

Article

Summer Outdoor Thermal Comfort of Lung Cancer Patients: Differences by Treatment Modality and Disease Stage

Zihao Qin ¹, Xinke Wu ¹, Yufan Dai ¹, Xinyu Tan ¹, Houxiang Wang ¹, Weijie Xia ² and Meng Zhen ^{3,*}

¹ Department of Architecture, XJTU-POLIMI Joint School, Xi'an Jiaotong University, Xi'an 710049, China; qin_polimi_arch@stu.xjtu.edu.cn (Z.Q.); keke802170@stu.xjtu.edu.cn (X.W.); xajd22yx@stu.xjtu.edu.cn (Y.D.); 13368096018@stu.xjtu.edu.cn (X.T.); houxiangwang@stu.xjtu.edu.cn (H.W.)

² Department of Architecture, School of Design, Shanghai Jiao Tong University, Shanghai 200240, China; xwj2023207404@hebiace.edu.cn

³ School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an 710049, China

* Correspondence: zhenmeng@xjtu.edu.cn

Abstract

Outdoor thermal comfort models are generally developed for healthy populations and may not be directly applicable to patients with altered thermoregulatory capacity. This study examined summer outdoor thermal responses of lung cancer patients in Shenyang, China, focusing on differences by treatment modality and disease stage. Field microclimatic measurements and questionnaire surveys were conducted in four typical outdoor microenvironments: waterfront place, tree-shaded space, open square, and enclosed porch. A total of 706 lung cancer patients were surveyed and stratified by treatment modality and disease stage. Physiologically equivalent temperature (PET) was calculated using RayMan Pro based on measured air temperature, mean radiant temperature, air velocity, relative humidity, clothing insulation, and activity-based metabolic rate. Subgroup differences were observed in neutral PET and thermal comfort ranges. Chemotherapy patients had the highest neutral PET at 26.0 °C, while immunotherapy patients had the lowest at 22.6 °C. Radiotherapy, surgery, and targeted therapy groups showed neutral PET values of 23.3 °C, 23.7 °C, and 24.5 °C, respectively. Early-stage patients had a neutral PET of 23.8 °C, whereas late-stage patients showed a higher value of 25.8 °C and a narrower neutral range of 23.1–28.5 °C. The surgery group had a broad acceptable PET range of 20.5–28.6 °C, while the late-stage group had a narrower range of 24.7–26.8 °C. Preferred temperature was also higher in the chemotherapy and late-stage groups. These findings indicate heterogeneous summer outdoor thermal responses among lung cancer patients and provide empirical evidence for subgroup-sensitive thermal assessment and outdoor space design near healthcare facilities.

Keywords: lung cancer; outdoor thermal comfort; physiologically equivalent temperature; thermal preference



Academic Editor: Antonio Caggiano

Received: 16 April 2026

Revised: 25 May 2026

Accepted: 27 May 2026

Published: 1 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

1.1. Research Background and Clinical Urgency

Driven by population aging and industrialization, lung cancer has become one of the leading causes of cancer-related mortality worldwide [1,2]. Epidemiological evidence indicates that Northeast China, particularly Shenyang, has remained a high-incidence hotspot for lung cancer because of its long-term industrial emission background and high smoking prevalence [3,4]. For this large population of patients with respiratory malignancies,

treatment is no longer confined to clinical intervention in operating rooms and wards. The outdoor microclimate of healthcare buildings is increasingly regarded as a relevant component of the healing environment [5]. Clinical evidence has shown that appropriate outdoor exposure may alleviate postoperative ventilatory dysfunction and cancer-related fatigue in lung cancer patients through improved oxygenation, circadian regulation, and biophilic effects [6,7]. Chemotherapy, radiotherapy, surgery, immunotherapy, and targeted therapy are common treatment modalities in lung cancer care. These treatments may affect thermal perception and adaptive capacity through different clinical pathways, such as peripheral neuropathy, radiation-induced skin sensitivity, immune-related inflammatory reactions, dermatologic toxicity, and postoperative changes in pulmonary function or physical activity. Disease stage may also modify thermal response. According to the TNM staging framework, early- and late-stage lung cancer reflect different degrees of tumor progression and systemic involvement [8]. Late-stage patients often experience greater symptom burden, fatigue, dyspnoea, and reduced exercise capacity, which may lower their tolerance to outdoor heat, humidity, and airflow variation [9]. Therefore, treatment modality and disease stage were used as clinically relevant stratification variables in this study.

Shenyang is located in a severe cold-climate zone, but its summer outdoor environment can still impose considerable heat stress because of elevated air temperature, humidity, and solar exposure. Such conditions may be particularly relevant for patients with impaired pulmonary function [10]. Inappropriately designed outdoor thermal environments may induce respiratory distress or heat stress and may hinder recovery [11]. Establishing a thermal comfort benchmark for a specific pathological population under local climatic conditions is therefore relevant to the improvement of regional cancer care services [12].

1.2. Literature Review

Lung cancer patients represent an important subgroup of patients with respiratory malignancies, and their thermal comfort requirements may differ from those of the general population. Previous studies have established a general framework for thermal comfort assessment based on field measurements and subjective surveys, with the PMV–PPD model remaining a common reference [13,14]. At the same time, indices developed for complex environments, such as PET and UTCI, have been increasingly examined and applied in recent years, particularly in outdoor microclimate studies [15,16]. However, existing studies on thermal comfort in healthcare buildings have mainly focused on indoor environmental control, PMV/PPD-based assessment, and general occupant satisfaction in wards or treatment spaces, while patient-specific differences related to health status, disease condition, or treatment modality have received comparatively limited attention [16].

In hospital indoor environments, empirical studies have shown that the standard PMV model has limited applicability to patient groups. Yau and Chew reported that PMV predictions were broadly consistent with trends in thermal sensation vote (TSV), but systematic deviations remained, with actual dissatisfaction exceeding PPD estimates, particularly during periods of high summer heat load [17]. Pourshaghagh and Omidvari further showed that, under naturally ventilated conditions, hospital wards with PMV values above +1 at midday in summer were associated with clearly elevated dissatisfaction and deviated from the comfort zone recommended by ASHRAE [18]. These studies indicate that patient thermal comfort remains temporally and spatially heterogeneous even under controlled indoor conditions [15–17].

Recent studies have also examined differences in thermal response between patients and healthy populations. Although dedicated thermal comfort datasets for cancer patients are still scarce, existing evidence suggests that vulnerable groups show greater thermal sensitivity than healthy adults, partly because of differences in behavior, rest patterns,

and adaptive capacity. Guan et al., 2024., reported that subjective thermal evaluations in hospital populations were more widely distributed and that the neutral range showed greater variation, suggesting that thermal perception in patient groups differs from that of the general adult population [15]. Other field studies have shown that subjects with different health conditions, such as older adults and patient groups, may have different thermal thresholds. For example, older adults in outdoor environments showed greater heat sensitivity than younger subjects, and their neutral thermal indices were systematically shifted [18,19].

From the perspective of model applicability, several studies have reported larger PMV prediction errors in hospital environments than in other building types. In these studies, the mean error between PMV and actual TSV was generally above 0.5, and PPD tended to underestimate actual dissatisfaction. This indicates that physiological assumptions derived from healthy adults, including a standard metabolic rate of 1.0–1.2 met, may not be suitable for patient groups [15,17,20].

Thermal comfort is fundamentally governed by the human heat balance equation, shown in Equation (1):

$$M - W = E + C + R + S \quad (1)$$

where M is metabolic heat production, W is mechanical work, E is evaporative heat loss, C is convective heat exchange, R is radiative heat exchange, and S is body heat storage. PMV, PET, and UTCI can all be understood as simplified or empirical representations of this balance [13].

In outdoor environments, mean radiant temperature (T_{mrt}) has been identified as one of the dominant determinants of thermal sensation. For example, a recent field study reported that a 10 °C increase in T_{mrt} was associated with an increase of about 0.9 in TSV [21,22]. Another recent field study reported clear variation in neutral PET (NPET) across different microenvironments, reflecting the strong effect of urban spatial conditions on thermal comfort [22].

Summer field studies in China have further shown that when air temperature reaches 28–32 °C under strong solar exposure, average thermal sensation commonly shifts toward “slightly warm” or “warm,” with high dissatisfaction rates. Increased wind speed can reduce equivalent temperature, including PET or UTCI, and improve thermal sensation [23,24]. These findings identify radiation and airflow as key determinants of outdoor thermal comfort. Case studies in urban environments have also shown that surface heat accumulation at midday can raise T_{mrt} well above air temperature, making the outdoor thermal environment strongly radiation-driven [25]. Also, the effect of thermal exposure on respiratory function provides indirect evidence relevant to patient populations. Experimental studies with healthy subjects have shown that each one-step increase in thermal sensation, for example, a shift from moderate-temperature to high-temperature exposure, can be accompanied by measurable decreases in pulmonary function indices, particularly forced expiratory volume in one second (FEV_1) and the FEV_1 /FVC ratio [26].

Direct evidence on thermal comfort in cancer patients remains limited, but available studies indicate that vulnerable groups show substantial variation in neutral range and behavioral adjustment. In a 2025 study of gynecological tumor patients and their accompanying family members, the temperature corresponding to the most comfortable condition was reported as 32.2 °C for patients ($TCV = -0.16$) and 25.6 °C for family members ($TCV = 0.15$) [27]. Sun et al., 2025. reported in 2025 that orthopedic patients were more sensitive to thermal changes, with a neutral SET^* of 17.7 °C compared with 21.7 °C in healthy individuals [28]. A study conducted in a comparable climate zone found that older adults had an outdoor neutral UTCI of 16.1 °C and a preferred UTCI of 24.3 °C [29]. Guan et al., 2024, [15] further argued that broader investigation across different climate zones in

China is needed to support the development of individualized thermal comfort strategies. Studies in high-density urban environments have also shown that street canyon geometry can substantially increase T_{mrt} at midday, with values in high H/W streets often exceeding 50 °C, thereby increasing thermal discomfort [21].

1.3. Research Objectives

In response to the gaps identified above, this study aims to establish an outdoor thermal comfort benchmark for lung cancer patients under summer conditions through high-resolution field measurements and on-site subjective assessment. The study has two primary objectives and one secondary objective. The first primary objective is to evaluate outdoor thermal comfort responses among lung cancer patients by measuring and comparing thermal sensation vote (TSV), thermal acceptability vote (TAV), and neutral PET across four outdoor microenvironments in summer. The second primary objective is to examine whether these thermal responses differ by treatment modality and disease stage, and to analyze the effects of key microclimatic variables, including air temperature, relative humidity, wind speed, and mean radiant temperature (T_{mrt}). As a secondary objective, this study further proposes evidence-based urban microclimate modification and spatial design strategies to support the improvement of outdoor thermal comfort for lung cancer patients.

2. Methodology

2.1. Study Site

Shenyang is located in northeastern China, extending from 41°11'51" N to 43°02'13" N and from 122°25'09" E to 124°48'24" E. The city has a temperate semi-humid continental monsoon climate. Although it is classified as a cold-region city, summer is characterized by substantial fluctuations in thermal conditions and by combined heat–humidity exposure [30]. Meteorological records indicate that the mean maximum temperature in July reaches approximately 30.5 °C, with an average relative humidity of about 75%. The monthly average temperature in Shenyang is shown in Figure 1. In addition, short-duration heavy rainfall and thunderstorms frequently occur in the afternoon during summer. Together with the intensification of the urban heat island effect, these conditions can produce a hot and humid outdoor environment. Such exposure may be particularly relevant for lung cancer patients, whose respiratory sensitivity and impaired pulmonary function may increase their vulnerability to outdoor thermal stress [10,31].

The positions of the test sites are shown in Figure 2. This study was conducted across four representative outdoor microenvironments: waterfront place (WP), tree-shaded area (TS), open square area (OS), and enclosed porch zone (EP), with details in Figure 3. They are located within or adjacent to the hospital outdoor activity area and are connected with major treatment, waiting, and circulation routes. During the field survey, lung cancer patients were observed using these spaces for short-term waiting, walking, resting, and communication with accompanying family members. Participants were recruited only when they were actually present in these spaces and had stayed there long enough to perceive the local thermal environment. Also, these sites can reflect the diversity of thermal conditions encountered by lung cancer patients during routine outdoor activities in summer, thereby ensuring ecological validity [32]. During the hottest period of summer (10:00–16:00 local time), on-site microclimate measurements were taken, including air temperature, relative humidity, wind speed, globe temperature, and shortwave solar radiation. They were synchronously recorded at each site [33]. To reduce the potential influence of short-term thermal adaptive behaviors on subjective thermal responses, the field survey followed a standardized procedure. Participants were interviewed only after they had stayed in the selected outdoor space for a period of time sufficient for perceiving the local

thermal environment. Concurrently, standardized thermal sensation and comfort questionnaires were administered to lung cancer patients to quantitatively assess how variations in shading configuration and how surface characteristics influence their subjective thermal perception and comfort responses [34].

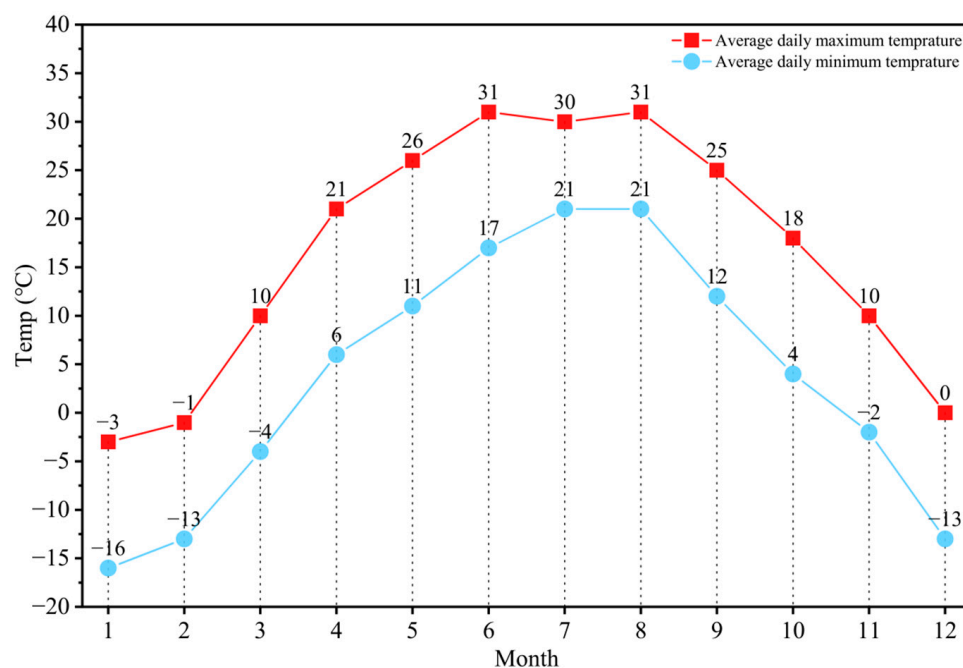


Figure 1. Monthly average temperature in Shenyang.

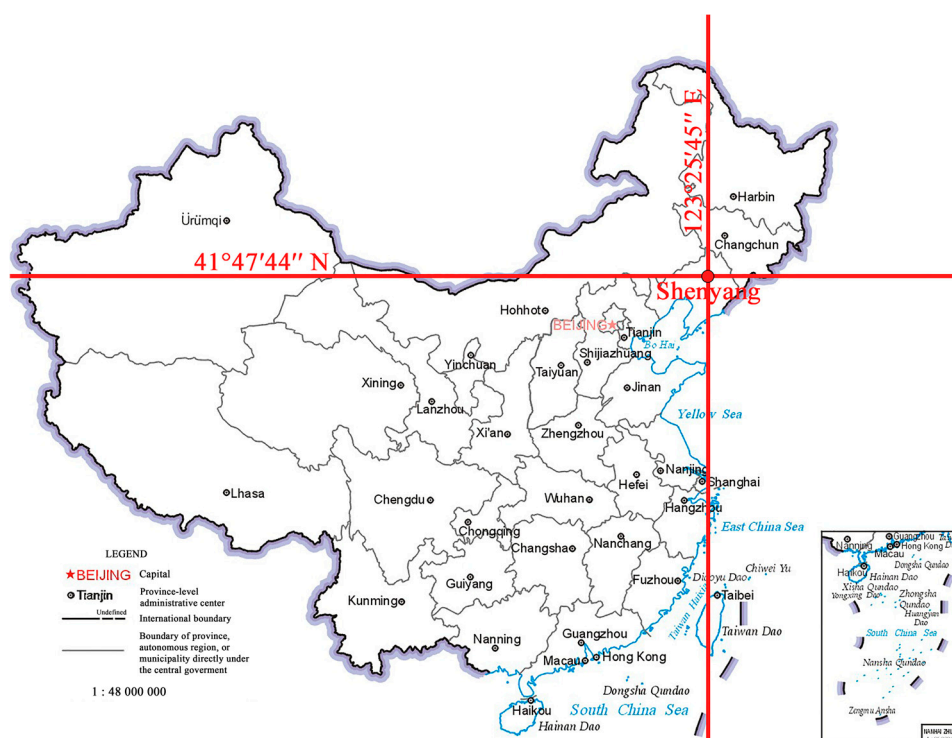


Figure 2. Cont.



Figure 2. The relative position of the test site.

(A)



Figure 3. Cont.

(B)

(a) Waterfront place.



Large water body moderates temperature (cooler summers, milder winters); high humidity from evaporation; localized land–lake breezes.

(b) Tree shade space.



Dense foliage blocks direct solar radiation; evapotranspiration from leaves lowers air temperature and raises humidity; calm, stable conditions.

(c) Open square.



Unshaded, maximum solar exposure; surfaces absorb heat, causing high daytime temperatures; good wind flow but very low humidity

(d) Enclosed porch.



Structure provides shade, blocking direct sun; open sides allow wind through; no evapotranspiration, so humidity remains low; cooler than open plaza but warmer and drier than under trees

Figure 3. (A) Four outdoor measurement zones. (B) Four outdoor measurement zones (fish-eye lens).

2.2. Microclimatic Measurements

Microclimatic parameters were measured simultaneously with the questionnaire survey using portable environmental monitoring instruments. Air temperature and relative humidity were measured using the temperature–humidity sensor of a JT2020 thermal comfort meter, with measurement ranges of -20 – 125 °C and 0–100% RH and accuracies

of ± 0.5 °C and $\pm 3\%$ RH, respectively. Wind speed was recorded using a JT2020 omnidirectional wind speed sensor, with a measurement range of 0.05–5 m/s and an accuracy of ± 0.05 m/s. Black globe temperature was measured using a JT2020 black globe temperature sensor, with a measurement range of -20 – 85 °C and an accuracy of ± 0.5 °C. Global horizontal irradiance was measured using a Kipp & Zonen CMP3 pyranometer, which has a maximum irradiance range of 2000 W/m². Details of the instruments are shown in Table 1.

Table 1. The characteristics of the instruments.

Meteorological Parameter	Units	Type	Accuracy	Range	Resolution
Air Temperature	°C	JT2020 Thermal comfort meter (temperature and humidity sensor)	-20 – 125 °C	± 0.5 °C	0.1 °C
Relative Humidity	%		0 – 100%	$\pm 3\%$	0.1%
Wind Speed	m/s	JT2020 Omnidirectional wind speed sensor	0.05 – 5 m/s	± 0.05 m/s	0.01 m/s
Black Globe Temperature	°C	JT2020 Black ball temperature sensor	-20 – 85 °C	± 0.5 °C	0.1 °C
Global Horizontal Irradiance	W/m ²	Kipp & Zonen CMP3 pyranometer	1% /year	0 – 2000 W/m ²	1 W/m ²

2.3. Questionnaire Survey

We integrated the environmental monitoring and questionnaire surveys. Physical parameters, participant characteristics, and thermal perception data were collected simultaneously [35]. Fieldwork took place from July to August 2025, covering the typical high-temperature period of the Shenyang summer. Participants were recruited from four outdoor microenvironments at the First Hospital of China Medical University and Shengjing Hospital: water place (WP), tree shade (TS), open square (OS), and enclosed porch (EP). Participants were recruited through field-based convenience sampling with eligibility screening. Lung cancer patients who were present in the selected outdoor spaces during the survey were invited to participate. Eligible participants were clinically diagnosed with lung cancer, able to complete the questionnaire, had stayed outdoors long enough to perceive the local thermal environment, and provided informed consent. Patients who had just left an air-conditioned indoor space, had recently engaged in intense physical activity, or could not provide valid thermal comfort responses were excluded. Surveys were reviewed by the Ethics Committee; the exemption approval number is [2025-KY-129-01]. Informed consent was obtained from all participants before the questionnaire survey.

The questionnaire consisted of three sections. The primary section collected demographic information, including gender, age, occupation, education, length of residency in the local climate zone, and real-time clothing insulation (Clo) estimations. The second section recorded clinical characteristics based on medical histories, encompassing disease staging, diagnosis time, and dominant treatment modality (surgery, chemotherapy, radiotherapy, targeted therapy, or immunotherapy).

The third section comprised the subjective evaluation of the immediate outdoor microenvironment. The assessment system included the thermal sensation vote (TSV), thermal comfort vote (TCV), thermal acceptability vote (TAV), and environment satisfaction vote (ESV), as well as preference votes for temperature (TPV), humidity (HPV), and wind speed (WPV). TAV was evaluated using a binary classification scale, while all other indices employed continuous or categorical scales. TSV followed the ASHRAE seven-point standard scale, ranging from “cold” (-3) to “hot” ($+3$) [13,14], and TCV utilized a corresponding seven-point scale [36], details are shown in Table 2.

Table 2. Subjective perception evaluation scales.

Rating	−3	−2	−1	0	1	2	3
TSV	Very cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Very hot
TCV	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Comfortable	Very comfortable
Rating	−1			0		1	
TPV	Cooler			Unchanged		Hotter	
WPV	Smaller			Unchanged		Larger	
HPV	Smaller			Unchanged		Larger	
Rating	−1					1	
TAV	Unacceptable					Acceptable	

2.4. Selection of Thermal Index

Physiologically equivalent temperature (PET) was used as the main index for evaluating physiological adaptation of lung cancer patients to thermal comfort under complex outdoor settings [37]; PET is based on the Munich Energy-balance Model for Individuals (MEMI), which can convert the thermal environment into a single temperature value and can also convert the temperature, humidity, and wind speed of multiple points into a single temperature value (°C) [37]. PET can also reflect the influence of individual factors, including metabolism, clothing insulation, and so on, and can describe the physical index of the heat exchange period (convection, radiation, and volatilization) [38].

PET was selected as the primary thermal index because it is consistent with the aim of this study, which was to examine the thermal perception of lung cancer patients under different outdoor microclimatic conditions. The selected spaces showed clear differences in wind speed, humidity, and radiation exposure due to variations in surface materials, spatial enclosure, and shading conditions. Therefore, a single-parameter index cannot adequately represent the combined thermal effect of these environments [39]. PET is based on the human energy balance model and integrates air temperature, mean radiant temperature, air velocity, and relative humidity. It also allows clothing insulation and metabolic rate, which were recorded during the questionnaire survey, to be included in the calculation. Compared with HI and WBGT, PET provides a more comprehensive assessment of outdoor thermal exposure. Although UTCI is also widely used, PET was considered more suitable for this study because it can directly incorporate the individual clothing and activity information of lung cancer patients [32].

PET was calculated using RayMan Pro based on measured air temperature, relative humidity, air velocity, and mean radiant temperature. Individual clothing insulation was estimated from the clothing items reported by each participant according to ASHRAE Standard 55 [14]. Metabolic rate was assigned according to the activity state reported during the survey, following ISO 7730 [20].

2.5. Investigative Process

Microclimatic measurements were conducted at the four selected outdoor locations simultaneously with the questionnaire survey. Air temperature (T_a), relative humidity (RH), air velocity (V_a), globe temperature (T_g), and global horizontal irradiance (GHI) were recorded at a height of 1.5 m above the ground, corresponding approximately to the center of gravity of a standing person. The measurement procedure followed ISO 7726 for thermal environment measurements, while GHI was measured using an ISO 9060:2018 Class C pyranometer. The field measurement protocol was also designed with reference to ASHRAE Standard 55 [14,40].

Mean radiant temperature (T_{mrt}) was not measured directly but derived from the measured variables. In this study, T_{mrt} was calculated following the ISO 7726 standard [40]

using T_g , T_a , and V_a . T_{mrt} represents the radiative environment to which the human body is exposed. The ground surface contributes substantially to long-wave radiation exchange in outdoor settings, and its influence, conditional on surface material and solar exposure, is captured through the globe temperature measurement, as shown in Equation (2) [40]:

$$T_{mrt} = (T_g + 273)^4 + \frac{1.10 \times 10^8 V_a^{0.6}}{\epsilon D^{0.4}} (T_g - T_a)^{-\frac{1}{4}} - 273 \quad (2)$$

where D is the diameter of the globe (in this study, $D = 0.05$ m), and ϵ is the emissivity (for a black globe, $\epsilon = 0.95$).

2.6. Statistical Analysis

Data processing and statistical analysis were conducted using Microsoft Excel 2021, IBM SPSS Statistics 26.0, and Originpro 2021. Descriptive statistics were first used to summarize participant characteristics, questionnaire responses, and microclimatic parameters. Linear regression was applied to determine neutral PET (NPET) from the relationship between mean thermal sensation vote (MTSV) and PET. Quadratic regression was used to identify the PET corresponding to the maximum mean thermal comfort vote (MTCV) and the associated comfort range. Preferred temperature (T_{pref}) was derived using a binary logistic regression model based on thermal preference votes (TPV). In this procedure, “no change” responses were redistributed into the “prefer warmer” and “prefer cooler” categories following the equiprobable principle. Correlation analysis was used to examine the associations between physical environmental variables and subjective responses. Statistical significance was evaluated at $p < 0.05$. Pearson or Spearman correlation coefficients were selected according to data distribution.

3. Results

3.1. Descriptive Analysis

3.1.1. Meteorological Parameters of Survey Areas

The measurements were conducted from 20 July to 20 August 2025 in four outdoor microenvironments and were conducted from 10:00 to 1600 on sunny or partly cloudy days to ensure sufficient solar exposure. Compared with the other spaces, the tree-shaded space (TS) and enclosed porch (EP) showed lower air temperature (T_a), global horizontal irradiance (GHI), and globe temperature (T_g). In TS, the tree canopy reduced direct solar radiation, while plant transpiration and the natural ground surface further limited heat accumulation. The natural surface also had lower heat storage capacity than artificial paving. However, dense vegetation could partly obstruct airflow. As a result, TS recorded relatively low air velocity (V_a), depending on vegetation density.

The open square (OS) lacked shading and was surfaced with high-thermal-admittance artificial pavement; we recorded the highest T_a , T_g , and V_a , GHI alongside the lowest RH. The water proximity (WP) zone registered the highest RH, driven by evaporation from the adjacent water body under summer insolation. Enclosed porch (EP) recorded intermediate values across all parameters. Table 3 below summarizes average meteorological parameters and instrumentation details for each sampling site.

Table 3. Climate parameters.

Place	Climate Parameters in Different Measurement Area									
	Ta			RH			Va		Tg	
	Average	Min	Max	Average	Min	Max	Average	Max	Min	Average
Tree shade(TS)	29.4 °C	25.7 °C	33.7 °C	68%	65%	63%	1.1 m/s	2.6 m/s	0.2 m/s	33.3 °C
Open square(OS)	32.7 °C	27.3 °C	36.6 °C	57%	38%	69%	3 m/s	6.5 m/s	1.1 m/s	45.0 °C
Waterfront place (WP)	29.6 °C	24.4 °C	33.0 °C	78%	74%	82%	2 m/s	3.4 m/s	0.9 m/s	32.9 °C
Enclosed porch(EP)	30.2 °C	27.5 °C	34.2 °C	65%	61%	69%	1.8 m/s	2.4 m/s	1.0 m/s	34.8 °C

3.1.2. Participant Demographics

We recruited 706 lung cancer patients for outdoor surveys. Eligible participants were identified with the assistance of hospital staff based on clinical diagnosis records. A two-tier stratification scheme was applied to account for differences in treatment exposure and disease stage.

Patients were grouped according to the dominant treatment received within the previous three months: chemotherapy (CHE), radiotherapy (RAD), targeted therapy (TAR), immunotherapy (IMU), and surgery (OPR). This grouping was used to distinguish differences in activity level, outdoor exposure, and adaptive behavior, which may affect thermal perception under outdoor conditions.

Disease stage was classified based on the AJCC TNM framework (8th edition). Patients with stage I–II non-small-cell lung cancer or limited-stage small-cell lung cancer were defined as early-stage (ES). Patients with stage III–IV non-small-cell lung cancer or extensive-stage small cell lung cancer were defined as late-stage (LS). This classification reflects differences in mobility and environmental exposure, which are relevant to field-based thermal comfort assessment.

The above groupings were used to compare thermal sensation, neutral temperature, and acceptable ranges across subgroups. Analysis focused on relationships between individual condition and environmental variables, including air temperature, wind speed, and mean radiant temperature.

A total of 706 questionnaires were collected to assess the high productivity assessment rate, classified by treatment research methods: there were 132 cases of radiotherapy, 137 cases of chemotherapy, 231 cases of surgery, 120 cases of targeted therapy, and 86 cases of immunotherapy; the age of patients varied between 26 and 87 years old. There are 439 males in the sample, compared to 267 females. Table 4 provides a complete breakdown for each subgroup.

Table 4. Disease classification.

Classification	Introduction	Number of Questionnaires	Age Ranges	Number in Different Sites
Radiotherapy group (RAD)	Utilizes high-energy radiation (e.g., X-rays or proton beams) focused on the tumor site to induce DNA damage and apoptosis in malignant cells, serving as a critical modality for local control.	Male: 82 Female: 50	Under 35 (2 cases) 35–50 (14 cases) 50–70 (71 cases) Over 70 (45 cases)	WP: 31 TS: 40 OS: 25 EP: 36
Chemotherapy group (CHE)	Employs cytotoxic agents to systemically eradicate rapidly proliferating cancer cells (including metastases) by interfering with DNA synthesis or inhibiting mitosis, functioning as a primary systemic therapy.	Male: 98 Female: 39	Under 35 (3 cases) 35–50 (19 cases) 50–70 (85 cases) Over 70 (30 cases)	WP: 35 TS: 34 OS: 29 EP: 39

Table 4. Cont.

Classification	Introduction	Number of Questionnaires	Age Ranges	Number in Different Sites
Surgery group (OPR)	Involves the surgical resection of the primary tumor and regional lymph nodes en bloc. This remains the cornerstone approach for achieving accurate pathological staging and local curative intent.	Male: 126 Female: 105	Under 35 (27 cases) 35–50 (42 cases) 50–70 (126 cases) Over 70 (36 cases)	WP: 54 TS: 63 OS: 46 EP: 68
Immunotherapy group (IMU)	Restores the host immune system's capacity to recognize and eliminate malignant cells by overcoming immunosuppression within the tumor microenvironment (e.g., via PD-1/PD-L1 inhibitors) or enhancing effector cell activity (e.g., CAR-T therapy).	Male: 58 Female: 28	Under 35 (0 cases) 35–50 (9 cases) 50–70 (48 cases) Over 70 (29 cases)	WP: 19 TS: 25 OS: 18 EP: 24
Targeted therapy group (TAR)	Delivers precise inhibition against specific oncogenic driver mutations or aberrant signaling pathways (e.g., EGFR, ALK) utilizing small-molecule inhibitors or monoclonal antibodies, characterized by high biological specificity.	Male: 75 Female: 45	Under 35 (12 cases) 35–50 (22 cases) 50–70 (56 cases) Over 70 (30 cases)	WP: 33 TS: 27 OS: 27 EP: 33
Early-stage group (ES)	Refers to localized primary tumors with no or limited regional lymph node involvement and absence of distant metastasis. Biologically characterized by local growth, this stage is highly amenable to curative modalities such as surgery or radiotherapy.	Male: 153 Female: 165	Under 35 (29 cases) 35–50 (51 cases) 50–70 (163 cases) Over 70 (75 cases)	WP: 81 TS: 77 OS: 72 EP: 80
Late-stage group (LS)	Indicates the presence of distant organ metastasis or non-regional lymph node involvement. Characterized by systemic dissemination, the therapeutic objective shifts toward long-term disease control and quality of life improvement, primarily managed through systemic pharmacotherapies (chemotherapy, targeted therapy, or immunotherapy).	Male: 286 Female: 102	Under 35 (14 cases) 35–50 (58 cases) 50–70 (223 cases) Over 70 (93 cases)	WP: 91 TS: 112 OS: 73 EP: 120

3.1.3. Distribution Characteristics of Thermal Sensation and Thermal Comfort

In the comparison of different treatment groups, distinct differences in thermal sensation voting (TSV) were observed. Among radiotherapy patients (RAD), the highest proportion of votes occurred at “slightly warm” (TSV = +1), accounting for 33%. For chemotherapy patients (CHE), the votes tended toward “neutral” (TSV = 0), accounting for 26%. However, 35% of CHE patients reported “slightly uncomfortable” (TCV = −1). Surgery (OPR) and immunotherapy (IMU) groups exhibited a similar pattern, with the highest proportion of votes at “slightly warm” (TSV = +1), accounting for 29% and 32%, respectively. In addition, 26% of IMU patients reported “warm” (TSV = +2). Targeted therapy patients (TAR) showed a similar distribution, with 30% voting for “slightly warm” (TSV = +1), although their comfort responses varied.

Regarding disease stage, early-stage patients (ES) mainly reported “slightly warm” (TSV = +1), accounting for 31%. Late-stage patients (LS) showed a similar preference for “slightly warm,” but the proportion of “neutral” votes was lower, and “slightly uncomfortable” (TCV = −1) became the dominant comfort vote at 29%.

In terms of thermal comfort votes (TCV), the OPR, RAD, and TAR groups reported the highest shares of “neutral” (TCV = 0) responses, with proportions of 27%, 25%, and 24%,

respectively. In the OPR group, “slightly comfortable” ($TCV = +1$) accounted for 24%, which was higher than any discomfort votes. For RAD and TAR, the peak occurred at neutral comfort, while the second highest proportion for RAD was “slightly uncomfortable” (23%). In contrast, CHE and IMU groups showed different characteristics. Their comfort votes peaked at “slightly uncomfortable” ($TCV = -1$), accounting for 31% and 26%, respectively. The proportions of neutral votes were markedly lower, at 18% and 24%.

Comparisons between disease stages indicate that ES patients most frequently reported “neutral” ($TCV = 0$; 28%) and “slightly comfortable” ($TCV = +1$; 22%). Conversely, for LS patients, “slightly uncomfortable” ($TCV = -1$) accounted for the largest share (27%), followed by neutral votes (21%). The total proportion of “uncomfortable” ($TCV = -2$) and “very uncomfortable” ($TCV = -3$) for LS patients was 34%, markedly higher than the 14% observed in ES patients.

These results indicate a divergence between thermal sensation and thermal comfort among different groups. Although OPR and TAR groups reported feeling slightly warm, they maintained a high level of neutral comfort ($TCV = 0$). In contrast, CHE and IMU groups exhibited a sensation–comfort mismatch. CHE patients reported neutral sensation but high discomfort, while over half of IMU patients reported warm sensations with peak discomfort at “slightly uncomfortable,” details are shown in Figures 4 and 5.

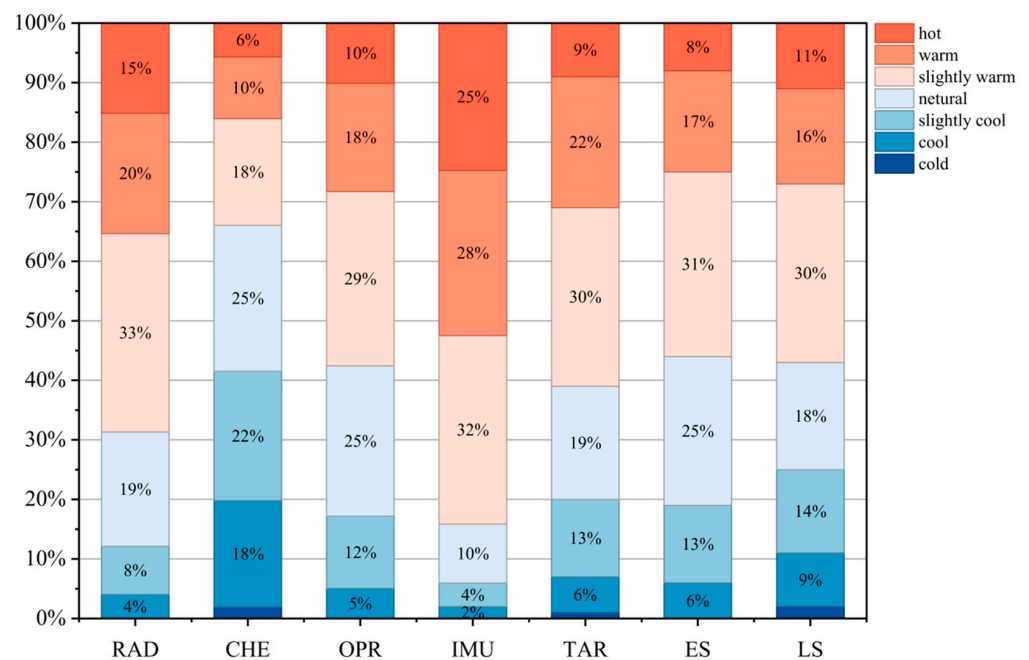


Figure 4. Thermal sensation vote.

3.1.4. Correlation Between TSV and TCV

In this study, the relationship between TCV and TSV is analyzed, and the fitting curve is drawn to show the relationship between the two, as shown in Figure 6. It can be seen that the relationship between the two is nonlinear, and the comfort threshold is significantly different.

Analyzing the characteristics of OPR and TAR patients, it is known that they have a strong adaptability to the thermal environment when the TSV is 0.37. In the OPR group, thermal comfort peaked at a TSV of 0.37, with a maximum TCV of 0.36. This suggests that the OPR group achieved the highest comfort level under a slightly warm condition. The TSV range associated with this comfort level extended from -0.79 to 1.46 . In this range, OPR patients can achieve good thermal comfort. TAR has a tolerance interval of -1.00 to 1.29 , and the comfort peak is the highest in all treatment groups, with a TCV of 0.37 and a

TSV of 0.15. This conclusion shows that the thermal regulation capacity of the two groups is relatively stable.

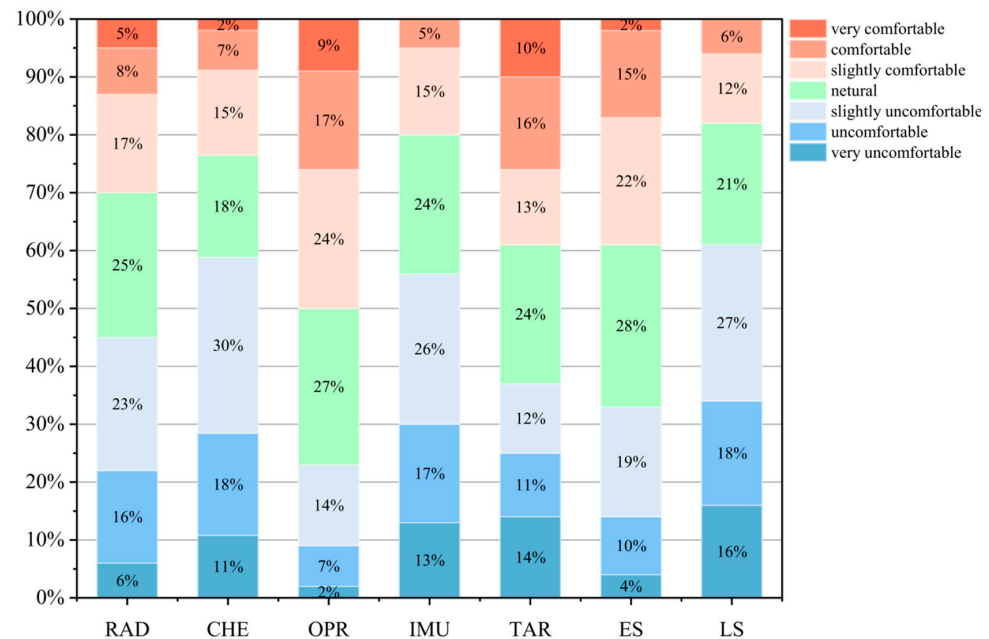
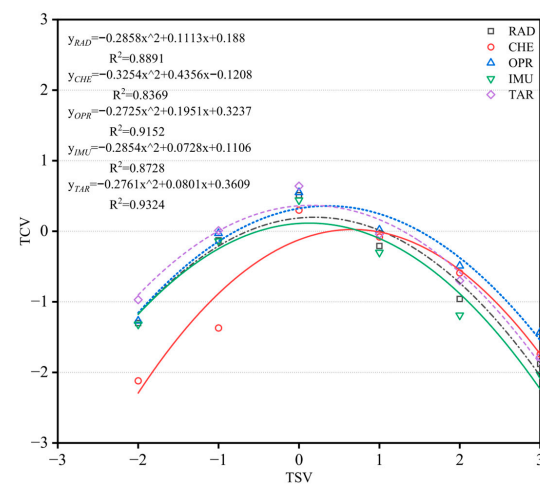
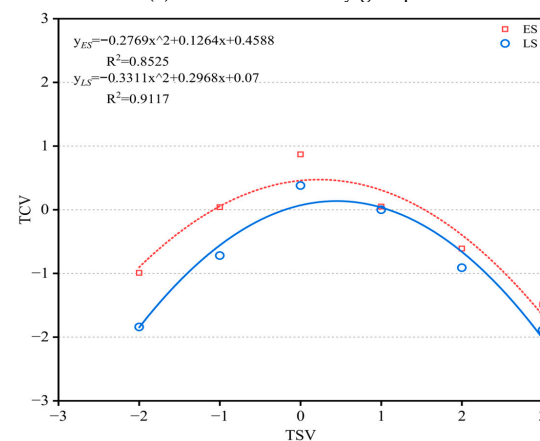


Figure 5. Thermal comfort vote.



(a) Treatment modality group.



(b) Cancer staging group.

Figure 6. The correlation between TSV and TCV. (a) Treatment modality group; (b) Cancer staging group.

For patients with RAD disease, the comfort peak is 0.19 (TCV = 0.20), and the interval is -0.64 to 1.02 . In contrast, the comfort peak of the IMU group is only 0.11 (TSV = 0.12), and the tolerance range is -0.48 to 0.76 , which is significantly narrower. The CHE group is the most restricted, with a TCV of only 0.04 and a narrow adaptive window of 0.39 – 0.95 . The comfort peak of CHE is 0.06 (TSV = 0.66), which is significantly different from that of other groups.

Through the comparison of the development of the disease, it is known that the development of the disease will have a negative impact on the body's tolerance to heat. ES patients have the strongest regulatory ability in all groups, with a comfort peak of 0.50 (TSV = 0.25) and a wide range of acceptance (-1.07 – 1.58). LS patients have obvious deterioration, with a comfort peak of 0.10 (TSV = 0.46), and the comfort interval is significantly reduced (-0.13 – 1.09).

3.1.5. Influence of Physical Environmental Parameters on TSV

Experimental data shows that physical environmental parameters influenced thermal sensation votes (TSV) differently across treatment groups, as shown in Figure 7.

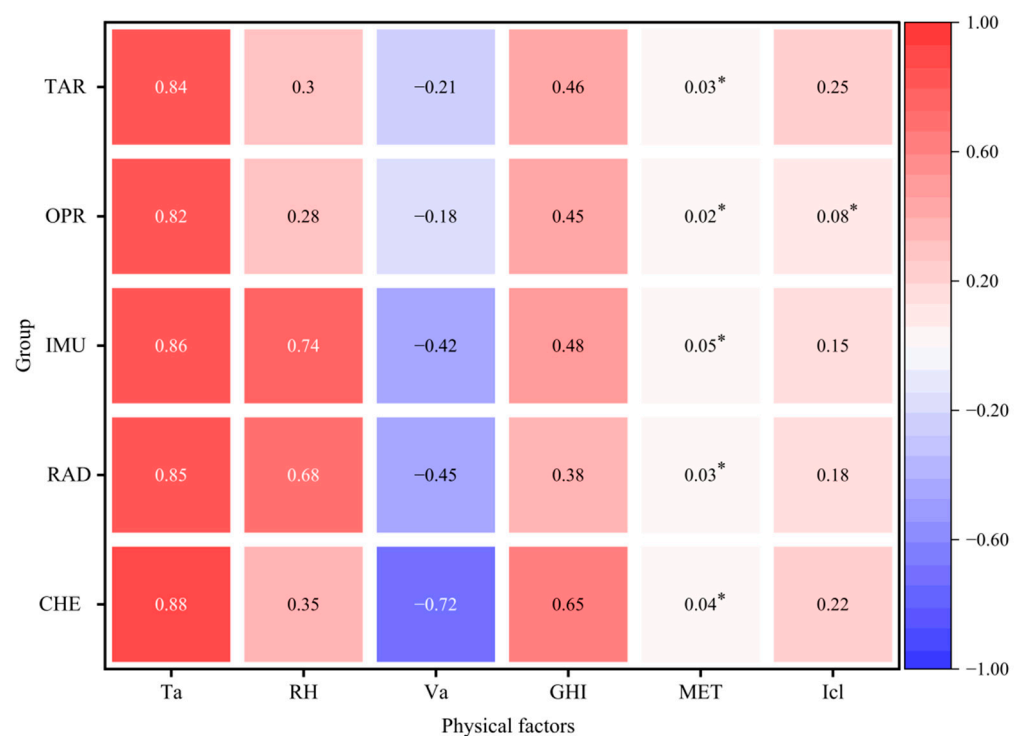


Figure 7. The correlation between physical parameters and TSV, * indicates $p < 0.05$.

Air temperature (Ta) led to TSV variation in all groups, but its effect size depended on other environmental parameters.

Relative humidity (RH) modulates evaporative cooling efficiency. This effect held particularly for immunotherapy (IMU) and radiotherapy (RAD) patients. IMU patients are often in a state of systemic inflammation with elevated thermoregulatory set-points in this setting, showing a strong positive correlation between RH and TSV ($\rho > 0.7$, $p < 0.01$). RAD patients showed rapid TSV increases as the environmental humidity rose.

Air velocity (Va) affects convective heat exchange, and chemotherapy (CHE) patients were found to be highly sensitive to changes in Va: moderate air movement ($Va \geq 0.5$ m/s) produced sharp declines in mean TSV. In that group, some individuals reported TSV = -2 ("cool"). Targeted therapy (TAR) and surgery (OPR) patients, by contrast, showed minimal TSV response to increased air movement.

Global horizontal irradiance (GHI) can raise mean radiant temperature, increasing radiative heat gain. CHE patients showed the strongest positive correlation between GHI and TSV. RAD patients displayed a more complex pattern: TSV increased modestly with GHI, but thermal comfort votes (TCV), thermal acceptability votes (TAV), and environmental satisfaction votes (ESV) deteriorated sharply with increasing GHI. Most groups except the OPR group showed declining TCV and TAV with increasing GHI.

Metabolic rates (MET), estimated from activity levels, remained low across all groups due to cancer-related fatigue and impaired pulmonary function. We found no significant relationship between MET and TSV.

Clothing insulation (clo) showed a weak but consistent positive association with Ta in all groups except OPR. clo rarely fell below 0.5 clo (that means long-sleeved garments) even under high temperature.

3.1.6. Meteorological Preferences

Across all treatment groups, the open square (OS) produced the highest thermal stress. Owing to the absence of shade and the high reflectance of paved surfaces, mean radiant temperature (T_{mrt}) was strongly coupled with air temperature (Ta), resulting in substantial radiant heat exposure. Accordingly, votes for reducing Ta and solar radiation reached their highest proportions in this setting. The demand in this survey for lower Ta exceeded 50% in the immunotherapy group (IMU), whereas the chemotherapy group (CHE) showed the strongest demand for reduced radiation intensity (>70%). In terms of wind preference, airflow was relatively unobstructed in the OS area, and the CHE group showed a markedly higher demand for lower wind speed than the other groups.

In the tree-shaded area (TS) and water place (WP), solar radiation was substantially reduced, whereas evaporative cooling maintained relatively high local relative humidity (RH), particularly during the morning and evening periods. Under these conditions, the strongest demand for lower humidity was observed in the IMU and radiotherapy (RAD) groups. Wind speed was generally low in both TS and WP. The IMU and RAD groups showed a relatively strong demand for increased airflow, while the CHE group showed only limited demand for higher wind speed. The enclosed porch (EP) provided effective shading. However, the dense artificial stone paving had high thermal capacity and surface emissivity, which promoted daytime heat storage and afternoon long-wave re-radiation, thereby increasing local T_{mrt}. As a result, votes for reducing Ta and radiation remained substantial in this setting, although their proportions were lower than those in the OS area, indicating a partial mitigation effect of shading. In terms of wind preference, the EP often functioned as a low-air-movement space because of structural obstruction. The targeted therapy group (TAR) showed a bidirectional preference pattern in this area: some patients preferred increased ventilation, whereas others preferred to maintain low air movement.

By disease stage, the early-stage group (ES) showed temperature and wind preferences broadly similar to those reported for healthy populations, with a relatively wide tolerance to airflow. In contrast, the late-stage group (LS) showed clear discomfort under both higher and lower temperatures, a thermally neutral-to-warm preference, and a markedly narrower tolerance range for air movement. All details are shown in Figure 8.

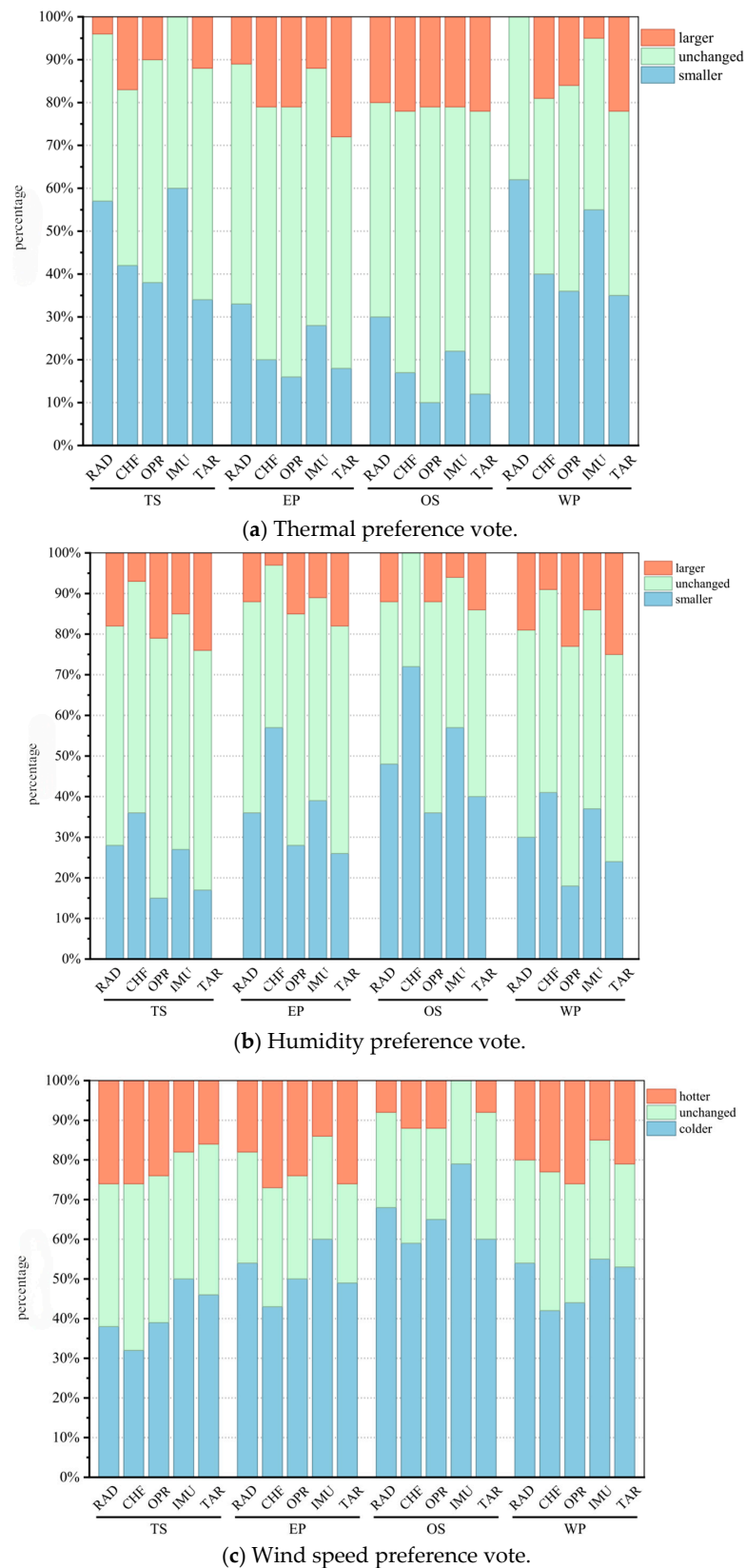


Figure 8. Meteorological factor preference vote. (a) Thermal preference vote; (b) Humidity preference vote; (c) Wind speed preference vote.

3.2. Thermal Benchmarks

3.2.1. Neutral PET and Neutral PET Range

Neutral physiologically equivalent temperature (NPET) was determined using a segmented statistical approach. PET values were grouped at 1 °C intervals. Mean thermal sensation vote (MTSV) was calculated for each interval. Linear regression was fitted between MTSV and PET. NPET corresponded to MTSV = 0. Neutral PET range (NPETR) corresponded to $-0.5 \leq \text{MTSV} \leq +0.5$.

Intergroup differences were substantial. Chemotherapy patients (CHE) showed the highest NPET at 26.0 °C. Immunotherapy patients (IMU) showed the lowest at 22.6 °C. Radiotherapy (RAD), targeted therapy (TAR), and surgery (OPR) groups registered 23.3 °C, 24.5 °C, and 23.7 °C, respectively. For patients in different stages, NPET in ES patients is 23.8 °C. NPET of LS is 25.8 °C. NPETR for each group: IMU 19.1–26.2 °C, RAD 19.4–27.2 °C, TAR 20.4–28.5 °C, and OPR appear in Table 5 and Figure 9.

Table 5. Linear equations between mean thermal sensation vote (MTSV) and physiologically equivalent temperature (PET) of participants.

Participants	NPET	NPETR	Linear Function	R ²	Gradient
RAD	23.3 °C	19.4–27.2 °C	$Y = 0.1272 \times X - 2.9616$	0.9361	0.1272
CHE	26.0 °C	22.4–29.7 °C	$Y = 0.1372 \times X - 3.5703$	0.9089	0.1372
OPR	23.7 °C	19.0–28.4 °C	$Y = 0.1076 \times X - 2.5508$	0.9268	0.1076
IMU	22.6 °C	19.1–26.2 °C	$Y = 0.1390 \times X - 3.1477$	0.9064	0.1390
TAR	24.5 °C	20.4–28.5 °C	$Y = 0.1248 \times X - 3.0514$	0.8862	0.1248
ES	23.8 °C	18.6–29.1 °C	$Y = 0.0949 \times X - 2.2616$	0.9664	0.0949
LS	25.8 °C	23.1–28.5 °C	$Y = 0.1873 \times X - 4.8316$	0.9367	0.1873

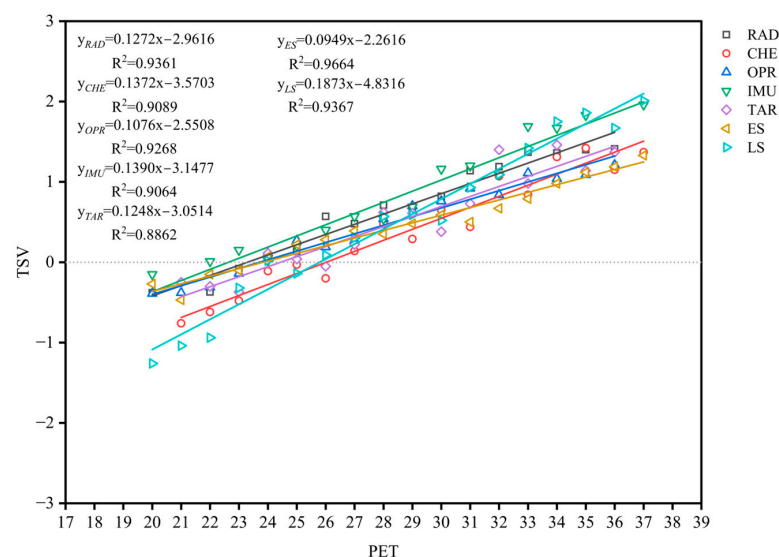


Figure 9. The correlation between PET and MTSV.

3.2.2. PET and MTCV

The binning method was applied, using 1 °C PET intervals. The mean thermal comfort vote (MTCV) was calculated for each bin, and a quadratic relationship between MTCV and PET was fitted. Figure 10 presents the fitted MTCV–PET curves for five treatment groups and different disease stages.

By treatment type, the PET corresponding to maximum thermal comfort ($\text{TCV}_{\max}$) varied across groups. The CHE group reached its peak at 26.8 °C ($\text{TCV} = 0.08$). The IMU group reached its peak at 21.6 °C ($\text{TCV} = 0.17$). For the RAD, OPR, and TAR groups, the corresponding PET values were 22.4 °C ($\text{TCV} = 0.27$), 24.3 °C ($\text{TCV} = 0.36$), and 23.8 °C ($\text{TCV} = 0.31$), respectively.

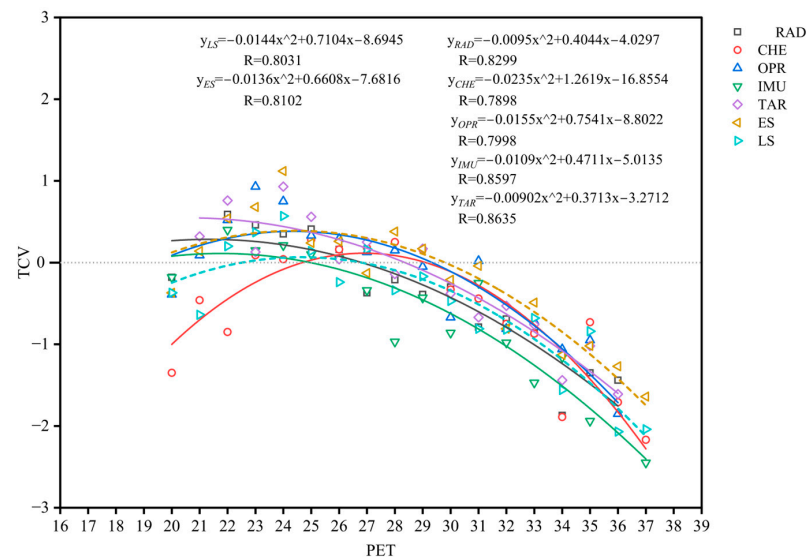


Figure 10. The correlation between PET and MTCV.

The PET ranges with positive mean thermal comfort votes (MTCV > 0) were 24.8–28.7 °C for CHE, 19.7–26.6 °C for RAD, 18.5–25.1 °C for IMU, 19.4–29.1 °C for OPR, and 18.8–27.8 °C for TAR.

By disease stage, the ES group reached peak comfort at PET = 24.5 °C (TCV = 0.40), with an acceptable range of 19.0–29.9 °C. The LS group showed a lower peak (TCV = 0.07) at PET = 24.7 °C, with a narrower acceptable range of 22.5–26.9 °C. Detailed results are shown in Figure 10 and Table 6 below.

Table 6. Curvilinear equations between mean thermal comfort vote (MTCV) and physiologically equivalent temperature (PET) of participants.

Participants	Vertex Coordinates	TCV > 0, Range of PET	Function	R ²
RAD	PET = 22.4 °C TCV = 0.27	19.7–26.6 °C	$Y = -0.0095X^2 + 0.4044 \times X - 4.0297$	0.8299
CHE	PET = 26.8 °C TCV = 0.08	24.8–28.7 °C	$Y = -0.0235X^2 + 1.2619 \times X - 16.8554$	0.7898
OPR	PET = 24.3 °C TCV = 0.36	19.4–29.1 °C	$Y = -0.0155X^2 + 0.7541 \times X - 8.8022$	0.7998
IMU	PET = 21.6 °C TCV = 0.17	18.5–25.1 °C	$Y = -0.0109X^2 + 0.4711 \times X - 5.0135$	0.8597
TAR	PET = 23.8 °C TCV = 0.31	18.8–27.8 °C	$Y = -0.00902X^2 + 0.3713 \times X - 3.2712$	0.8635
ES	PET = 24.5 °C TCV = 0.40	19.0–29.9 °C	$Y = -0.0144X^2 + 0.7104 \times X - 8.6945$	0.8031
LS	PET = 24.7 °C TCV = 0.07	22.5–26.9 °C	$Y = -0.0136X^2 + 0.6608 \times X - 7.6816$	0.8102

3.3. Thermal Acceptability Range

According to the ASHRAE 55 framework, thermal acceptability hinges on occupants' subjective evaluation. A "thermally acceptable zone" is defined as the range of environmental conditions—air temperature, humidity, and air movement—under which at least 80% of occupants express satisfaction, corresponding to a dissatisfaction rate no higher than 20%. Delineating this threshold accurately is fundamental to thermal comfort assessment. The correlation between PET and the unacceptable heat preference vote is shown in Figure 11.

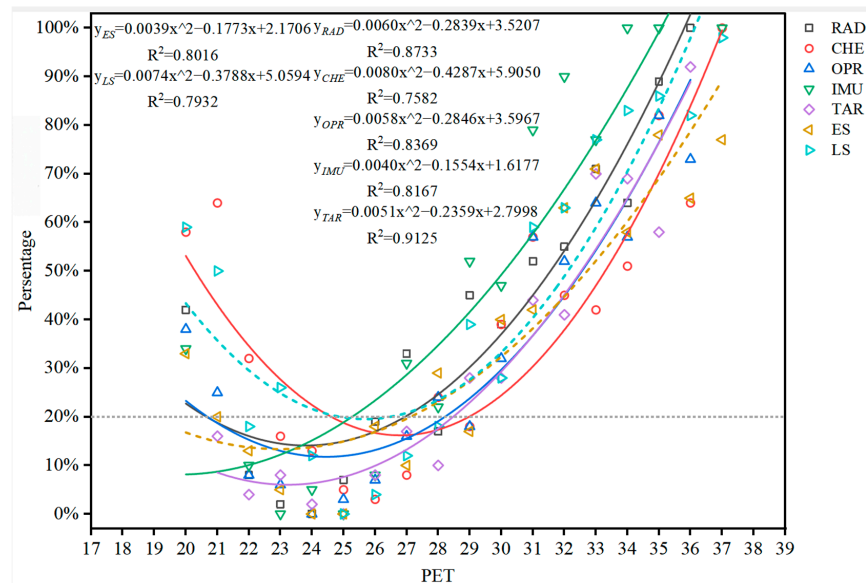


Figure 11. The correlation between PET and the unacceptable heat preference vote.

In our analysis, PET served as the primary outdoor thermal index. Acceptable PET ranges varied substantially across treatment groups, conditional on treatment type. Radiotherapy (RAD) and surgery (OPR) groups exhibited comparable ranges: 21.1–26.2 °C PET and 20.5–28.6 °C PET, respectively. Immunotherapy (IMU) patients, in this setting, tolerated cooler environments more readily (16.0–24.3 °C PET). Chemotherapy (CHE) patients, by contrast, shifted toward higher thermal demand (24.6–28.9 °C PET). Targeted therapy (TAR) occupied an intermediate position (19.7–28.1 °C PET).

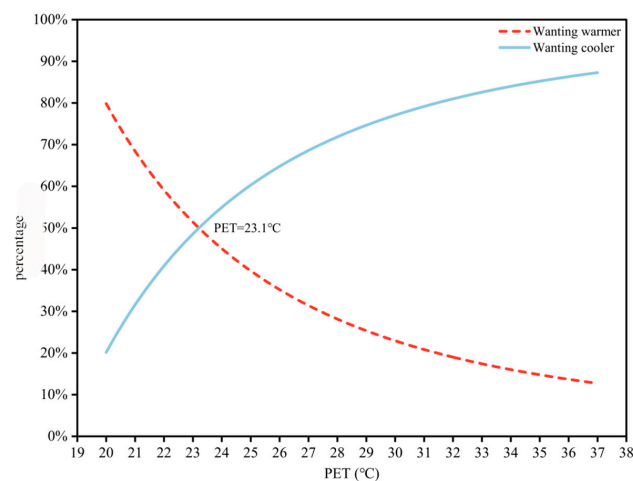
Stage-based comparison revealed that disease progression further modulated thermal adaptability. Early-stage patients (ES) maintained a relatively broad acceptable range (19.3–26.1 °C PET). Late-stage patients (LS) showed a markedly constricted zone, limited to 24.7–26.8 °C PET.

3.4. Preferred Temperature

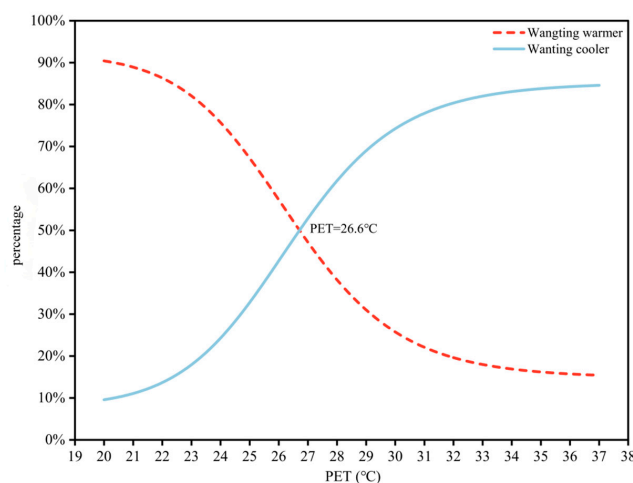
We developed a Logit regression model using thermal preference vote (TPV) data to quantify preferred temperature (T_{pref}) in lung cancer patients. PET was first discretized at 1 °C intervals. Because “no change” responses accounted for only a very small proportion of the thermal preference votes, their redistribution according to the equiprobable principle was unlikely to substantially affect the estimation of preferred temperature. We implemented a binary recording procedure: following the equiprobable principle, “no change” votes were randomly redistributed into “prefer warmer” and “prefer cooler” categories. For each PET interval, we calculated probabilities for both preference directions, fitted Logit curves, and defined T_{pref} as their intersection point.

Across treatment groups, T_{pref} showed marked bidirectional divergence. Immunotherapy (IMU) and radiotherapy (RAD) patients preferred cooler conditions: T_{pref} values reached 22.8 °C and 23.1 °C, respectively. In RAD patients, preferred temperature (23.1 °C) fell marginally below neutral PET (23.3 °C). Chemotherapy (CHE) patients, by contrast, showed strong preference for warmer conditions. Their T_{pref} reached 26.6 °C, approximately 3.8 °C higher than IMU and slightly exceeding their already elevated neutral PET (26.0 °C). Surgery (OPR) and targeted therapy (TAR) groups occupied intermediate positions, with T_{pref} of 24.2 °C and 24.5 °C, respectively. In both groups, T_{pref} marginally exceeded neutral PET, suggesting modest positive thermal demand conditional on treatment type: even after achieving physiological neutrality, these patients favored slightly warmer environments for psychological satisfaction.

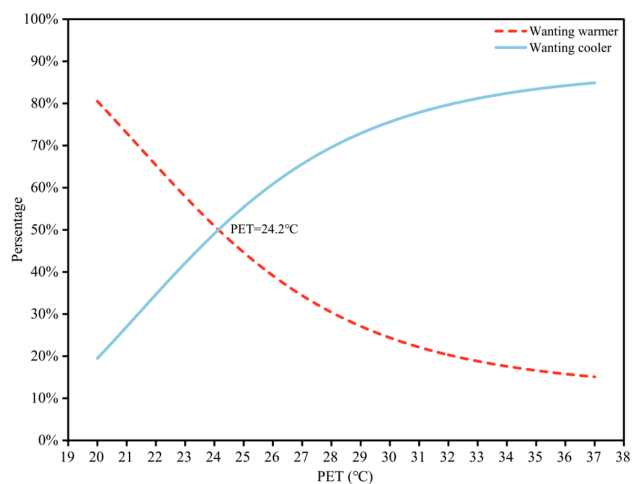
Disease stage further modulated preference patterns. Early-stage patients (ES) showed T_{pref} of 24.1 °C, closely aligned with conventional design standards and consistent with estimated neutral range. Late-stage patients (LS) demonstrated a distinct pathological thermal shift: T_{pref} increased to 26.2 °C. A clear preference–neutrality gap emerged in this group. Although neutral PET was already elevated (25.8 °C), preferred temperature remained approximately 0.4 °C higher. Details are shown in Figure 12.



(a) RAD group patients.

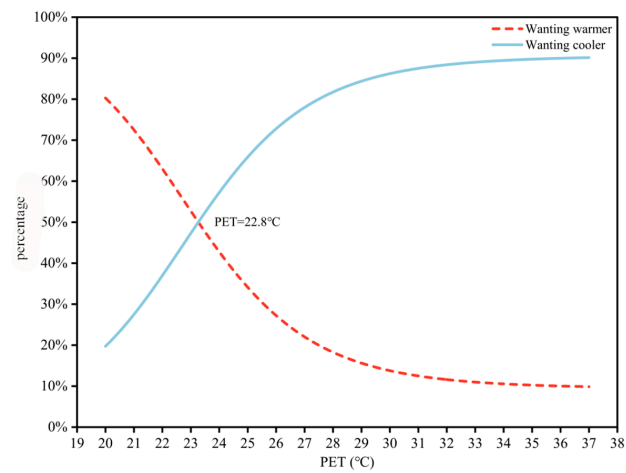


(b) CHE group patients.

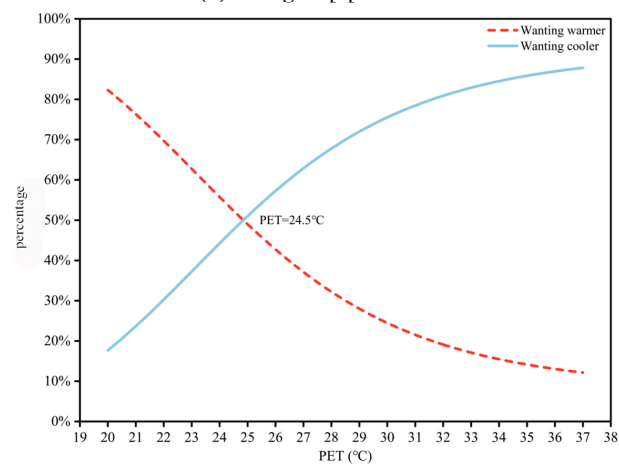


(c) OPR group patients.

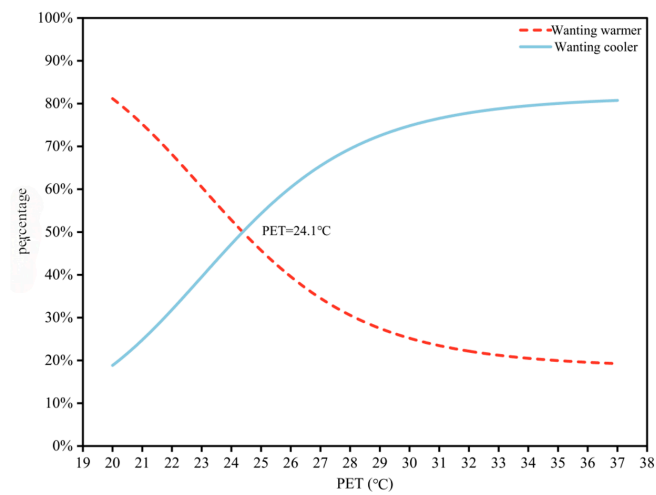
Figure 12. Cont.



(d) IMU group patients.

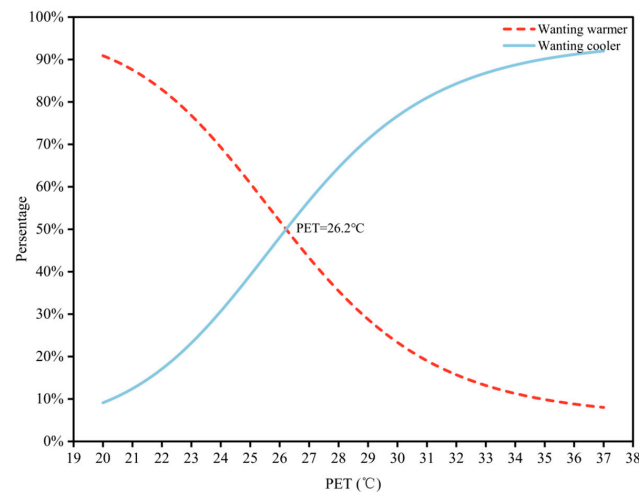


(e) TAR group patients.



(f) ES group patients.

Figure 12. Cont.



(g) LS group patients.

Figure 12. Preferred temperatures among different groups. (a) RAD group patients; (b) CHE group patients; (c) OPR group patients; (d) IMU group patients; (e) TAR group patients; (f) ES group patients; (g) LS group patients.

4. Discussion

4.1. Treatment-Induced Heterogeneity in Thermal Comfort and Underlying Pathophysiological Determinants

Differences in preferred temperature were observed across treatment groups. The chemotherapy group showed a higher preferred temperature ($T_{pref} \approx 26.6$ °C). Under outdoor conditions, higher wind speed may enhance convective heat loss and reduce thermal acceptability in this group. This pattern is consistent with reports that chemotherapy-induced peripheral neuropathy is associated with altered thermal perception and cold-related sensory symptoms [41]. The immunotherapy group preferred lower temperatures ($T_{pref} \approx 22.8$ °C) and showed lower tolerance to high humidity. Thermal responses in this group were more sensitive to combined heat and moisture exposure. Lower air temperature and increased air movement were associated with improved thermal acceptability. This may be related, in part, to the fever-like and inflammatory adverse events reported during PD-1/PD-L1 inhibitor treatment [42]. The radiotherapy group showed a negative thermal shift. Compared with other groups, thermal acceptability in this group was more strongly influenced by radiant heat than by air temperature alone. Under high solar exposure, discomfort increased even when air temperature remained within a moderate range. Shaded conditions and reduced mean radiant temperature (T_{mrt}) were associated with improved thermal response. A limited clinical explanation is that radiotherapy is commonly associated with radiation-induced skin damage, which may increase local sensitivity to environmental stimuli [43]. The targeted therapy group showed reduced tolerance to solar radiation. Direct exposure resulted in lower thermal acceptability than shaded exposure at similar air temperatures. This indicates a relatively large contribution of shortwave radiation to perceived thermal load in this group. Such a result is consistent with previous reports that EGFR-targeted therapy can be accompanied by cutaneous toxicity, including photosensitivity [44]. For patients in later stages, the preferred temperature shifted toward higher values ($T_{pref} \approx 26.2$ °C), while the acceptable range became narrower. Thermal responses in this group were less tolerant to environmental variation, and stable thermal conditions were associated with higher acceptability. Advanced cancer is frequently accompanied by cachexia and metabolic imbalance, which may reduce tolerance to outdoor thermal stress [45,46].

4.2. Associations with and Differentiation from Previous Research

First, a comparison between the neutral temperature (T_n) identified for lung cancer patients in this study and published summer benchmarks for healthy populations in northern cold and severe-cold regions of China indicates a marked shift in thermal response. In Harbin, a year-long field survey reported a summer neutral PET of 20.0 °C for healthy residents [47]. In another summer field study conducted in high-density commercial streets in Harbin, the preferred PET was reported as 24.8 °C [48]. In Beijing, a summer field investigation in public spaces reported a neutral PET of 21.9 °C, with a neutral PET range of 15.2–28.6 °C [49]. In Xi'an, a summer field survey in an urban riverfront open square reported a neutral PET of 18.9 °C and an 80% acceptable PET range of 17.6–31.8 °C [50].

In contrast, the neutral temperature observed in late-stage patients (LS) in this study reached 25.8 °C, while the chemotherapy group (CHE) showed an even higher value of 26.0 °C. Relative to the healthy benchmarks reported above, these values are consistently shifted toward warmer conditions. The difference is approximately 4–8 °C when compared with published neutral PET values for healthy populations in northern cold-climate cities [47,49,50]. This result indicates that long-term climatic adaptation alone is not sufficient to explain thermal expectation in this cohort. Disease status and treatment exposure may modify the thermal response pattern under outdoor conditions. A limited clinical explanation is that advanced cancer is often accompanied by altered energy balance, while chemotherapy may affect thermal perception through treatment-related sensory symptoms [41,45]. Details can be found in Table 7.

Table 7. Summary of other research.

Regions	Functional Areas	Participants	Season	Index	Neutral Temperature (°C)
Shenyang, China (this study)	Monsoon climate of medium latitudes	Patients with lung cancer who have received different treatments and at different stages of the disease	Summer	PET	RAD: 23.3 °C CHE: 26.0 °C OPR: 23.7 °C IMU: 22.6 °C TAR: 24.5 °C ES: 23.8 °C LS: 25.8 °C
Xi'an, China [51]	Warm, temperate, semi-humid continental monsoon climate	All age groups (including a large number of middle-aged and elderly people)	Summer	PET, UTCI	24.8 °C
Shanghai, China [52]	North subtropical monsoon climate	Tourists and local residents	Summer	PET	24.2–26.5 °C
Guangzhou, China [53]	Subtropical monsoon climate	Students and residents in the university campus area	Summer	PET, SET*, UTCI	26.5 °C
Tel Aviv, Israel [54]	Mediterranean	City residents	Summer	PET	25.5 °C
Several European countries [55]	Temperate and continental	Recreational visitors in the park	Summer	PET	22.0–23.0 °C

This observation is consistent with the need to reconsider the applicability of the classical heat balance framework proposed by Fanger [13] when applied to special populations, while the present study provides, for the first time, a quantitative estimate of the magnitude of such deviation.

From an international perspective, the neutral PET values identified for the lung cancer cohort also diverge from regional baselines established for healthy populations. Specifically, the neutral PET of the chemotherapy group (26.0 °C) is markedly higher than the summer benchmark reported by Xu et al. [51] for healthy individuals in a comparable climate zone (e.g., Xi'an, 24.8 °C), and is instead closer to the adaptation level observed in

subtropical Guangzhou (26.5 °C) reported by Fang et al. [53]. This pattern suggests that chemotherapy-induced neuropathy and metabolic suppression may effectively diminish the influence of long-term climatic adaptation.

By contrast, the immunotherapy group (IMU) exhibited a preference for cooler conditions, with a neutral PET of 22.6 °C. This value falls within the comfort range reported for temperate European climates (22.0–23.0 °C) [54], indicating that systemic inflammatory responses may drive an increased physiological demand for cooling under hot summer conditions.

4.3. Design Strategy

Open paved spaces should not serve as primary stay areas, as they generated the highest thermal stress across all treatment groups. Shaded environments should be prioritized, but shade alone is not sufficient. In tree-shaded and waterfront spaces, airflow and humidity should be controlled simultaneously, particularly for the IMU and RAD groups. Semi-covered spaces such as enclosed porches (EPs) may be used as transitional or short-stay areas, but surface heat storage and afternoon re-radiation should be reduced through material selection. At the spatial level, outdoor areas should be organized as a sequence of microclimatic zones, including low-disturbance sheltered spaces for CHE and late-stage patients, and shaded but moderately ventilated spaces for IMU and RAD patients; a case is shown in Figure 13.

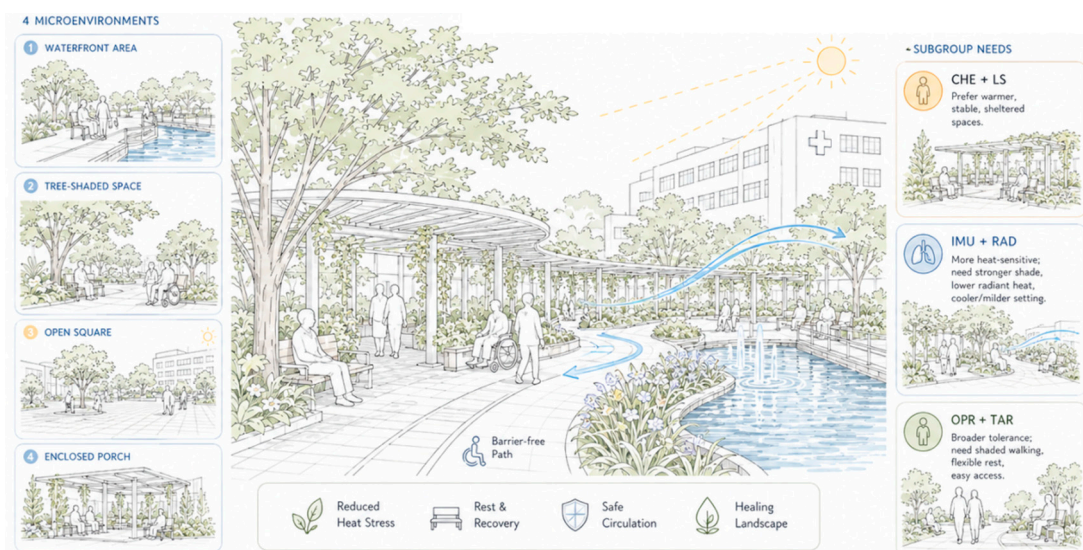


Figure 13. Design strategy for lung cancer patients.

4.4. Limitations and Future Directions

Several limitations should be acknowledged. First, the present study was based on subjective votes and environmental observations, without direct physiological measurements such as metabolic rate or core body temperature. As a result, the physiological basis of subgroup differences was not directly examined. Future studies could incorporate physiological monitoring to provide a more complete understanding of thermoregulatory responses in lung cancer patients.

Second, the study was conducted in one season and one climatic context, and thus mainly reflects summer conditions in a cold-region city. Although the sample size was sufficient for the present analysis, broader investigations across other seasons, climate zones, and larger cohorts would help to strengthen the generalizability of the findings.

In addition, treatment modality and disease stage may be affected by potential confounding factors, including age, sex, mobility, comorbidities, medication use, smoking

history, clinical condition, and time since treatment. Some patients may also have received combined or sequential therapies, which cannot be fully captured by classification according to dominant treatment modality. The clustering of participants within specific hospitals, outdoor spaces, and survey days may also influence the results. Moreover, thermal sensation, comfort, acceptability, and preference votes are ordinal outcomes, while the present analysis mainly used regression-based methods commonly adopted in thermal comfort studies.

5. Conclusions

The main contribution of this study lies not only in deriving PET benchmarks for different patient groups, but also in providing empirical evidence that lung cancer patients may require subgroup-sensitive thermal comfort assessment in healthcare outdoor settings. The results suggest that patients with different treatment modalities and disease stages should not be regarded as a thermally homogeneous group.

Thermal sensation and comfort responses varied across treatment groups. Radiotherapy (RAD) and immunotherapy (IMU) patients showed greater heat sensitivity, with higher proportions reporting “slightly warm” or warmer sensations. Chemotherapy (CHE) patients most frequently reported neutral thermal sensation, but many still reported slight discomfort, indicating a mismatch between sensation and comfort.

Neutral PET also differed among subgroups. The CHE group showed the highest neutral PET at 26.0 °C, while the IMU group showed the lowest value at 22.6 °C. The RAD, surgery (OPR), and targeted therapy (TAR) groups had neutral PET values of 23.3 °C, 23.7 °C, and 24.5 °C, respectively. Disease stage further affected thermal response: early-stage patients (ES) had a neutral PET of 23.8 °C, whereas late-stage patients (LS) showed a higher neutral PET of 25.8 °C and a narrower neutral range of 23.1–28.5 °C.

Thermal comfort and preference showed similar subgroup differences. The comfort-positive PET ranges were wider for OPR and TAR patients, at 19.4–29.1 °C and 18.8–27.8 °C, respectively, but narrower for LS patients, at 22.5–26.9 °C. CHE and LS patients preferred warmer conditions, with preferred PET values of 26.6 °C and 26.2 °C, whereas IMU and RAD patients preferred cooler conditions, at 22.8 °C and 23.1 °C, respectively.

Overall, in cold-region summer conditions, outdoor spaces adjacent to healthcare facilities should be evaluated and designed with attention to subgroup differences in thermal sensitivity, acceptable range, and thermal preference. This study provides empirical support for patient-oriented and subgroup-sensitive outdoor microclimate design in healthcare environments.

Author Contributions: Z.Q.: Writing—original draft, visualization, validation, investigation, data curation, and conceptualization. X.W.: Writing—review and editing, software, and methodology. Y.D.: Writing—original draft and visualization, X.T.: Writing. H.W.: Investigation. W.X.: Project supervisor. M.Z.: Project administration and methodology. All authors have read and agreed to the published version of the manuscript.

Funding: The paper was supported by Xi’an Jiaotong University’s second batch of industry–university collaborative education projects in 2025 (No. 25CXHZ031).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Honghui hospital, Xi’an (protocol code [2025-KY-129-01]).

Informed Consent Statement: Written informed consent was obtained from all subjects involved in the study. No personally identifiable information of the participants is disclosed in this article.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: There are no conflicts of interest to declare.

Abbreviations

Nomenclature		
Abbreviation	Parameters	Units
RAD	Radiotherapy group	
CHE	Chemotherapy group	
OPR	Surgery group	
IMU	Immunotherapy group	
TAR	Targeted therapy group	
ES	Early-stage group	
LS	Late-stage group	
WP	Waterfront place	
TS	Tree shade place	
OS	Open square	
EP	Enclosed porch	
T _a	Air temperature	°C
V _a	Air velocity	m/s
RH	Relative humidity	%
T _g	Black-globe temperature	°C
T _{mrt}	Mean radiant temperature	°C
Clo	Unit of clothing insulation	m ² °C/W
GHI	Global horizontal irradiance	W/m ²
PET	Physiologically equivalent temperature	°C
TSV	Thermal sensation vote	
TCV	Thermal comfort vote	
TAV	Thermal acceptability vote	
ESV	Environment satisfaction vote	
TPV	Temperature preference vote	
HPV	Humidity preference vote	
WPV	Wind speed preference vote	
MTSV	Mean thermal sensation vote	
MTCV	Mean thermal comfort vote	
T _n	Neutral temperature	°C
NPET	Neutral physiologically equivalent temperature	°C
NPETR	Neutral physiologically equivalent temperature range	°C
T _{pref}	Preference temperature	°C

References

1. Sung, H.; Ferlay, J.; Siegel, R.L.; Laversanne, M.; Soerjomataram, I.; Jemal, A.; Bray, F. Global Cancer Statistics 2020: GLOBOCAN Estimates of Incidence and Mortality Worldwide for 36 Cancers in 185 Countries. *CA Cancer J. Clin.* **2021**, *71*, 209–249. [\[CrossRef\]](#)
2. Bade, B.C.; Dela Cruz, C.S. Lung Cancer 2020: Epidemiology, Etiology, and Prevention. *Clin. Chest Med.* **2020**, *41*, 1–24. [\[CrossRef\]](#)
3. Chen, W.; Zheng, R.; Baade, P.D.; Zhang, S.; Zeng, H.; Bray, F.; Jemal, A.; Yu, X.Q.; He, J. Cancer Statistics in China, 2015. *CA Cancer J. Clin.* **2016**, *66*, 115–132. [\[CrossRef\]](#)
4. Cao, M.; Li, H.; Sun, D.; Chen, W. Cancer Burden of Major Cancers in China: A Need for Sustainable Actions. *Cancer Commun.* **2020**, *40*, 205–210. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Jiang, S. Therapeutic Landscapes and Healing Gardens: A Review of Chinese Literature in Relation to the Studies in Western Countries. *Front. Archit. Res.* **2014**, *3*, 141–153. [\[CrossRef\]](#)
6. Ulrich, R.S. View through a Window May Influence Recovery from Surgery. *Science* **1984**, *224*, 420–421. [\[CrossRef\]](#)
7. Kaplan, S. The Restorative Benefits of Nature: Toward an Integrative Framework. *J. Environ. Psychol.* **1995**, *15*, 169–182. [\[CrossRef\]](#)
8. Detterbeck, F.C.; Boffa, D.J.; Kim, A.W.; Tanoue, L.T. The Eighth Edition Lung Cancer Stage Classification. *Chest* **2017**, *151*, 193–203. [\[CrossRef\]](#)

9. Peddle-McIntyre, C.J.; Singh, F.; Thomas, R.; Newton, R.U.; Galvão, D.A.; Cavalheri, V. Exercise Training for Advanced Lung Cancer. *Cochrane Database Syst. Rev.* **2019**, *2*, CD012685. [\[CrossRef\]](#)
10. Fan, L.; Li, Z.; Zhou, Y. Seasonal Outdoor Thermal Comfort and Neutral PET Thresholds in a Severe Cold Dwa Climate City of Shenyang, China. *Sci. Rep.* **2026**, *16*, 15265. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Conti, S.; Meli, P.; Minelli, G.; Solimini, R.; Toccaceli, V.; Vichi, M.; Beltrano, C.; Perini, L. Epidemiologic Study of Mortality during the Summer 2003 Heat Wave in Italy. *Environ. Res.* **2005**, *98*, 390–399. [\[CrossRef\]](#)
12. Brown, R.D. *Design with Microclimate: The Secret to Comfortable Outdoor Space*; Island Press: Washington, DC, USA, 2010.
13. Fanger, P.O. *Thermal Comfort: Analysis and Applications in Environmental Engineering*; Danish Technical Press: Copenhagen, Denmark, 1970.
14. ANSI/ASHRAE Standard 55-2020; Thermal Environmental Conditions for Human Occupancy. ASHRAE: Atlanta, GA, USA, 2020.
15. Guan, R.; Lu, J.; Peng, Z.; Ma, S.; Deng, W.; Zhang, Z.; Beccarelli, P.; He, T. Thermal Comfort of Healthcare Facilities in China: A Review. *Build. Environ.* **2024**, *265*, 111927. [\[CrossRef\]](#)
16. Pereira, P.F.C.; Broday, E.E.; Xavier, A.A.P. Thermal Comfort Applied in Hospital Environments. *Appl. Sci.* **2020**, *10*, 7030. [\[CrossRef\]](#)
17. Pourshaghagh, A.; Omidvari, M. Examination of Thermal Comfort in a Hospital Using PMV–PPD Model. *Appl. Ergon.* **2012**, *43*, 1089–1095. [\[CrossRef\]](#)
18. Wang, B.; Zhao, H.; Han, B.; Jiang, X. An Investigation of Outdoor Thermal Comfort Assessment for Elderly Individuals in a Field Study in Northeastern China. *Buildings* **2023**, *13*, 2458. [\[CrossRef\]](#)
19. Wei, R.; Yan, J.; Cui, Y.; Song, D.; Yin, X.; Sun, N. Studies on the Specificity of Outdoor Thermal Comfort during the Warm Season in High-Density Urban Areas. *Buildings* **2023**, *13*, 2473. [\[CrossRef\]](#)
20. Zhen, M.; Zhou, W.; Zheng, R.; Lu, Y. Study on Thermal Comfort and Optimization Strategies in Outdoor Open Spaces of Hospitals in Cold Regions of China during Summer. *Urban Clim.* **2024**, *58*, 102135. [\[CrossRef\]](#)
21. Bian, G.; Gao, X.; Zou, Q.; Cheng, Q.; Sun, T.; Sha, S.; Zhen, M. Effects of Thermal Environment and Air Quality on Outdoor Thermal Comfort in Urban Parks of Tianjin, China. *Environ. Sci. Pollut. Res.* **2023**, *30*, 97363–97376. [\[CrossRef\]](#)
22. Jing, W.; Qin, Z.; Mu, T.; Ge, Z.; Dong, Y. Evaluating Thermal Comfort Indices for Outdoor Spaces on a University Campus. *Sci. Rep.* **2024**, *14*, 21253. [\[CrossRef\]](#)
23. Li, K.; Zhang, Y.; Zhao, L. Outdoor Thermal Comfort and Activities in the Urban Residential Community in a Humid Subtropical Area of China. *Energy Build.* **2016**, *133*, 498–511. [\[CrossRef\]](#)
24. Xu, M.; Hong, B.; Jiang, R.; An, L.; Zhang, T. Outdoor Thermal Comfort of Shaded Spaces in an Urban Park in the Cold Region of China. *Build. Environ.* **2019**, *155*, 408–420. [\[CrossRef\]](#)
25. Oke, T.R. *Boundary Layer Climates*, 2nd ed.; Routledge: London, UK, 1987.
26. Zhu, Y.; Jiang, Y.; Du, X.; Zhu, X.; Zhou, L.; Niu, Y.; Liu, C.; Kan, H.; Chen, R. Heat Exposure Changes Lung Function, Biomarkers of Airway Injury, and Airway Microbiota: A Randomized, Crossover Trial. *Environ. Health* **2025**, *3*, 1344–1352. [\[CrossRef\]](#)
27. Zhen, M.; Zhang, L.; She, X.; Nan, K. Study on Thermal Comfort of Gynecological Tumor Patients in Hospital Ward Area. *Energy Build.* **2025**, *329*, 115230. [\[CrossRef\]](#)
28. Sun, T.; Luo, A.; Lu, Y.; Zhen, M.; Zhang, Y.; Bian, G. Research on Indoor Thermal Comfort of Orthopedic Patients in Hospital. *Sci. Rep.* **2025**, *15*, 9053. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Li, L.; Wang, Z.; Zhen, M.; Nan, K. Study on Outdoor Thermal Comfort of Older People in Age-Friendly Communities in Cold Regions. *Energy Build.* **2025**, *329*, 115265. [\[CrossRef\]](#)
30. Xi, T.; Li, Q.; Mochida, A.; Meng, Q. Study on the Outdoor Thermal Environment and Thermal Comfort around Campus Clusters in Subtropical Urban Areas. *Build. Environ.* **2012**, *52*, 162–170. [\[CrossRef\]](#)
31. Tan, J.; Zheng, Y.; Tang, X.; Guo, C.; Li, L.; Song, G.; Zhen, X.; Yuan, D.; Kalkstein, A.J.; Li, F.; et al. The Urban Heat Island and Its Impact on Heat Waves and Human Health in Shanghai. *Int. J. Biometeorol.* **2010**, *54*, 75–84. [\[CrossRef\]](#)
32. Lin, T.-P.; Matzarakis, A.; Hwang, R.-L. Shading Effect on Long-Term Outdoor Thermal Comfort. *Build. Environ.* **2010**, *45*, 213–221. [\[CrossRef\]](#)
33. Nikolopoulou, M.; Lykoudis, S. Thermal Comfort in Outdoor Urban Spaces: Analysis across Different European Countries. *Build. Environ.* **2006**, *41*, 1455–1470. [\[CrossRef\]](#)
34. Chen, L.; Ng, E. Outdoor Thermal Comfort and Outdoor Activities: A Review of Research in the Past Decade. *Cities* **2012**, *29*, 118–125. [\[CrossRef\]](#)
35. Zhen, M.; Zou, W.; Zheng, R.; Lu, Y. Urban Outdoor Thermal Environment and Adaptive Thermal Comfort during the Summer. *Environ. Sci. Pollut. Res.* **2022**, *29*, 77864–77883. [\[CrossRef\]](#)
36. Gagge, A.P.; Stolwijk, J.A.J.; Hardy, J.D. Comfort and Thermal Sensations and Associated Physiological Responses at Various Ambient Temperatures. *Environ. Res.* **1967**, *1*, 1–20. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Höppe, P. The Physiological Equivalent Temperature—A Universal Index for the Biometeorological Assessment of the Thermal Environment. *Int. J. Biometeorol.* **1999**, *43*, 71–75. [\[CrossRef\]](#) [\[PubMed\]](#)

38. Matzarakis, A.; Rutz, F.; Mayer, H. Modelling Radiation Fluxes in Simple and Complex Environments—Application of the RayMan Model. *Int. J. Biometeorol.* **2007**, *51*, 323–334. [[CrossRef](#)] [[PubMed](#)]
39. Jendritzky, G.; de Dear, R.; Havenith, G. UTCI—Why Another Thermal Index? *Int. J. Biometeorol.* **2012**, *56*, 421–428. [[CrossRef](#)]
40. ISO 7726:1998; Ergonomics of the Thermal Environment—Instruments for Measuring Physical Quantities. International Organization for Standardization: Geneva, Switzerland, 1998.
41. Burgess, J.; Ferdousi, M.; Gosal, D.; Boon, C.; Matsumoto, K.; Marshall, A.; Mak, T.; Marshall, A.; Frank, B.; Malik, R.A.; et al. Chemotherapy-Induced Peripheral Neuropathy: Epidemiology, Pathomechanisms and Treatment. *Oncol. Ther.* **2021**, *9*, 385–450. [[CrossRef](#)]
42. Su, C.; Wang, H.; Liu, Y.; Guo, Q.; Zhang, L.; Li, J.; Zhou, W.; Yan, Y.; Zhou, X. Adverse Effects of Anti-PD-1/PD-L1 Therapy in Non-Small Cell Lung Cancer. *Front. Oncol.* **2020**, *10*, 554313. [[CrossRef](#)]
43. Li, K.; Yin, R. A Critical Review of the Progress in Prevention and Treatment of Radiation-Induced Skin Damage. *Front. Oncol.* **2024**, *14*, 1395778. [[CrossRef](#)]
44. Abdullah, S.E.; Haigentz, M., Jr.; Piperdi, B. Dermatologic Toxicities from Monoclonal Antibodies and Tyrosine Kinase Inhibitors against EGFR: Pathophysiology and Management. *Chemother. Res. Pract.* **2012**, *2012*, 351210. [[CrossRef](#)]
45. Fearon, K.; Strasser, F.; Anker, S.D.; Bosaeus, I.; Bruera, E.; Fainsinger, R.L.; Jatoi, A.; Loprinzi, C.; MacDonald, N.; Mantovani, G.; et al. Definition and Classification of Cancer Cachexia: An International Consensus. *Lancet Oncol.* **2011**, *12*, 489–495. [[CrossRef](#)]
46. Petruzzelli, M.; Wagner, E.F. Mechanisms of Metabolic Dysfunction in Cancer-Associated Cachexia. *Genes Dev.* **2016**, *30*, 489–501. [[CrossRef](#)] [[PubMed](#)]
47. Chen, X.; Xue, P.; Liu, L.; Gao, L.; Liu, J. Outdoor Thermal Comfort and Adaptation in Severe Cold Area: A Longitudinal Survey in Harbin, China. *Build. Environ.* **2018**, *143*, 548–560. [[CrossRef](#)]
48. Zhu, Z.; Zhang, Y.; Gao, Y.; Luo, Y. Summer Outdoor Thermal Comfort in Urban Commercial Pedestrian Streets in Severe Cold Regions of China. *Sustainability* **2020**, *12*, 1876. [[CrossRef](#)]
49. Ma, T.; Zhang, J. Integrating Thermal Perception and Public Space Use: An Experimental Outdoor Comfort Study in Cold Winter-Hot Summer Zone: Beijing, China. *Urban Clim.* **2024**, *58*, 102138. [[CrossRef](#)]
50. Liu, L.; Xia, B.; Zhang, L. Outdoor Thermal Comfort of Urban River Landscape Belt in China’s Cold Region: A Case Study of Xi’an. *Urban Clim.* **2023**, *48*, 101406. [[CrossRef](#)]
51. Xu, M.; Hong, B.; Mi, J.; Yan, S. Outdoor Thermal Comfort in an Urban Park during Winter in Cold Regions of China. *Sustain. Cities Soc.* **2018**, *43*, 208–220. [[CrossRef](#)]
52. Li, J.; Liu, N. The Perception, Optimization Strategies and Prospects of Outdoor Thermal Comfort in China: A Review. *Build. Environ.* **2020**, *170*, 106614. [[CrossRef](#)]
53. Fang, Z.; Feng, X.; Liu, J.; Lin, Z.; Mak, C.M.; Niu, J.; Tse, K.-T.; Xu, X. Investigation into the Differences among Several Outdoor Thermal Comfort Indices against Field Survey in Subtropics. *Sustain. Cities Soc.* **2019**, *44*, 676–690. [[CrossRef](#)]
54. Cohen, P.; Potchter, O.; Matzarakis, A. Human Thermal Perception of Coastal Mediterranean Outdoor Urban Environments. *Appl. Geogr.* **2013**, *37*, 1–10. [[CrossRef](#)]
55. Kántor, N.; Égerházi, L.; Unger, J. Subjective Estimations of Thermal Environment in Recreational Urban Spaces—Part 2: International Comparison. *Int. J. Biometeorol.* **2012**, *56*, 1089–1101. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.