studies on personal cooling technologies have increasingly focused on contextual and outdoor applications. He *et al.* reported that personal cooling devices can significantly enhance comfort in high-temperature environments while reducing overall air-conditioning demand.(5) Mun *et al.* showed that airflow direction and velocity distribution strongly affect the perceived cooling sensation through combined physical measurement and subjective evaluation.(6) Tang *et al.* demonstrated that task load and movement patterns directly affect the cooling effectiveness in portable devices.(7) Sajjad *et al.* emphasized the applicability of personal cooling systems in outdoor high-temperature environments.(8) Nevertheless, most existing investigations remain limited to fixed sites or laboratory settings, and few incorporate real-time environmental sensing—such as that involving wind speed, radiant temperature, or thermal indices like the universal thermal climate index (UTCI) and/or physiological equivalent temperature (PET)—into integrated performance and experience evaluations. Consequently, under conditions of outdoor mobility and urban microclimate variability, there remains a lack of sensor-informed assessment of handheld and wearable cooling products.

Outdoor thermal comfort and microclimate modeling further underline the importance of context-aware evaluation. Frontczak and Wargocki noted that thermal comfort is affected not only by meteorological parameters but also by psychological expectations, perceived control, and activity patterns.(9) Salata *et al.* used UTCI to analyze outdoor heat stress and identified wind speed, shading, and radiative conditions as dominant factors shaping perceived thermal environments.(10) These findings suggest that mobile cooling product evaluation must be explicitly linked to realistic usage environments, such as sidewalks, transit nodes, night markets, and tourist areas, where microclimatic conditions vary dynamically. However, integrated analyses combining microclimate sensing, user sensory evaluation, and device performance comparison remain limited. Given the multiple interdependent attributes involved in mobile cooling products—including airflow, noise, energy consumption, weight, and appearance—multicriteria decision-making (MCDM) methods provide an appropriate analytical foundation. Saaty introduced AHP as a structured approach for deriving criterion weights through hierarchical decomposition and pairwise comparison.(11) Hwang and Yoon proposed TOPSIS as a ranking method based on distances to positive and negative ideal solutions.(12)

To address uncertainty in subjective evaluations, Chen extended TOPSIS to fuzzy environments using triangular fuzzy numbers (TFNs).(13) Behzadian *et al.* confirmed that Fuzzy-TOPSIS is well suited to solving product comparison problems involving sensory evaluation and fuzzy judgments.(14) Nevertheless, the joint application of AHP and Fuzzy-TOPSIS within a unified framework that also incorporates environmental sensing and sustainability considerations remains relatively unexplored for personal cooling devices. Sustainability has become an increasingly important design objective for personal cooling technologies. Manzini and Vezzoli emphasized modularity, repairability, and lifecycle thinking as strategies to reduce environmental impact,[15] while Tukker discussed product–service systems as a means of meeting user needs with reduced resource consumption.[16] Sajjad *et al*. further noted that effective localized cooling can reduce building-level heating, ventilation, and air conditioning demand and associated carbon emissions.[8] Thermoelectric cooling has been widely explored for portable and wearable applications because of its compactness and controllability,[17–19] with recent work by Wiharti *et al*. demonstrating that appropriate heat dissipation design can further enhance performance.[20]

However, sustainability indicators such as energy efficiency ratio, endurance efficiency, carbon footprint, recyclability, and maintenance accessibility are still rarely integrated into formal multicriteria evaluation frameworks alongside sensory experience. In this study, we have made the following contributions. We establish a sensing-driven evaluation framework that explicitly integrates environmental measurement with mobile cooling product assessment, enabling performance and user experience to be analyzed under realistic microclimatic conditions. By combining AHP and Fuzzy-TOPSIS, the framework provides a transparent and reproducible multicriteria decision structure that balances sensory experience and sustainability considerations while accommodating uncertainty in subjective judgments. Furthermore, the proposed approach bridges objective sensor data and human-centered evaluation by linking measured environmental parameters to multisensory user responses. Through the comparative analysis of representative product categories across different usage scenarios, we demonstrate how airflow characteristics, energy-related performance, acoustic behavior, and tactile ergonomics jointly shape overall user satisfaction.

2. Methodology

In this study, we develop a sensor-assisted evaluation methodology that integrates environmental sensing, user experience (UX) measurement, and a MCDM framework based on the AHP and Fuzzy-TOPSIS to assess the performance and user experience of mobile cooling devices under real outdoor conditions. By explicitly linking sensor-derived microclimate measurements with structured user experience data and decision analysis, the proposed methodology enables the context-aware and reproducible evaluation of mobile cooling products.

2.1 Research design, test devices, and participants

Four commercially available mobile cooling devices were selected to represent typical product archetypes commonly found on the market. These included a turbo-type device utilizing a high-speed impeller to generate high static pressure and strongly directed airflow; an ice-crystal-type device equipped with an evaporative cooling module incorporating an ice or water cartridge to enhance cooling performance while maintaining relatively low noise levels; a folding-type device designed with lightweight construction and collapsible geometry to improve portability and commuting convenience; and a hybrid-type device combining evaporative cooling with a folding-type structure, offering multiple airflow modes and comparatively low energy consumption. All devices were equipped with similar battery capacities ranging from approximately 3600 to 4000 mAh and employed USB-C charging interfaces. Nominal specifications, including rated airflow, battery endurance, and power consumption, were used as baseline references for normalization in subsequent analysis.

A total of 60 general users were recruited through convenience and snowball sampling, with an approximately balanced gender distribution and an age range of 20–50 years. To reflect diverse usage contexts, participants were categorized on the basis of dominant daily activity patterns, including commuters characterized by frequent walking and public transportation transfers, students alternating between indoor and outdoor environments with low-to-moderate mobility, and outdoor workers exposed to high thermal loads and physical activity. In addition, 15 domain experts with backgrounds in thermal comfort, product design, and sustainable design were invited to participate in the AHP-based weight construction process by completing pairwise comparison questionnaires.

2.2 Environmental sensing and contextual data acquisition

The environmental data were collected using a portable environmental sensing unit designed for outdoor microclimate assessment. The sensing unit integrated multiple calibrated sensors, including a digital temperature and relative humidity sensor (accuracy: ±0.3 °C for air temperature and ±2% for relative humidity), a compact ultrasonic anemometer for wind speed measurement (accuracy: ±0.1 m/s), and a globe-temperature-based module for estimating mean radiant temperature (*Tmrt*). All sensors were factory-calibrated and verified before field deployment to ensure reliable outdoor measurements. Data were recorded at 1 s intervals and time-stamped for synchronization with behavioral observations and questionnaire responses. The environmental sensing dataset consisted of air temperature (*Ta*), relative humidity (*RH*), wind speed (*Va*), and mean radiant temperature (*Tmrt*). Using the environmental sensing data, thermal indices, including *UTCI* and/or *PET*, were calculated to quantify physiological thermal stress levels. These indices were used to classify measurement points into comparable thermal contexts, providing a sensor-based foundation for subsequent performance comparison and thermal comfort analysis. For example, during a representative summer afternoon measurement, *Ta* ranged from 32.1 to 34.8 °C, *RH* from 58 to 71%, *Va* from 0.3 to 1.6 m/s depending on site exposure, and the corresponding *UTCI* values ranged from approximately 38 to 42 °C, indicating strong to very strong heat stress conditions.

The sensor-derived environmental data were used to classify usage contexts and support subsequent performance comparisons of mobile cooling devices. A standardized observation protocol was applied to consistently record key contextual variables, including activity type, movement intensity, the duration of device use, and basic interaction patterns. The protocol was intentionally lightweight and focused on real-world usage characteristics rather than detailed motion capture. All observation records were time-synchronized with environmental sensing data, enabling the integrated analysis of microclimate conditions, user behavior, and perceived sensory responses. In parallel, contextual and behavioral observations were conducted using a standardized observation protocol. Participants' activity states, including standing, walking, queuing, and exercising, were recorded along with movement patterns, dwell time, and device usage behaviors such as handheld or neck-mounted operation, airflow mode selection, usage timing, and airflow direction. All behavioral records were time-stamped and synchronized with the environmental sensing data, enabling the construction of a linked dataset representing the relationship between environmental context, user behavior, and perceived thermal sensation. On the basis of the thermal stress levels and behavioral characteristics, usage contexts were further clustered into representative scenarios such as commuting, leisure walking or tourism, night market or high-density heat exposure, exercise, and quiet indoor environments.

2.3 UX measurement and sustainability indicators

UX measurement was conducted using a structured questionnaire developed on the basis of Norman's emotional design theory and prior research on multisensory product interaction. Four sensory UX dimensions encompassing a total of 16 indicators were defined, covering thermal sensation, auditory perception, tactile comfort, and visual evaluation. Participants evaluated each device using a five-point Likert scale ranging from 1 (very dissatisfied) to 5 (very satisfied), enabling the quantitative representation of subjective user experience. Reliability and validity analyses demonstrated strong the psychometric performance of the UX measurement instrument. Cronbach's alpha values for individual sensory dimensions ranged from 0.84 to 0.88, with an overall Cronbach's alpha of 0.93. The Kaiser–Meyer–Olkin (KMO) measure was 0.89, and Bartlett's test of sphericity was significant ($p < 0.001$), indicating good internal consistency and construct validity suitable for subsequent multicriteria analysis.

To incorporate sustainability considerations into the decision framework, three groups of sustainability indicators were defined. These included energy performance indicators such as energy consumption per unit time (Wh/h), energy efficiency ratio (*EER*), and battery endurance; material and end-of-life indicators including material recyclability, the degree of disassemblability based on fastening methods, and the proportion of environmentally friendly materials; and lifecycle-oriented indicators derived from a screening-level lifecycle assessment (LCA), estimating environmental impacts during manufacturing, use, and disposal phases in terms of CO_2-equivalent emissions. All sustainability indicators were converted to consistent units and normalized prior to integration with UX measurement indicators in the MCDM framework.

2.4 Construction of the AHP-based decision framework

An AHP-based hierarchical structure was established to construct criterion weights within the MCDM framework. The hierarchy consisted of three levels: a dimension level distinguishing sensory attributes and sustainable design, a factor level encompassing thermal, auditory, tactile, visual, energy efficiency, material, and reusability aspects, and an indicator level corresponding to the 16 UX measurement and sustainability indicators. Fifteen experts completed pairwise comparison questionnaires using Saaty's 1–9 scale, and individual judgments were aggregated into a group comparison matrix by the geometric mean method. The panel consisted of fifteen experts with backgrounds in thermal comfort evaluation, product and industrial design, energy efficiency and sustainable design, and user experience assessment. All experts had at least five years of relevant academic or industry experience and were familiar with product performance evaluation or multicriteria decision-making. They were selected by purposive sampling to ensure balanced and complementary perspectives aligned with the AHP evaluation framework, supporting consistent and reliable pairwise comparisons. For each comparison matrix, the maximum eigenvalue (λmax) and corresponding weight vector were calculated, followed by the computation of the consistency index (CI) and consistency ratio (CR). All matrices exhibited CR values below 0.10, indicating an acceptable consistency of expert judgments. The resulting weights at the dimension, factor, and indicator levels were adopted as global weights in the subsequent Fuzzy-TOPSIS analysis.

2.5 Fuzzy-TOPSIS-based decision analysis

Within the MCDM framework, participants' five-point Likert-scale UX measurement data were transformed into TFNs to represent linguistic uncertainty. A fuzzy decision matrix was constructed for each usage context and combined with the AHP-derived global weight vector to obtain a weighted fuzzy decision matrix. The fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS) were defined in accordance with the benefit or cost attributes of each indicator. Fuzzy Euclidean distances between each alternative and the FPIS and FNIS were calculated to obtain separation measures. The closeness coefficient was then computed as the ratio of the distance to the FNIS over the sum of distances to both ideal solutions. A higher closeness coefficient indicates closer proximity to the ideal solution and superior overall performance. This procedure enabled the context-aware ranking of mobile cooling devices by simultaneously accounting for environmental sensing data, UX measurement results, and sustainability indicators within a unified decision framework.

3. Results and Discussion

3.1 Description of study objects and usage scenarios

To examine the practical performance of mobile cooling devices across sensory attributes, sustainable design considerations, and contextual requirements, in this study, we selected four representative market-available models as experimental prototypes and evaluation targets, as shown in Fig. 1. The four devices were selected to represent typical market categories with distinct airflow output, cooling mechanism, acoustic profile, and portability. Manufacturer information and device dimensions ($L \times W \times H$) are summarized in Table 1. On the basis of the differences in airflow output, cooling mechanism, acoustic profile, energy consumption characteristics, and portability, the devices were categorized into four types: turbo type, ice crystal type, folding type, and ice-crystal/folding hybrid type. This classification reflects the prevailing design strategies currently adopted in the market and aligns with common usage scenarios including commuting, tourism, outdoor sports, night markets, and office environments, as displayed in Table 2.

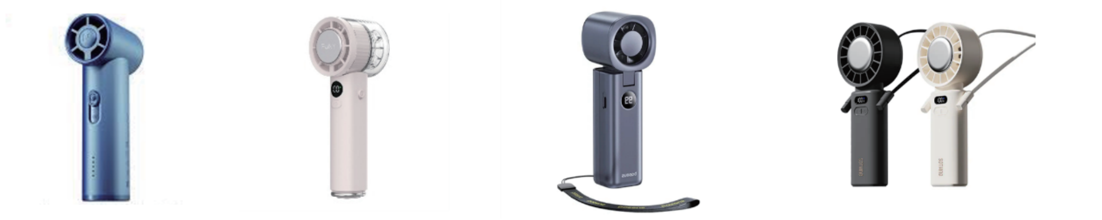

Fig. 1. (Color online) Representative mobile cooling devices used in this study.

Table 1
Specifications of the representative mobile cooling devices used in this study.

Category	Device (type)	Manufacturer (Brand)	Max. air speed (m/s)	Battery (mAh)	Fan-only runtime	Dimensions (*L* × *W* × *H*, mm)
Turbo type	NEF01	NITECORE	11	4000	3–13 h (level 5→1)	110 × 50.8 × 31.0
Ice crystal type	SS03	FUNY	7	4000	3.5–14 h	166 × 54.2 × 57.2
Folding type	GoTrip DT1	Baseus	5	4000	2.5–8 h	133 × 51 × 35
Hybrid type	Turbo Ice (DSHJ-S-2428)	SOTHING	8	3600	8 h+(up to 15 h)	166 × 60 × 33

(1) Turbo type (high airflow pressure with strongly directed flow): This type employs high-speed turbine blades capable of generating a concentrated, high-pressure airflow within a short time. It is particularly suitable for environments with high heat exposure, poor air circulation, and frequent movement, such as night market streets, outdoor sports settings, and queuing scenarios. Its primary advantages lie in the strong airflow and immediate cooling sensation; however, it is typically associated with higher noise levels, and battery endurance is highly sensitive to airflow settings. As such, this category represents a typical performance-oriented design.

(2) Ice crystal type (stable cooling with low noise): Equipped with an ice-crystal cartridge or an evaporative cooling module, this type provides stable cooling performance while operating at relatively low noise levels. It is well suited for quiet and stationary environments such as offices, classrooms, metro waiting areas, and libraries. Although its cooling effect is sustained and acoustically unobtrusive, the periodic water refilling and replacement of the ice-crystal cartridge are required, which slightly reduces operational convenience. This design can therefore be characterized as static-environment- and low-noise-oriented.

(3) Folding type (high portability and low energy consumption): Designed with lightweight construction and a folding form, this type emphasizes portability and ease of storage, making it suitable for commuting, travel, and short-duration outdoor stays. While its airflow output and cooling effectiveness are comparatively limited, it offers advantages in compact size, low noise, and extended battery life. Consequently, it aligns well with everyday commuting scenarios that prioritize low physical and energy burden.

Table 2
Summary of key advantages, representative usage scenarios, and potential limitations of different mobile cooling device types.

Device type	Key dvantages	Representative usage scenarios	Potential limitations
Turbo type	High airflow pressure; rapid cooling response	Night markets, sports activities, outdoor high-temperature environments	High noise levels; battery endurance sensitive to airflow settings
Ice crystal type	Low noise; stable cooling performance	Offices, classrooms, and other static indoor environments	Requires water refilling; reduced operational convenience
Folding type	High portability; low energy consumption; flexible use	Commuting and travel	Lower airflow; limited cooling effectiveness
Hybrid (ice-crystal/folding)	Balanced functionality; adaptable across multiple contexts	Suitable for both static and dynamic scenarios	Increased weight and structural complexity

(4) Ice-crystal/folding hybrid type (functional integration and contextual flexibility): This hybrid design integrates evaporative cooling with a folding structure, offering multiple airflow settings, cooling functionality, and relatively low noise while maintaining good portability. It allows flexible switching between static environments (such as offices and classrooms) and dynamic contexts (such as commuting and outdoor activities). Among the four categories, this type most closely approximates a "multicontext applicable" design, balancing performance, comfort, and adaptability.

Overall, the four device categories exhibit clear differences in performance characteristics, energy consumption patterns, and contextual suitability. These distinctions provide a robust comparative basis for subsequent questionnaire-based UX measurement, AHP-based hierarchical weighting, and Fuzzy-TOPSIS–based integrated decision analysis.

3.2 Results of AHP weight analysis

In this study, the AHP was employed to construct the evaluation framework for mobile cooling devices. A panel of 15 experts with professional backgrounds in product design, thermal comfort, sustainable energy, and user experience was invited to perform pairwise comparison judgments. Individual judgments were aggregated using the geometric mean method to establish group consensus matrices. For each matrix, the maximum eigenvalue (λmax), *CI*, and *CR* were calculated to assess the internal consistency of expert evaluations. Consistency verification was conducted following Saaty's methodology, in which the consistency ratio was computed as CR = *CI*/*RI*.[11] As summarized in Table 3, the *CR* values of all four pairwise comparison matrices were below the threshold of 0.10, indicating the satisfactory consistency and statistical reliability of the expert judgments. These results confirm that the derived weights are robust and suitable for subsequent integration into the sensor-assisted multicriteria decision-making framework used in this study.

With respect to the dimension- and indicator-level weights, the overall AHP analysis shows that the weights assigned to the sensory attributes and sustainable design dimensions are 0.515

Table 3
Consistency test results of pairwise comparison matrices at different hierarchical levels.

Dimension/Factor	*λmax*	*CI*	*CR*	Consistency judgment
Sensory attribute dimension	4.046	0.015	0.017	Acceptable
Sustainable design dimension	3.007	0.004	0.006	Acceptable
Thermal sensation factor	3.000	0.000	0.000	Acceptable
Energy efficiency factor	3.002	0.001	0.002	Acceptable

and 0.485, respectively, indicating a near-balanced importance between the two. This result suggests that experts generally regard user experience and sustainability performance as equally important considerations, as shown in Table 4. From a sensing-oriented perspective, this balance also reflects the need to interpret sensor-derived performance data alongside human-centered responses when assessing real-world product effectiveness. Within the sensory dimension, thermal sensation emerged as the most influential factor, with a weight of 0.540. Among its sub-indicators, airflow velocity (subweight 0.420) and cooling coverage area (0.366) were identified as dominant decision drivers. These results highlight the strong dependence of perceived cooling performance on airflow-related characteristics that are closely associated with environmental sensing measurements, particularly wind speed and airflow distribution under different microclimatic conditions.

Within the sustainable design dimension, energy efficiency was assigned the highest weight (0.656), indicating that energy-related considerations play a decisive role in expert evaluation. In particular, the *EER* (0.393) and battery endurance (0.366) were emphasized as key indicators, underscoring the importance of sustained operation and low energy consumption in mobile cooling applications, especially under prolonged outdoor use captured by environmental sensing scenarios. When the weights were synthesized across all dimensions and indicators, energy efficiency ratio, airflow velocity, and battery endurance emerged as the three most influential criteria overall. These were followed by grip comfort and visual appearance semantics, suggesting that the market expectation for mobile cooling products extends beyond immediate cooling effectiveness to include long-duration usability, low energy demand, and ergonomic as well as perceptual quality. Together, these findings indicate that high-efficiency cooling performance, as quantified through sensor-assisted airflow and energy measurements, must be complemented by sustained endurance and favorable user experience to meet practical usage demands.

3.3 Descriptive statistics of sensory and sustainability evaluations

A total of 60 valid questionnaires were collected in this study. Male participants accounted for 53.3% of the sample, while female participants accounted for 45.0%, with the majority of respondents aged between 18 and 35 years (63.3%). In terms of usage frequency, most participants reported using mobile cooling devices on a daily or weekly basis (78.4% combined),

Table 4
AHP-derived weights for dimensions and indicators of mobile cooling products.

Dimension	Dimension weight	Factor	Factor weight	Sub-indicator	Sub-indicator weight	Composite weight
Sensory attributes	0.515	Thermal sensation	0.540	Airflow velocity	0.420	0.117
				Airflow direction angle	0.214	0.060
				Cooling coverage area	0.366	0.102
		Auditory	0.086	Noise level	0.568	0.025
				Sound quality	0.432	0.019
		Tactile	0.182	Grip comfort	0.548	0.051
				Surface temperature response	0.452	0.042
		Visual	0.192	Appearance semantics	0.577	0.057
				Color harmony satisfaction	0.423	0.042
Sustainable design	0.485	Energy efficiency	0.656	Power consumption	0.241	0.077
				EER	0.393	0.125
				Battery endurance	0.366	0.116
		Materials	0.172	Carbon footprint	0.502	0.042
				Recyclability	0.498	0.042
		Assembly and reuse	0.171	Degree of modularity	0.454	0.038
				Maintenance accessibility	0.546	0.045

indicating that such devices have become commonly adopted solutions in high-temperature environments. The primary usage contexts were commuting (31.7%) and exercise-related activities (21.7%), followed by travel, night markets, and office settings. Across the 16 evaluation indicators, the mean scores of the four tested device types generally ranged from 3.70 to 4.30, reflecting an overall positive user perception. Among these indicators, airflow velocity (Q1) and EER (Q11) received the highest average ratings, suggesting that cooling effectiveness and energy efficiency are the attributes of greatest concern to users. From a sensor-assisted perspective, this finding is consistent with the strong effects of airflow- and energy-related parameters that can be directly quantified through environmental sensing and device performance measurements. Detailed descriptive statistics for the four device types are presented in Table 5.

The integrated analysis reveals distinct performance profiles among the four device types. The turbo type demonstrates outstanding performance in airflow velocity (Q1) and energy efficiency ratio (Q11), but exhibits a high noise level; it is therefore best suited for high-heat, high-mobility scenarios such as night markets and outdoor sports. The ice crystal type records the lowest noise level (Q4) and the highest rating for appearance semantics (Q8), making it

Table 5
Descriptive statistics of sensory and sustainability evaluations for the four tested device types. Note: ratings were obtained using a five-point Likert scale (1 = very dissatisfied, 5 = very satisfied, Q indicates the questionnaire item numbered from "Q1 to Q16", and M and SD denote mean and standard deviation, respectively).

Item	Indicator	Turbo type M (*SD*)	Ice crystal type M (*SD*)	Folding type M (*SD*)	Hybrid type M (*SD*)	Description
Q1	Airflow velocity	4.35 (0.55)	4.21 (0.63)	4.18 (0.69)	4.27 (0.61)	Turbo type shows the highest airflow
Q2	Airflow direction angle	3.92 (0.72)	3.98 (0.70)	3.85 (0.74)	4.00 (0.66)	Comparable directional stability
Q3	Cooling coverage area	4.20 (0.60)	4.08 (0.68)	4.00 (0.70)	4.15 (0.65)	Broad cooling coverage
Q4	Noise level	3.75 (0.78)	3.90 (0.70)	3.88 (0.77)	3.83 (0.74)	Ice crystal type is the quietest
Q5	Sound quality	4.00 (0.66)	4.10 (0.69)	3.98 (0.70)	4.07 (0.65)	Smooth and pleasant acoustic quality
Q6	Grip comfort	4.28 (0.71)	4.18 (0.70)	4.12 (0.75)	4.20 (0.72)	Good operational comfort
Q7	Surface temperature response	3.88 (0.69)	3.94 (0.70)	3.80 (0.77)	3.90 (0.71)	Minimal heat buildup during prolonged use
Q8	Appearance semantics	4.15 (0.64)	4.23 (0.66)	4.10 (0.70)	4.22 (0.65)	High visual appeal
Q9	Color harmony satisfaction	4.05 (0.68)	4.12 (0.65)	4.00 (0.69)	4.08 (0.67)	Well-coordinated color schemes
Q10	Power consumption	3.72 (0.82)	3.80 (0.78)	3.70 (0.85)	3.78 (0.80)	Stable energy-saving performance
Q11	EER	4.30 (0.56)	4.18 (0.61)	4.10 (0.65)	4.22 (0.60)	Turbo type exhibits the highest efficiency
Q12	Battery endurance	4.12 (0.68)	4.15 (0.67)	4.05 (0.70)	4.10 (0.69)	Comparable endurance across devices
Q13	Carbon footprint	3.82 (0.77)	3.90 (0.72)	3.84 (0.75)	3.88 (0.74)	Moderate environmental awareness
Q14	Recyclability	3.95 (0.70)	4.00 (0.68)	3.90 (0.72)	3.96 (0.70)	Clear recyclability information
Q15	Degree of modularity	3.80 (0.73)	3.85 (0.70)	3.78 (0.75)	3.82 (0.72)	Moderately high structural rationality
Q16	Maintenance accessibility	3.88 (0.70)	3.92 (0.68)	3.85 (0.72)	3.90 (0.71)	Good maintenance convenience

particularly appropriate for quiet environments such as offices and classrooms. The folding type shows generally balanced but slightly lower scores across most indicators; its primary advantages lie in compact size, light weight, and favorable battery endurance, which align well with short-duration use cases such as commuting and travel. The ice-crystal/folding hybrid type achieves intermediate-to-high scores across most indicators, reflecting a balanced combination of cooling performance, low noise, and endurance, and is thus suitable for a wide range of everyday usage contexts.

3.4 Results of Fuzzy-TOPSIS multicriteria analysis

To integrate the evaluations of sensory attributes and sustainable design, we applied a Fuzzy-TOPSIS model that combines AHP-derived weights with TFNs to conduct multicriteria decision analysis for the four device types within a unified, sensor-assisted decision framework. Regarding the computational procedure, first, the five-point Likert-scale responses for indicators Q1–Q16 were transformed into corresponding TFNs to construct the fuzzy decision matrix. The dimension-, factor-, and indicator-level weights obtained by AHP analysis were then incorporated to form the weighted fuzzy decision matrix. Subsequently, the FPIS and FNIS were defined on the basis of the benefit or cost attributes of each indicator. The distances between each alternative and the FPIS and FNIS, denoted as D_i^+ and D_i^-, respectively, were calculated using fuzzy distance measures. Finally, the relative closeness coefficient, denoted as CC_i and expressed in Eq. (1), can be derived to quantify the proximity of each alternative to the ideal solution, providing the basis for the overall ranking of mobile cooling devices under combined sensory, sustainability, and context-aware (environmental sensing-informed) considerations. A larger CC_i value indicates that the corresponding alternative is closer to the ideal solution and therefore exhibits superior overall performance.

$$CC_i = \frac{D_i^-}{D_i^- + D_i^+} \tag{1}$$

The fuzzy distances and relative closeness coefficients of the four device types are summarized in Table 6. The results indicate that the ice-crystal/folding hybrid type achieved the highest relative closeness coefficient (CC_i = 0.913), ranking first among the evaluated alternatives. This outcome suggests that, when environmental sensing-informed performance measures and UX measurement results are jointly considered within the decision framework, the hybrid design most closely approximates the ideal solution. The ice crystal type ranked second with a CC_i value of 0.900, followed by the turbo type with CC_i = 0 .819. In contrast, the folding type exhibited a substantially lower relative closeness coefficient (CC_i = 0.438), indicating weaker overall performance across the combined sensory and sustainability criteria.

By comparing the Fuzzy-TOPSIS results with the AHP composite weights and descriptive statistics, it can be observed that indicators with higher weights—namely, airflow velocity (Q1),

Table 6
Fuzzy-TOPSIS results of fuzzy distances and relative closeness coefficients.

Device Type	D_i^+	D_i^-	CCi	Rank
Turbo type	0.047	0.213	0.819	3
Ice crystal type	0.032	0.288	0.900	2
Folding type	0.067	0.052	0.438	4
Ice-crystal/folding hybrid type	0.029	0.303	0.913	1

energy efficiency ratio (Q11), and battery endurance (Q12)—also correspond to the best-performing device types, specifically the ice-crystal/folding hybrid and ice crystal types, which rank first and second in the Fuzzy-TOPSIS analysis, as shown in Table 7. This consistency indicates a high level of agreement between expert-derived weights and users' subjective ratings. Moreover, the same three indicators exhibit the highest mean scores in the descriptive statistics, further confirming that the Fuzzy-TOPSIS model effectively captures users' actual perceptions and overall preferences. From a sensor-assisted perspective, this alignment suggests that the decision framework successfully integrates environmental-sensing-related performance measures with UX measurement, yielding rankings that are both data-driven and perceptually meaningful.

From the design implications derived by integrated Fuzzy-TOPSIS analysis, several important insights for mobile cooling product development can be identified. The results indicate that design balance is a critical determinant of overall product competitiveness. The ice-crystal/folding hybrid type, which achieved the highest ranking, demonstrates a well-balanced combination of airflow performance, low-noise operation, portability, and battery endurance. This finding suggests that achieving balanced performance across multiple dimensions is more advantageous than optimizing a single attribute to an extreme level, particularly when products are evaluated under sensor-informed, real-world usage conditions. In addition, sustainable design emerges as a key source of medium- to long-term competitive advantage. Although indicators related to modularity and maintenance accessibility were assigned slightly lower weights than core cooling and energy-efficiency metrics, they exert a substantial effect on product lifecycle performance, maintenance costs, and resource utilization efficiency.

From a design perspective, these attributes should therefore be regarded as strategic elements for brand differentiation and long-term sustainability rather than as secondary considerations. The analysis further demonstrates the decision-support value of methodological integration. AHP provides a structured mechanism for incorporating expert knowledge and establishing

Table 7
Comparative analysis of indicators based on AHP weights and Fuzzy-TOPSIS results.

Indicator	AHP composite weight	Representative factor	Best-performing device(s) in Fuzzy-TOPSIS	Consistency interpretation
Airflow velocity (Q1)	0.117	Thermal-sensation-driven	Turbo type; Hybrid type	Turbo type provides strong airflow pressure, while the hybrid type balances airflow intensity with stability
Energy efficiency ratio (Q11)	0.125	Sustainability-driven	Ice crystal type; Hybrid type	Most stable energy efficiency and optimal energy utilization
Battery endurance (Q12)	0.116	Extended energy performance	Hybrid type	Superior endurance across multiple usage contexts
Appearance semantics (Q8)	0.057	Visual design	Ice crystal type	Highest visual recognizability and design semantics
Degree of modularity (Q15)	0.038	Structural design	Hybrid	Improved disassembly convenience and maintenance accessibility

transparent criterion weights, while Fuzzy-TOPSIS captures users' subjective preferences and uncertainty through fuzzy linguistic representation. When integrated with environmental sensing data, the combined decision framework forms a transparent and traceable design-support system that bridges objective measurements and human-centered evaluation, enhancing the reliability and interpretability of design decisions.

3.5 Sensory ratings and contextual preference analysis

Here, we further examine the implications of sensory experience results by analyzing measurement reliability and validity, the relationship between sensory factors and emotional satisfaction, the impact of noise under quiet conditions, and preference ranking across different usage contexts. Reliability and validity testing was conducted for the four sensory dimensions—thermal sensation, auditory perception, tactile comfort, and visual evaluation—as well as for the overall scale. Cronbach's α-values ranged from 0.84 to 0.88 across individual dimensions, with an overall α-value of 0.93, indicating excellent internal consistency. The Kaiser–Meyer–Olkin (KMO) value reached 0.89, and Bartlett's test of sphericity was significant ($p < 0.001$). Exploratory factor analysis yielded a four-factor solution with a cumulative explained variance of approximately 72.4% and factor loadings predominantly between 0.60 and 0.82, strongly supporting the structural validity of the UX measurement instrument. The analysis of the relationship between sensory factors and emotional satisfaction revealed that tactile comfort (grip comfort) and perceived airflow cooling are the two primary determinants of emotional satisfaction. The standardized regression coefficients of these determinants were approximately 0.34 and 0.31, respectively, and both effects were statistically significant. Although sound quality and appearance semantics also exhibited positive associations with emotional satisfaction, their effect sizes were smaller, indicating that they function as secondary enhancement factors rather than primary drivers.

The effect of noise under quiet conditions was examined using a two-factor analysis of variance, revealing significant main effects of both usage context (quiet versus general) and noise level on overall preference, as well as a significant interaction between the two. In quiet environments such as classrooms and offices, user preference declined notably when noise levels exceeded approximately 45 dB(A), indicating that noise is a critical negative factor in these contexts and highlighting the importance of low-noise design, particularly when supported by sensor-based acoustic measurements. Preference rankings also varied significantly across usage contexts. Folding and hybrid types were favored in commuting and travel scenarios owing to their portability and endurance, while turbo and hybrid types were preferred in night market and sports settings where strong airflow is required under high thermal stress.

In office and classroom environments, ice crystal and hybrid types were more favorably rated because of their quieter operation and stable cooling performance. These results confirm that product preference is highly context-dependent and support the adoption of context-driven design strategies for mobile cooling devices. Overall, the sensory evaluation instrument demonstrated strong reliability and validity, consistently capturing user sensory experience. Tactile comfort and airflow-related cooling sensation were identified as the primary contributors to emotional satisfaction, whereas noise effects showed pronounced context sensitivity. By integrating AHP, Fuzzy-TOPSIS, and sensory evaluation with environmental sensing data, we established a quantifiable, context-driven evaluation framework, demonstrating that user preference arises from the combined effect of usage context, sensory experience, and sustainable design rather than any single performance attribute.

3.6 Design value of multidimensional integration

The AHP results reveal that the weights assigned to the sensory attributes (0.515) and sustainable design (0.485) dimensions are nearly equivalent. This close weighting indicates that while users seek strong airflow and immediate cooling sensations, they are simultaneously attentive to energy consumption, battery endurance, and environmental responsibility. Such results suggest that design evaluations focusing solely on isolated performance metrics—such as airflow intensity and noise level—are insufficient to capture the holistic structure of user experience. From a sensor-assisted evaluation perspective, this underscores the importance of jointly considering measurable physical parameters and perceptual responses when assessing real-world product effectiveness. The results of Fuzzy-TOPSIS analysis further confirm that the highest-ranked devices tend to exhibit a balanced performance profile, simultaneously achieving favorable airflow, endurance, energy efficiency, and noise control. This outcome is consistent with the psychological concept of the context effect, which posits that user judgments are shaped by task demands, situational constraints, and individual perception rather than by absolute parameter values alone. Consequently, product evaluation and optimization must account for contextual requirements and usage variability instead of relying exclusively on a single engineering indicator derived from laboratory testing.

3.7 Necessity of context-driven design

The results clearly indicate that user preference rankings vary significantly across different usage contexts. Devices characterized by strong airflow output are favored in high-heat and high-activity environments such as night markets, outdoor spaces, and sports settings. In contrast, devices offering stable airflow and low acoustic output are preferred in quiet environments such as offices and classrooms. Folding-type designs demonstrate advantages in mobile scenarios such as commuting and travel, where portability and battery endurance are critical. Among the evaluated prototypes, the hybrid-type design exhibits the most balanced performance across contexts, combining moderate airflow, acceptable noise levels, and reliable endurance. These findings suggest that product design should not pursue a single "optimal" solution applicable to all situations. Instead, differentiated contextual design strategies should be adopted, aligning specific performance priorities with the dominant demands of target usage environments. Context-driven design, supported by environmental sensing data, enables designers to identify core requirements in different scenarios—for example, high airflow pressure in outdoor settings, acoustic comfort and visual semantics in quiet environments, and weight optimization with extended battery life in mobile scenarios.

3.8 Theoretical and methodological contributions of the integrated framework

One of the principal contributions of this study lies in the development of an integrated design decision framework that combines AHP for structured weighting, Fuzzy-TOPSIS for handling uncertainty and linguistic ambiguity, and sensory evaluation for capturing experiential responses. This framework effectively bridges the gap between objective engineering parameters and subjective user experience, allowing product design decisions to be both scientifically grounded and human-centered. Within this framework, AHP establishes a hierarchical decision structure spanning dimensions, factors, and indicators, thereby clarifying the relative importance of evaluation criteria. Fuzzy-TOPSIS captures the inherent uncertainty in subjective ratings by modeling linguistic assessments as fuzzy numbers, while sensory evaluation reflects users' actual perceptual preferences under sensor-measured environmental conditions. The integration of these components enables the simultaneous consideration of functional performance, sensory experience, and sustainability value. Importantly, the proposed framework is replicable and extensible, making it applicable to a broad range of climate-adaptive products beyond mobile cooling devices, including wearable cooling systems, fan-integrated backpacks, and portable air-conditioning solutions. By combining environmental sensing with multicriteria decision analysis and sensory evaluation, we provide a systematic and transferable methodology for context-aware product design and evaluation in increasingly complex thermal environments.

4. Conclusions

We proposed a context-driven product design evaluation model that integrates the AHP, Fuzzy-TOPSIS, and sensory rating data, and applied it to mobile cooling devices as an empirical case. By jointly considering usage context, sensory attributes, and sustainability indicators, the proposed framework enabled a quantitative and systematic assessment of product preference under real-world conditions informed by environmental sensing. The results showed that the weights of sensory attributes and sustainable design were nearly equivalent, indicating that users simultaneously pursue immediate cooling comfort and longer-term concerns such as energy efficiency, battery endurance, and environmental impact. This finding suggested that evaluations focusing on a single performance metric are insufficient to capture the holistic structure of user experience. The Fuzzy-TOPSIS ranking results (hybrid type > ice crystal type > turbo type > folding type) were consistent with descriptive statistics, confirming the internal consistency and predictive validity of the proposed model. Further analysis revealed that tactile comfort and perceived airflow cooling were the primary drivers of emotional satisfaction, while noise became a strong negative factor in quiet environments such as offices and classrooms.

Moreover, user preference rankings vary significantly across different usage contexts, demonstrating that product performance and acceptance are highly context-dependent. These findings provide strong empirical support for context-driven design strategies and highlight their importance for market differentiation and targeted product development. From a methodological perspective, this study bridges the gap between objective engineering parameters and subjective user perception by combining structured expert weighting, fuzzy multicriteria decision analysis, and sensory evaluation. The proposed framework is reproducible and extensible, and can be applied to other climate-adaptive products beyond mobile cooling devices. In future research, this work may be extended by increasing sample size and conducting cross-cultural comparisons, integrating physiological signals such as skin temperature and heart rate variability to validate perceptual responses, and incorporating IoT sensors and AI-based adaptive control to develop next-generation intelligent cooling products capable of dynamically responding to environmental and user conditions.

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