buildings

Systematic Review

A Review of Comprehensive Post-Occupancy Evaluation Feedback on Occupant-Centric Thermal Comfort and Building Energy Efficiency

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Abstract: The post-occupancy evaluation process is pivotal for assessing the performance of indoor and outdoor living environments after occupation. This evaluation involves a multifaceted analysis, encompassing energy efficiency, indoor environmental quality, outdoor spaces, and occupant satisfaction. Despite the inherent advantages and potential applicability of post-occupancy evaluation in residential buildings, the lack of uniformity in research methodologies, data collection techniques, investigative approaches, and result interpretation has impeded cross-comparisons and method replication. In a concerted effort to enhance the understanding of prevailing post-occupancy evaluation methodologies, this study undertook a comprehensive systematic literature review of post-occupancy evaluation practices within the residential domain from 2000 to 2023. The results unequivocally underscored the pervasive lack of consistency in methodological applications, tool deployment, and data reporting across diverse post-occupancy evaluation investigations. The objectives of this review aimed to examine the existing post-occupancy evaluation (POE) methods, assess occupant-centric thermal comfort, evaluate the impact of POE feedback on building design, and develop recommendations for architects, engineers, facility managers, and policymakers on leveraging POE feedback to enhance thermal comfort and energy efficiency in buildings. This study offers critical insights into advocating for a more standardized and cohesive post-occupancy evaluation approach. The findings of this review can direct the establishment of a coherent and consistently implemented post-occupancy evaluation framework within the realm of residential architecture.

Keywords: post-occupancy evaluation; thermal comfort; energy consumption; occupant behavior; occupant-centric building energy; scientometric analysis

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1. Introduction

1.1. Background

Currently, we are amidst a period of a polycrisis, characterized by conflicts, climate change, the lingering aftermath of the COVID-19 pandemic, as well as other global challenges that are jeopardizing the strides made in achieving the sustainability development goals (SDGs). In addition, the ongoing increase in greenhouse gas (GHG) emissions is further intensifying the severity of the climate catastrophe. Based on the latest evaluation by the Intergovernmental Panel on Climate Change, Earth's temperature has increased by 1.1 °C compared with the preindustrial average, as a result of the prolonged utilization of fossil fuels, unsustainable energy and land practices, and unsustainable consumption and production patterns. It is projected that the average surface temperature of the Earth will increase by between 1.1 °C and 1.9 °C, compared to the reference period of 1850–1900, for each year from 2024 to 2028 [1]. There is a strong likelihood that one of the next five years will surpass 2023 as the warmest year on record [1]. To avert this, urgent global reductions in GHG emissions are required.

Buildings and construction are significant sources of carbon dioxide (CO_2) emissions, accounting for >40% of material consumption, 30% of worldwide energy consumption, and >30% of global GHG emissions [2]. As temperatures rise, heating, ventilation, and air conditioning (HVAC) systems are operated more frequently and for longer periods, resulting in increased energy consumption within buildings [3]. Undoubtedly, the use of nonrenewable energy sources, such as fossil fuels, for electricity generation has resulted in an increase in GHG emissions, considerably influencing global climate change. Ensuring tenant comfort remains a paramount concern when addressing energy consumption in buildings [4]. Based on the available data, the energy-saving potential of occupant behavior (OB) can be at least 25% for residential buildings [5]. The energy consumption of a building is often characterized by unpredictability, owing to various factors, with OB emerging as a leading contributor [6]. Consequently, an increasing number of studies are recognizing the importance of OB in modeling building energy consumption [7]. In 2022, global energy-related CO_2 emissions increased by 0.9%, reaching a record-breaking 36.8 billion metric tons. This growth rate was considerably lower than the global GDP growth, indicating a return to the long-standing pattern of decoupling emissions from the economic growth that has persisted for the past decade. Following a decline of >5% in 2020 due to the pandemic, emissions experienced a growth of >6% in 2021, exceeding the levels observed before the outbreak. This increase was mostly caused by economic stimulus measures and a substantial rise in coal consumption (https://sdgs.un.org/goals, accessed on 6 January 2024). Post-occupancy evaluation (POE) plays a crucial role in this context by providing valuable feedback on occupant-centric thermal comfort and building energy efficiency, thereby informing strategies to optimize both comfort and energy use in buildings.

1.2. Good Health and Well-Being with Building Energy Sufficiency

In addition to the challenges related to the energy efficiency endeavor, the greatest challenge in enhancing sustainability is improving the well-being and health of everyone. Despite the promotion of emerging innovations that can enhance energy efficiency and nurture the use of renewable energy, there is clear evidence that less affluent and disadvantaged populations have benefited substantially less than wealthier populations [8]. With the extremely high amount of resource use, such as raw materials and energy, sustainable development is challenging to achieve for high-income nations [9]. However, achieving sufficient living conditions for everyone can also be made possible by the actions taken in the building sector addressing environmental sustainability, long-term viability, inequality, and poverty [8]. These are the research gaps in the current literature:

- The limited consideration of socioeconomic factors;
- The limited focus on specific building types;
- The lack of systematic and interdisciplinary research;
- The limited exploration of feedback mechanisms;
- The disparity between theory and actuality;
- The lack of guidelines and standards.

Protecting the ecological environment and improving its quality for the betterment of human life are fundamental goals of sustainable development. The association between human wellness, energy consumption in buildings, and carbon emissions has been the subject of numerous research studies. For instance, Agha-Hossein et al. (2013) [10] conducted a comparative analysis using pre-occupancy and POE studies to assess the former and current headquarter buildings of a corporation, both situated in the same vicinity in London. Following the relocation, employees reported increased productivity, satisfaction, well-being, and overall happiness in their work. Ildiri et al. (2022) [11] conducted a study analyzing over 1300 pre- and post-occupancy survey responses from occupants of six North American companies, both before and after transitioning to WELL Building Standard (WELL)-certified offices. They revealed a notable enhancement in occupants' contentment with the work environment, along with their perceived physical and mental health, overall well-being, and productivity. Rasheed et al. (2021) [12] discovered that those who dedicated a greater amount of time to their profession experienced lower levels of satisfaction with indoor environmental quality (IEQ) aspects. Nevertheless, the acoustic and air qualities were discovered to have an impact on productivity and well-being [13].

Nearly 90% of a human's life is spent indoors, and a wealth of research indicates that interior environments have an enormous influence on the productivity, health, and well-being of their inhabitants [14–20]. Figure 1 presents conceptual depictions that synthesize prior evaluations of building energy consumption intensity, human well-being, and sufficiency. The differences between these buildings, the buildings' energy use, and human well-being can be illustrated graphically and intuitively by the plots in Figure 2. The conceptual illustration depicts the correlation between excessive, insufficient, and sufficient energy regimes, represented from left (blue, indicating insufficient) to right (red, indicating excessive), with green denoting sufficient.

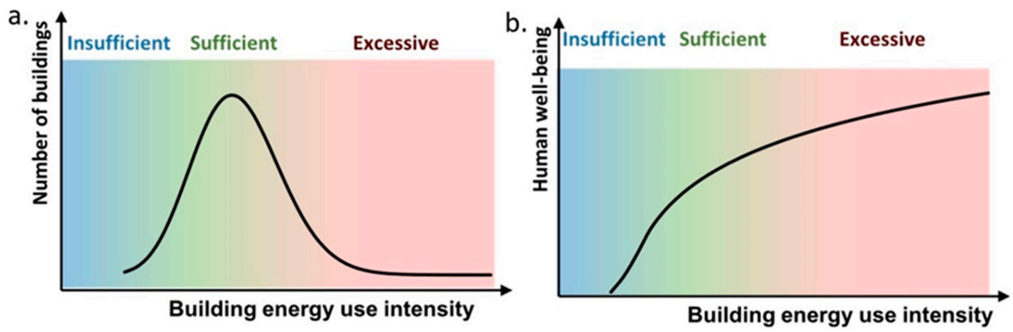

Figure 1. Conceptual conceptions: (**a**) Relationship between the number of buildings and building energy usage intensity. Adapted from Fournier et al. [8] and Hu et al. [21]. (**b**) Nonlinear relationship between human well-being and building energy use intensity. Adapted from Hu et al. 2023 [21].

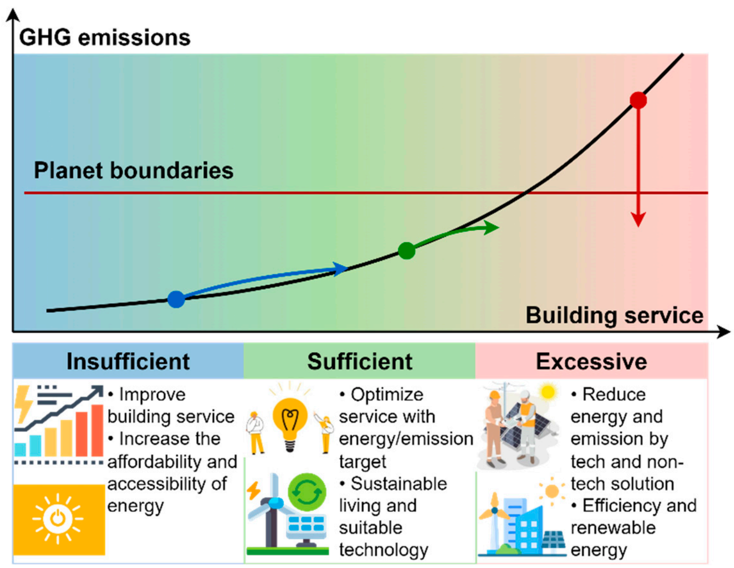

Figure 2. Appropriate selection of energy-sufficiency strategies for buildings. https://www.flaticon.com/, accessed on 7 January 2024. Adapted from Hu et al. 2023 [21].

2. Theoretical Framework

POE

In the late 1960s, investigations of dormitories were the earliest precursors to POE initiated in the United States. Silverstein and Ryn [15] presented case studies of dormitories in the University of California, Berkeley. Their study was an early attempt to examine building performance from the perspective of building users [16]. It is well recognized that

POE plays a pivotal role in facilitating the transfer of information from occupancy experiences to the design process and in fostering knowledge acquisition for the benefit of all stakeholders [17,18]. In 1997, Preiser and Schramm introduced an integrated framework of building performance evaluation (BPE) to further develop the notion of POE. Within this approach, POE signifies just one of the six internal review loops. BPE encompasses the whole lifespan of a building, that is, the stages of planning, programming, design, construction, occupancy, and potential adaptive reuse or recycling (Figure 3). While some studies may see BPE as an alternative term for POE, we recognize the distinction between the two and will solely concentrate on POE in this study, specifically referring to the occupation phase of a building's life cycle.

Stakeholders play a crucial role in shaping the nature and purpose of POE: investors assess the quality of design; building administrators strive to minimize energy consumption; occupants seek to improve productivity, well-being, and health; architects or consultants aim to create the most effective statutory building; and stakeholders from institutions promote the adoption of better design practices [19]. Several review studies have explored POE research, including modeling methodologies [20–23]. Nevertheless, the precise definition of POE considerably varies and lacks specificity [20,23,24]. Despite these variations, three fundamental principles—centering on an occupant-centric approach, employing systematic and rigorous methodologies, and providing actionable feedback—persist in various definitions, thereby establishing a common understanding of the essential attributes that characterize POE. Consequently, POE is increasingly important in modeling building energy usage. The indoor environment plays a pivotal role in influencing occupants' health and well-being. As buildings become more sophisticated, the need for robust evaluation methodologies becomes increasingly apparent. This is where POE steps in, serving as a dynamic process that gauges how well a building design and its operational strategies align with the health needs of its occupants.

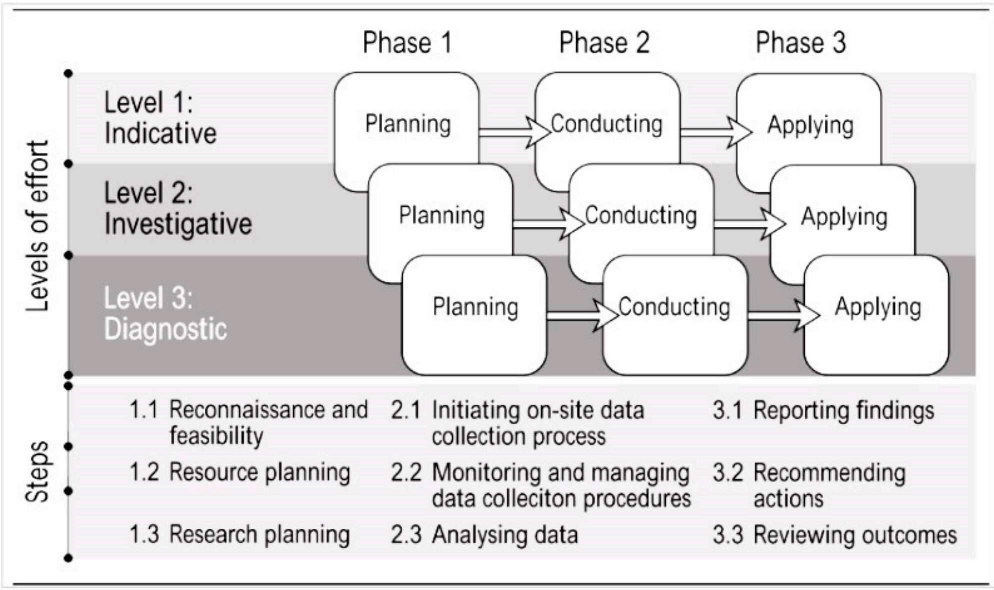

Figure 3. POE Framework, adapted from Ponterosso et al. 2018 [25].

3. Materials and Methods

3.1. Literature Filtration

3.1.1. Data Collection Process

As depicted in Figure 4, this study employed a mixed strategy that integrated two distinct approaches, namely, the bibliometric approach and the systematic literature review (SLR). The SLR was carried out following the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) methodology. The study procedure was divided into seven stages: (1) identification, (2) screening, (3) eligibility, (4) inclusion, (5) bibliometric analysis, (6) systematic analysis, and (7) synthesis.

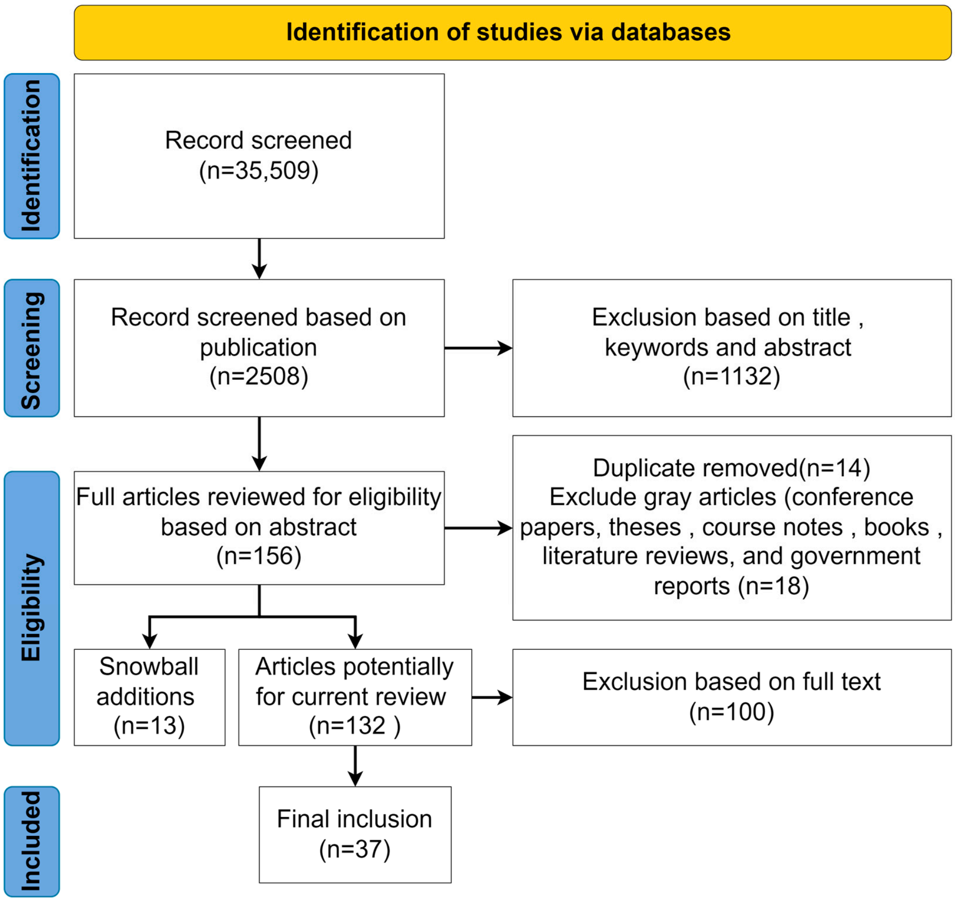

Figure 4. Prisma, from author.

The bibliometric technique was selected as the quantitative method to map and display the dynamic aspects of the knowledge field and research trends. By contrast, the SLR served as a qualitative method for summarizing the current research status, delineating its limitations, and outlining prospects. The fusion of these two methodologies offers several advantages, including the production of more robust, consistent, and unbiased results. Additionally, it enhanced the depth and breadth of knowledge within the field of POE research. Thus, this study adopted a combination of these methodologies.

3.1.2. Eligibility Criteria

This study selected a set of terms derived from the subjects of POE. The Web of Science (WoS) Core Collection was selected as the primary database for this article, owing to its inclusion of peer-reviewed, indexed papers that are highly esteemed among scholars globally. The dataset included 517 papers. The subdatabases included ProQuest Dissertation & Theses Citation, MEDLINE, the Chinese Science Citation Database, the SciELO Citation Index, Inspec, the Biosis Preview, and the Data Citation Index. The articles were refined using the WoS index from Sci-E, SSCI, ESCI, and A&HCI. To obtain high-quality publications, this study used seven filter criteria:

(i) Articles or review papers;
(ii) Peer-reviewed journals published between 2000 and 2023, which accounted for the most recent trends;
(iii) The journal's 3-year average impact factor being >2.5;
(iv) Complete texts linked to POE;
(v) The elimination of duplication and irrelevance;

(vi) Papers indexed in either Scopus or the WoS;
(vii) Papers written in English or Mandarin.

We began by screening 926 peer-reviewed papers by title, abstract, and keywords. The majority of them (179 publications) were then discarded, based on the filter criteria. Finally, we thoroughly reviewed 37 papers that satisfied all of the criteria. The distribution of the 37 publications in the journals/database is shown in Tables 1 and 2.

Table 1. Major journals used in the review.

No.	Journal	3-Year Average Impact Factor	Number of Articles
1	*Sustainable Cities and Society*	10	1
2	*Applied Energy*	10.8	1
3	*Building and Environment*	7.0	13
4	*Energy and Buildings*	6.6	4
5	*Journal of Building Engineering*	6.3	2
6	*Alexandria Engineering Journal*	5.7	1
7	*Building Research and Information*	4.7	1
8	*International Journal of Disaster Risk Reduction*	4.7	1
9	*Health and Place*	4.6	1
10	*Frontiers of Architectural Research*	3.5	3
11	*Sustainability*	3.7	5
12	*International Journal of Environmental Research and Public Health*	3.6	1
13	*Buildings*	3.3	1
14	*Energies*	3.2	1
15	*International Journal of Low-Carbon Technologies*	2.6	1

Table 2. Journal distribution of the 37 research articles reviewed in this study.

No.	Publishing Journal	No. of Articles	Country	Reference (Authors & Year)	Year
1	*Building and Environment*	13	UK	(Agha-Hossein et al., 2013) [10]	2013
2			United States	(Collinge et al., 2014) [22]	2014
3			Denmark	(Gonzalez-Caceres et al., 2019) [23]	2019
4			Turkey	(Göçer et al., 2018) [24]	2018
5			Switzerland	(Pastore and Andersen, 2019) [19]	2019
6			United Kingdom	(Ponterosso et al., 2018) [25]	2018
7			Australia	(Hirning et al., 2013) [26]	2013
8			China	(Li et al., 2018) [27]	2018
10			China	(Huang et al., 2022) [28]	2022
11			Netherlands	(Hou et al., 2020) [29]	2020
12			USA	(Ildiri et al., 2022) [11]	2022
13			Spain	(Martinez-Molina et al., 2017) [30]	2017
14	*Applied Energy*	1	UK	(Menezes et al., 2012) [31]	2012
15	*Journal of Building Engineering*	2	France	(Pannier et al., 2021) [18]	2021
16			China	(Tang et al., 2020) [32]	2020
17	*Energy and Buildings*	4	United Kingdom	(Pretlove and Kade, 2016) [33]	2016
18			Ireland	(Colclough et al., 2022) [34]	2022
19			Brazil	(Silva et al., 2017) [35]	2017
20			USA	(Choi et al., 2012) [36]	2012
21	*Frontiers of Architectural Research*	3	Nigeria	(David Jiboye, 2012) [37]	2012
22			Iraq	(Mustafa, 2017) [38]	2017
23			Mexico	(Mundo-Hernández et al., 2015) [39]	2015
24	*International Journal of Disaster Risk Reduction*	1	Turkey	(Dikmen and Elias-Ozkan, 2016) [40]	2016
25	*Alexandria Engineering Journal*	1	Egypt	(El-Darwish and El-Gendy, 2018) [41]	2018
26	*Sustainable Cities and Society*	1	UK	(Kansara and Ridley, 2012) [42]	2012
27	*Health and Place*	1	Australia	(Carnemolla et al., 2021) [43]	2021
28	*International Journal of Low-Carbon Technologies*	1	Saudi Arabia	(Shawesh and Mohamed, 2020) [44]	2020

Table 2. *Cont.*

No.	Publishing Journal	No. of Articles	Country	Reference (Authors & Year)	Year
29	*Building Research and Information*	1	UK	(Sharmin and Khalid, 2022) [45]	2022
30	*Sustainability*	5	China	(Ning&Chen, 2016) [46]	2016
31			China	(Bai et al., 2022) [47]	2022
32			China	(Khoo et al., 2022) [48]	2022
33			USA	(Asojo et al., 2021) [49]	2021
34			Australia	(Byrne and Morrison, 2019) [50]	2019
35	*International Journal of Environmental Research and Public Health*	1	Denmark	(Sidenius et al.,2017) [51]	2017
36	*Buildings*	1	Singapore	(Lei et al., 2022) [52]	2022
37	*Energies*	1	Brazil	(Bortolini and Forcada, 2021) [13]	2021

3.2. Bibliometric Analysis

3.2.1. Bibliographic Map of POE Research

Bibliometric analysis is an effective approach to illustrate the evolution and emerging trends within a specific sector, allowing for an organized evaluation through an extensive collection of documents [26]. Bibliographic mapping facilitates this process by visually representing the summary of the knowledge structure and employing domain analysis methods [27–29]. It comprises three networks, namely, cocitation, bibliographic coupling, and the co-occurrence of keywords. Bibliographic maps present an easily understood graphical illustration of the results of the quantitative reviews derived from the bibliometric analysis, which helps overcome the substantial subjectivity of the traditional manual review. Finally, to illustrate the current state of POE research, VOSviewer was used to create cocitation networks, clustering analyses, and keyword co-occurrence networks.

3.2.2. Classification of Articles

A co-occurrence matrix is the basis for the map that VOSviewer creates. Four procedures compose the process of creating a map, namely, a similarity matrix, VOS mapping technique and translation, rotation, and reflection. We will now go into greater depth about each of these procedures.

Step 1. Similarity matrix. A similarity matrix is required as the input for the VOS mapping procedure. By normalizing a co-occurrence matrix and adjusting it for variations in the total number of occurrences or co-occurrences of items, a similarity matrix is derived. VOSviewer employs association strength as a similarity metric [30]. The similarity, denoted as s_{ij}, between two items, i and j, is determined using this association strength as

$$S_{ij} = C_{ij}/(W_i W_j), \quad (1)$$

where W_i and W_j denote the overall frequency of either the items i and j or their co-occurrences, and C_{ij} refers to the number of times elements i and j appear together.

Step 2. Normalization. Initially, VOSviewer is used to adjust the nodes' variances in the number of edges they have with one another. Let a_{ij} represent the edge weight between the nodes i and j; if there is no edge between the two nodes, then $a_{ij} = 0$. We always have $a_{ij} = a_{ji}$ because VOSviewer regards all networks as undirected. A normalized network is created by association strength normalization, and the weight of the edge connecting nodes i and j is determined using the following formula:

$$S_{ij} = (2ma_{ij})/(k_i k_j), \quad (2)$$

where m refers to the total weight of all the edges in the network and k_i (k_j) refers to the total weight of all the edges of the node i (node j). Mathematically, the formula is as follows:

$$k_i = \sum_j a_{ij} \text{ and } m = 1/2 \sum_i 〖k_i.〗 \quad (3)$$

The similarity between the nodes i and j is referred to as S_ij. The readers can refer to Eck and Waltman (2009) for a detailed description of the normalization of association strength.

Step 3. VOS mapping technique.

$$V(X_1, \cdots, X_n) = \sum_{(i<j)} s_{ij} \|X_i - X_j\|^2, \quad (4)$$

Herein, in a two-dimensional map, the placement of item i is indicated by the vector "X" _i = (x_i1,x_i2), and the Euclidean norm is denoted by the symbol ||X_i-X_j||. The constraint influences the minimization of the objective function:

$$2/(n(n-1)) \sum_{(i<j)} \|''X''_i - X_j\| = 1. \quad (5)$$

Step 4. Clustering. Finally, for the clustering mechanism of VOSviewer, this function is maximized to assign nodes to clusters. In this context, there is a grouping of nodes (representing the elements of the analyzed data) into distinct clusters based on shared characteristics, thereby revealing underlying patterns, relationships, or thematic similarities within the dataset.

$$V(c_1, \cdots, c_n) = \sum_{(i<j)} \delta(c_i, c_j)(s_{ij} - \gamma), \quad (6)$$

Herein, δ(c_i,c_j) represents a function that equals 1 if c_i = c_j and 0 otherwise. In this context, c_i refers to the cluster to which node i is assigned and a resolution parameter that determines the level of detail in the clustering. A higher value of gamma will result in a greater number of clusters being produced.

3.2.3. Evolution of Papers with Significant Citation Spikes

Figure 5 illustrates that from 2000 to 2004, there was an annual average of six articles published. Subsequently, between 2004 and 2008, there was a notable fluctuation in the number of articles, following which, the number began to increase steadily. This trend signifies a surging level of attention on POE. The significant decrease in publications on POE starting from 2020, with a decline of 12.9% between 2020 and 2021, 4.2% from 2021 to 2022, and 37.7% between 2022 and 2023, could be attributed to several factors. The COVID-19 pandemic likely played a major role, disrupting research activities, shifting priorities, and causing logistical challenges in conducting the field studies essential for POE. Additionally, the economic impact of the pandemic may have led to reduced funding and support for research projects in this area. The marked drop in the most recent period suggests that the aftereffects of the pandemic, including changes in focus towards more immediate public health and digital transformation concerns, may have further deprioritized POE research in the academic and professional communities. In summary, the exponential growth trend depicted in Figure 6 serves as evidence for a significant increase in interest in the field of POE. Figure 5, which depicts the frequency of citations and publications for the publications, exhibits a similar growth pattern. The number of the citations of papers related to POE increased from 2005 to 2022. The number of articles on POE reviewed per author is shown in Figure 7, while that reviewed per research area is shown in Figure 8. Furthermore, it is anticipated that this trend will persist in the future.

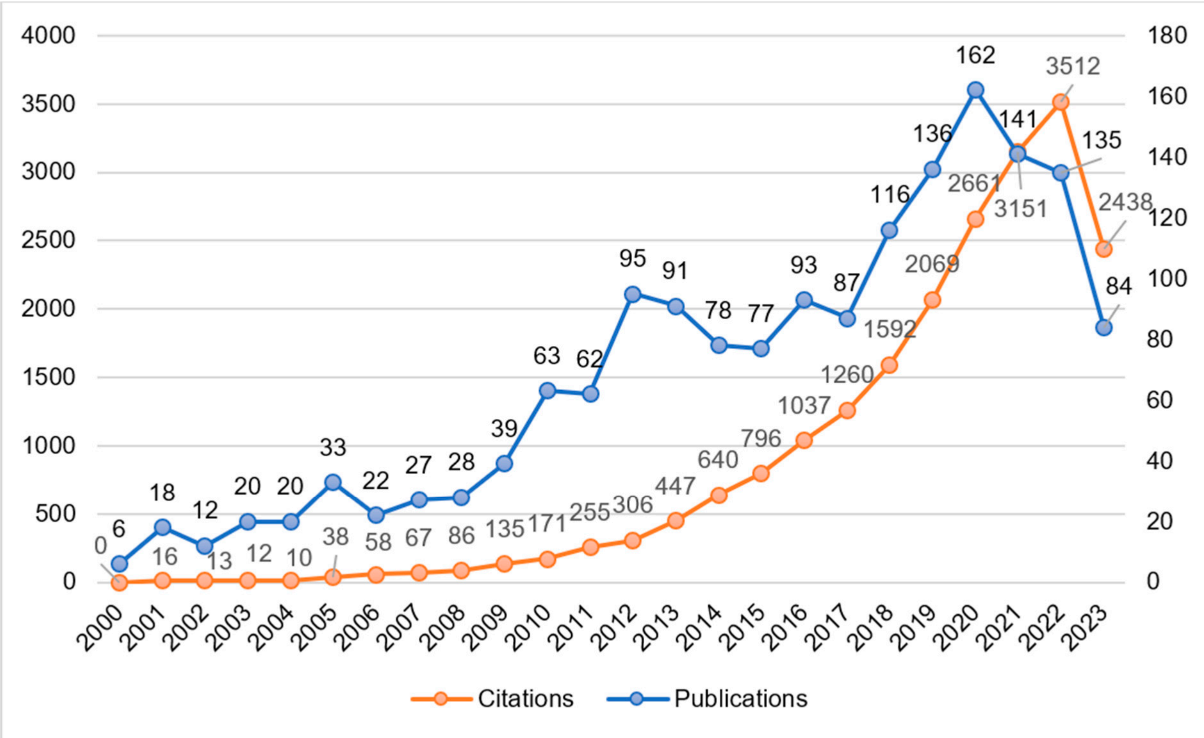

Figure 5. Number of publications and citations from 2000 to 2023.

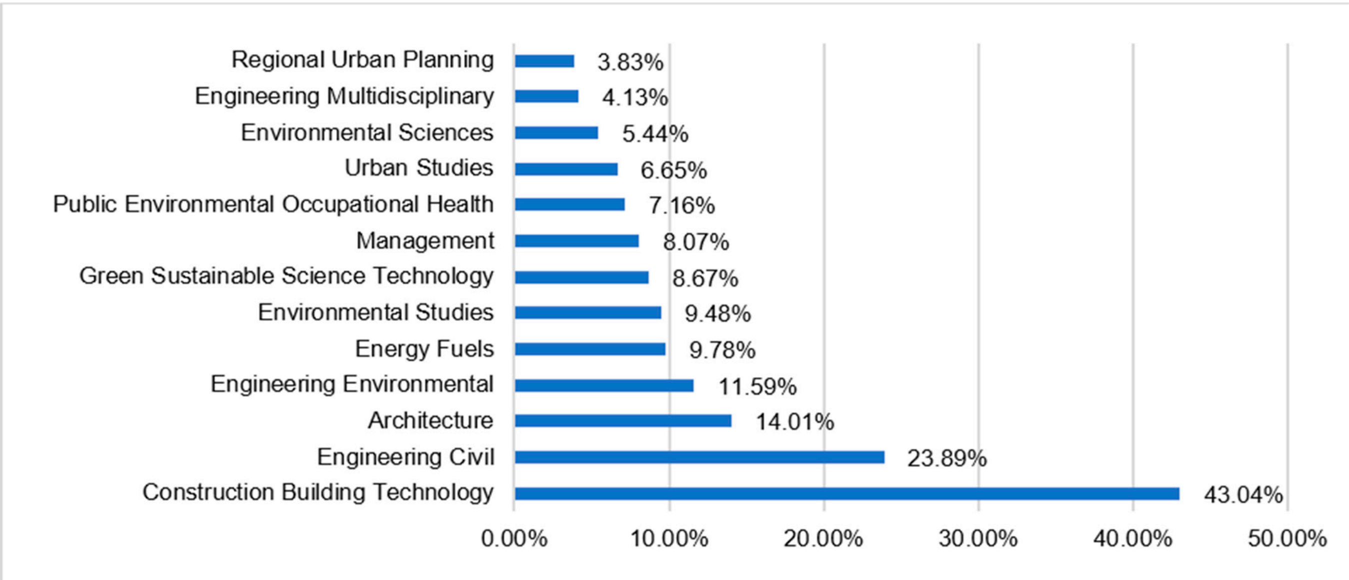

Figure 6. Web of Science Categories.

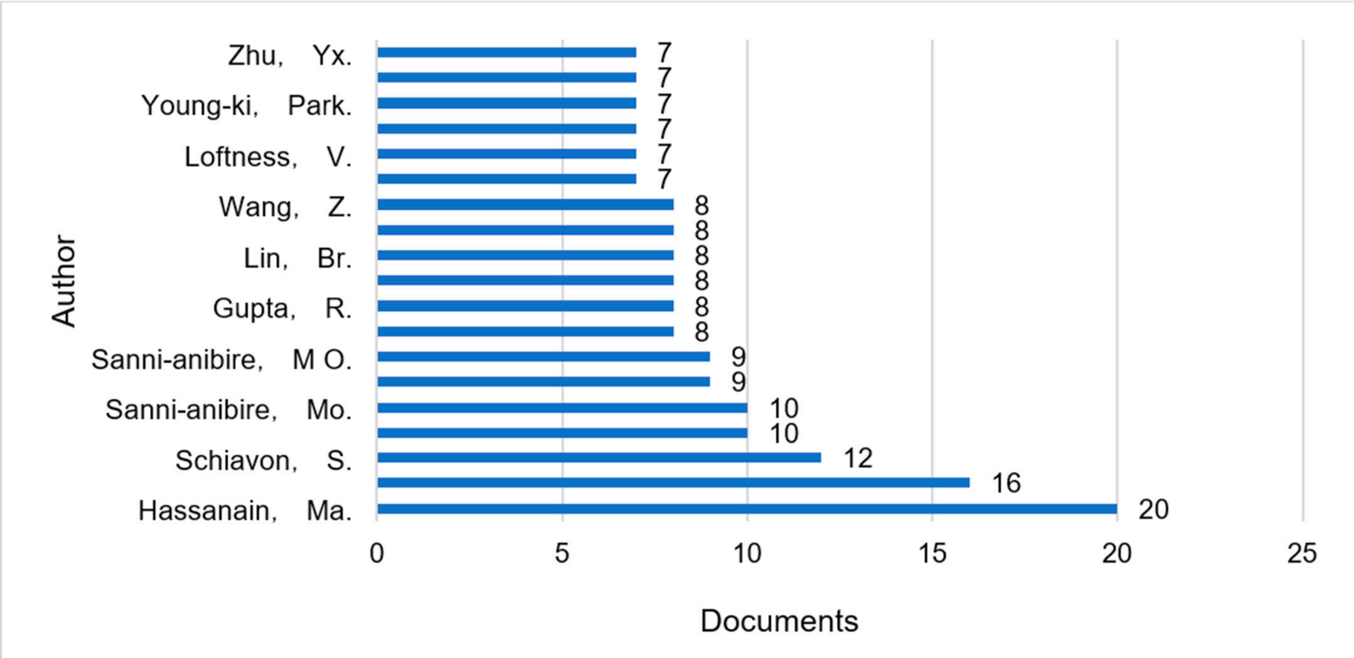

Figure 7. Number of research on post-occupancy evaluation reviewed per author.

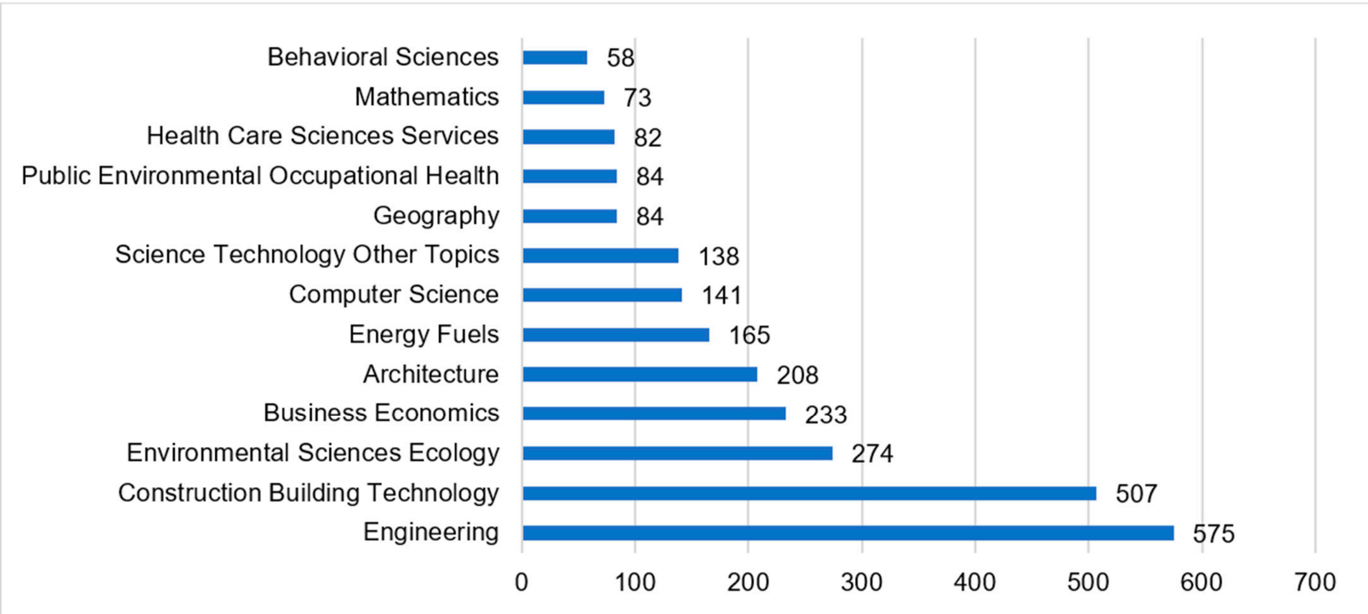

Figure 8. Number of research on post-occupancy evaluation reviewed research areas.

3.2.4. Keyword Co-Occurrence Analysis

To determine the main areas of interest within the POE field, this study used a keyword co-occurrence analysis, which enables a thorough understanding of the regions investigated. Moreover, this approach makes it possible to visualize study topic correlations and development trends, both of which are useful for performing an exhaustive literature review. Co-occurrence maps were created using the VOSviewer 1.6.18 software (Figure 9). A total of 2586 keywords were analyzed, with 90 meeting the threshold, which required a minimum number of occurrences of a keyword (set at 8). The resultant co-occurrence network comprised 90 nodes and 1084 linkages, in which each node represented a keyword. The cumulative link strength amounted to 5610. All 90 keywords satisfied two filtering circumstances: (1) a recurrence frequency >3 and (2) the absence of duplicates. Notably, the magnitude of each node was directly related to the frequency of recurrence.

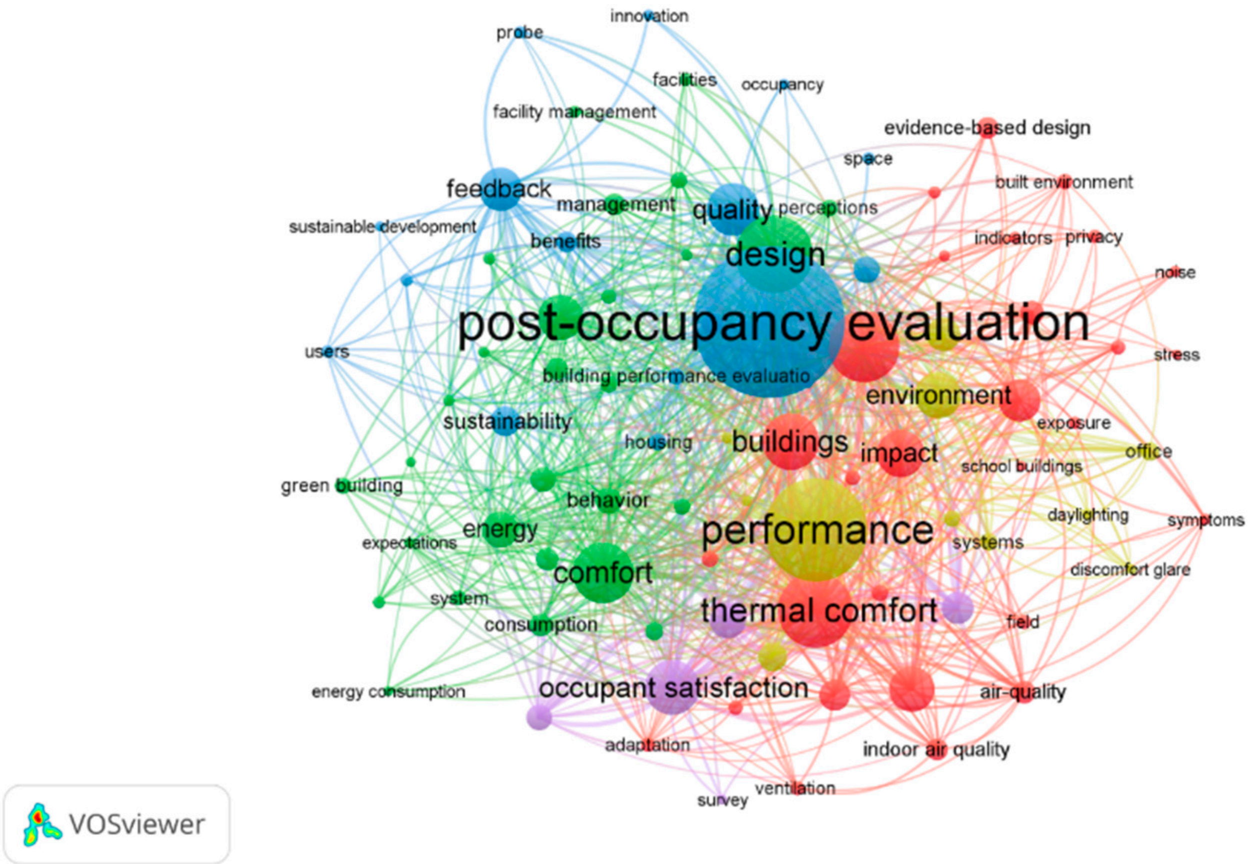

Figure 9. Visualization of the co-occurrence network of POE keywords.

The co-occurrence values of 30 terms are ranked in Table 3. The average year of publication and overall link strength can serve as indicators of the level of annual attention garnered by a particular subject. A higher link strength indicates that these keywords are more deeply connected with a wider range of research themes. High average citations suggest that they have a significant impact on other studies. For example, the keywords "Post-occupancy evaluation", "Performance", "Thermal comfort", "Satisfaction", "Design", "Comfort", "Occupant satisfaction", "Quality", "Buildings", and "Impact" are ranked among the top 10, indicating their significance in the POE field. By contrast, the keywords "sustainability" and "behavior" are positioned at the end of the list, indicating scarce investigation on their integration into POE.

3.2.5. Cluster Analysis

To ascertain the knowledge structure of the POE field and identify research centers, a cluster analysis was used in this study. The classification of the nodes (keywords) into five clusters, each denoted by a specific color, is illustrated in Figure 3, using the VOSviewer program. Cluster 1, represented in red and comprising 29 items, encompasses keywords such as "satisfaction", "thermal comfort", "buildings", "health", "indoor environmental quality", "impact", and "evidence-based design". Cluster 2, in green with 28 items, includes keywords such as "design", "building performance", "comfort", "energy", "energy consumption", and "management". Cluster 3, depicted in blue with 17 items, features keywords such as "post-occupancy evaluation", "feedback", "sustainability", "building performance evaluation", and "benefits". Cluster 4, depicted in yellow with 11 items, incorporates keywords such as "performance", "environment", "model", "systems", "daylighting", and "visual comfort". Finally, Cluster 5, presented in purple and comprising five items, contains keywords including "occupant satisfaction", "green buildings", "productivity", "LEED", and "survey".

Table 3. The top 25 keywords in terms of occurrences.

Rank	Keywords	Occurrences	Total Link Strength	Cluster
1	Post-occupancy evaluation	251	1016	3
2	Performance	151	833	4
3	Thermal comfort	101	573	1
4	Satisfaction	94	568	1
5	Design	105	497	2
6	Comfort	77	475	2
7	Occupant satisfaction	67	447	5
8	Quality	64	357	3
9	Buildings	71	340	2
10	Impact	56	333	1
11	Indoor environmental quality	53	295	1
12	Feedback	50	266	3
13	Green buildings	40	261	2
14	Health	48	261	1
15	Building performance	52	254	2
16	Environment	54	248	4
17	Productivity	33	219	5
18	Office buildings	30	213	1
19	Perception	32	213	2
20	Energy	40	208	2
21	Model	37	199	4
22	Leed	26	181	5
23	Occupants	24	164	2
24	Air quality	22	160	1
25	Workplace	23	155	3
26	Sustainability	31	136	3
27	Behavior	26	129	2
28	Management	21	122	2
29	User satisfaction	27	122	1
30	Benefits	19	121	3

Five primary research areas were identified: (1) the role of POE in enhancing the health and well-being of occupants; (2) exploring the tradeoff between energy consumption, building performance, and human comfort; (3) investigating feedback and sustainability in the context of POE; (4) developing models and systems for building environment POE; and (5) assessing occupant satisfaction in green buildings. These five study topics served as a structured framework for conducting a systematic analysis in the following sections.

3.3. Framework of the Review

After conducting the bibliometric analysis, the SLR was performed to offer comprehensive insights into the field of POE research. The bibliometric analysis identified five significant research domains, which were later categorized into the following four main areas:

1. The development of models and systems for building environment POE;
2. The exploration of the tradeoff between energy consumption, building performance, and human thermal comfort (TC);
3. The nvestigation of feedback and sustainability within the context of POE;
4. The role of POE in enhancing the health and well-being of occupants.

The following five sections provide more detailed information on the SLR. The comprehensive review framework of the study is illustrated in Figure 10.

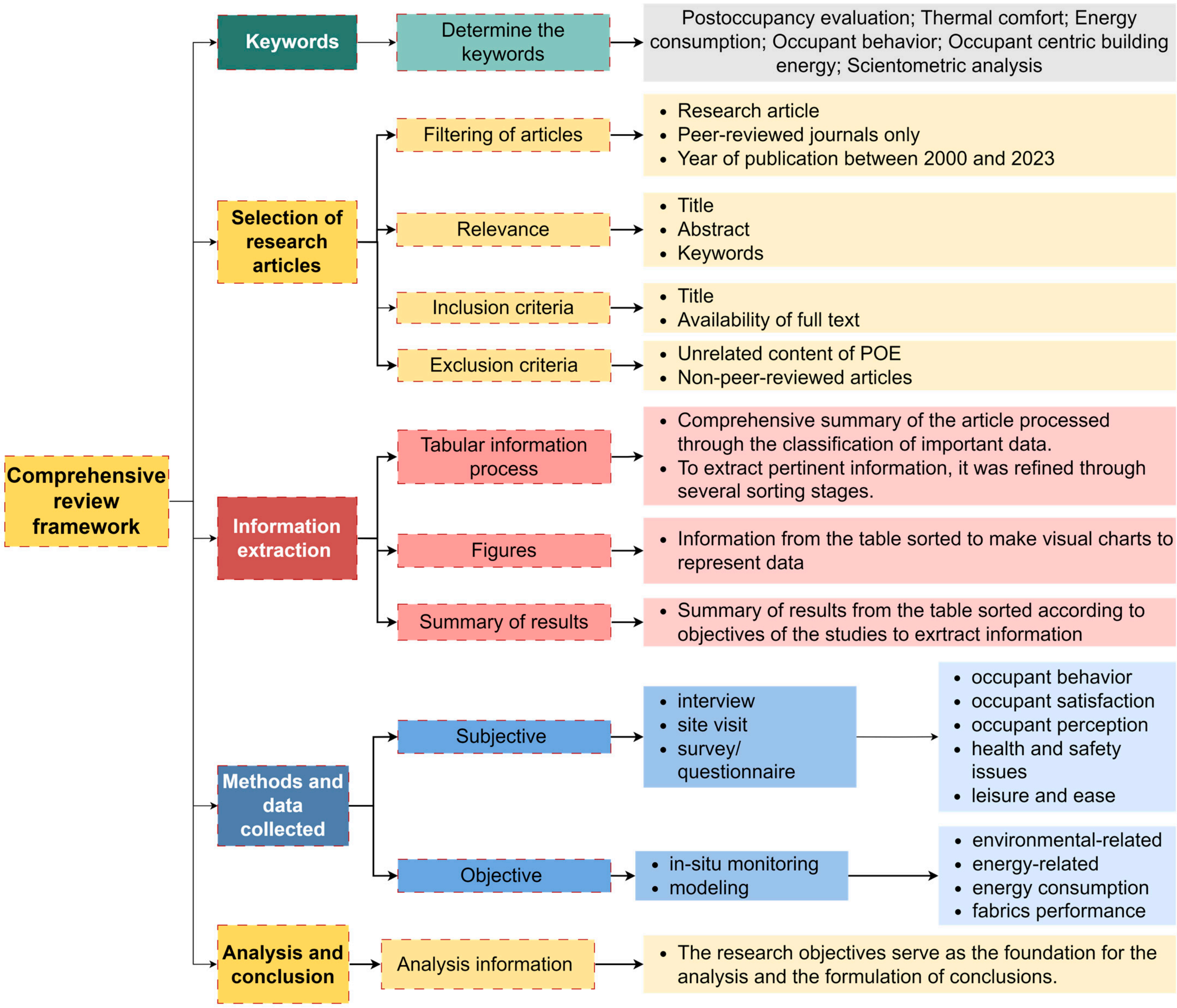

Figure 10. Classification of the primary categories and subcategories of the papers.

A summary of the literature on POE feedback on occupant-centric TC and building energy efficiency is provided in the Supplementary Materials.

4. Synthesis Analysis

4.1. The Development of Models and Systems for Building Environment POE

4.1.1. OB Model

According to Melfi et al. (2011) [53], the concept of active engagement by building occupants with renewable energy sources is a multifaceted mechanism influenced by a wide range of factors. Specifically, the idea of occupancy measurement should encompass evidence related to three crucial dimensions, namely, space, occupants, and time. Temporal resolution refers to the temporal scale, while spatial resolution pertains to the understanding of physical locations, such as whether the model accurately predicts the anticipated number of people in a building or a specific sector. Occupancy resolution encompasses the characterization of OB [6]. Temporal resolution, which ranges from seconds and minutes to weeks and days, indicates the degree of precision utilized to simulate the timing of an occurrence. The capacity of a model to forecast the number of occupants in a building or neighborhood is one example of spatial resolution, which is connected with accuracy on a physical scale. Occupant resolution refers to the method by which the model recognizes individual inhabitants; it can identify models that only know whether a space is inhabited or that can pinpoint the exact activity that an occupant is performing [33]. Sociological and psychological factors considerably influence individuals' behavior within a given space [34]. Generally, as measurement resolution increases, the spatial area becomes more defined, occupants are better characterized, and information becomes more accessible [33]. The resolution levels of the OB models are illustrated in Figure 11.

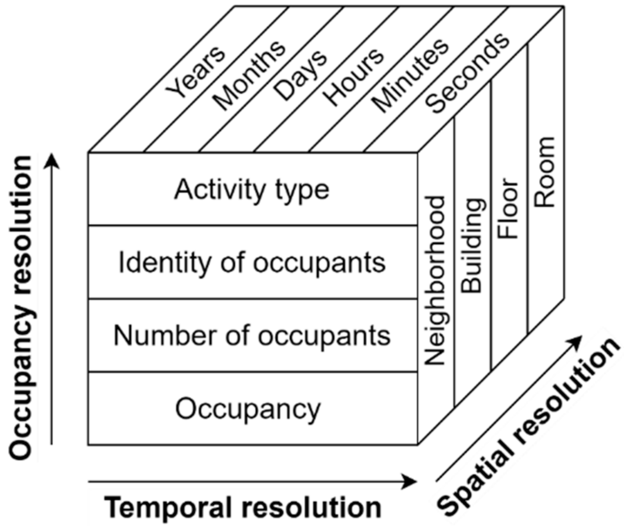

Figure 11. Temporal, spatial, and occupancy resolutions of OB modeling. Adapted from Melfi et al. (2011) [53], Anand et al. (2022) [54], and Ahmed et al. (2023) [55].

4.1.2. OB in Energy Consumption

It is widely recognized that OB is a primary factor influencing building energy consumption. The complexity of its creation mechanisms and its dynamic relationship with architectural design have generated considerable debate [6]. Traditionally, research on OB within buildings has been predominantly conducted within the social sciences, particularly environmental psychology, rather than architecture. Numerous reviews highlight how this discipline has developed up to the present as a popular area of study today [33]. Additionally, studies have documented that variations in electricity and gas consumption among dwellings with similar specifications underscore the substantial impact of differing occupancy patterns and behaviors on energy consumption [37].

In the last decade, key developments in the study of OB in energy consumption have focused on OB modeling and simulation, empirical approaches, field experiments, and advancements in real-time data collection and analysis [48,56,57]. Advances in computational models have enabled more accurate simulations that incorporate complex variables, such as behavioral patterns, weather conditions, and building characteristics, enhancing the precision of energy consumption predictions [27,33,58,59]. Empirical research, through field experiments, has provided critical insights into the gap between predicted and actual energy use, aiding in the development of more effective energy-saving strategies [19,42,60,61]. Additionally, the integration of Internet of Things (IoT) technologies and Digital Twins has transformed data collection and analysis, allowing for the continuous monitoring of and real-time adjustments to energy management systems based on occupants' behavior [48,56,57]. These advancements highlight the multidisciplinary nature of OB research, merging engineering, behavioral sciences, and data analytics to promote more sustainable building practices.

4.2. Exploration of the Tradeoff between Energy Consumption, Building Performance, and Human TC

Balancing energy efficiency and human comfort in sustainable building design requires interdisciplinary investigation into materials, insulation, HVAC systems, and occupant behavior to develop comprehensive solutions that minimize the environmental impact while ensuring occupants' well-being [11,62].

4.2.1. Energy Consumption

Amidst global urbanization, the primary impediment to sustainable urban development that has emerged is energy consumption related to building use and maintenance [45]. While renewable sources currently account for ~30% of energy consumption in the global electrical sector, there are still obstacles to overcome in the heating and transport sectors (Figure 12). Building energy consumption and environmental impacts are significantly influenced by how humans engage with buildings [41]. Notably, >80% of energy consumption occurs during the real occupancy operation stage, underscoring the importance of post-occupancy evaluation performance in determining overall sustainability. However, notably, green building labeling currently relies on data collected during the preconstruction stage [50], despite substantial evidence indicating that actual energy consumption in buildings consistently falls short of the anticipated targets or intended standards [9]. Bordass et al. (2016) [63] coined the term "credibility gap" to describe this phenomenon.

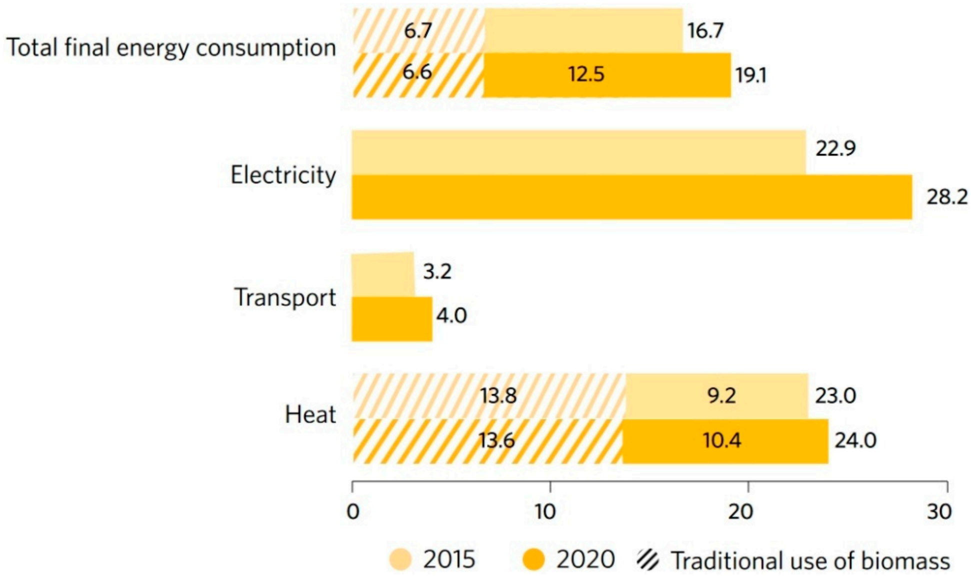

Figure 12. Percentage of renewable energy sources in the total energy consumption by end-use, between 2015 and 2020.

According to a study conducted on the postretrofit performance of a community of 12 one-story, one-bedroom social houses located in the southeast of Ireland, there is a direct link between higher-than-normal indoor temperatures and higher energy consumption, which is mainly caused by inefficient heat pump operation [51]. Moreover, time–use surveys have been used to pinpoint patterns in energy and occupancy usage [52,56]. Thus, employing a real-time model of OB to compare it against the expected maximum occupancy profile for HVAC control has the potential to decrease energy consumption while maintaining the desired levels of temperature and humidity comfort [57]. A previous study on restoration projects demonstrated that significant reductions in energy consumption can be achieved for pre-existing buildings with elevated energy usage through the integration of renewable energy sources and/or energy-efficient technologies [9].

4.2.2. Multi-Domain Comfort

As defined by the World Health Organization (WHO), "Health is not merely the absence of disease or infirmity; it is a state of complete physical, mental, and social well-being". Furthermore, according to the WHO, TC is "a state in which individuals are content with the thermal environment" [58]. When assessing the sustainability of buildings, it is crucial to thoroughly analyze the balance between energy consumption, building performance, occupant health, and human well-being.

To achieve optimal energy efficiency in buildings, architects must carefully consider the design and functionality of the structure. This entails not only reducing energy consumption but also enhancing the overall performance to meet evolving sustainability criteria. Moreover, it is essential to evaluate the impact of these decisions on human comfort, as occupant well-being is a fundamental measure of architectural success. Previous studies have highlighted a "performance gap" between users' subjective comfort experiences and the scientifically defined comfort requirements [59].

The existing body of research delves into the complex interplay between efficiency, performance, and comfort within building ecosystems that align with ecological imperatives and occupants' needs. For instance, Martinez-Molina et al. (2017) [30] employed questionnaires to subjectively assess TC in a historic primary school in Villar del Arzobispo, Spain. Their findings revealed disparities between the subjective perceptions of 6- and 7-year-old students and teachers, indicating differing indoor TC thresholds, with children generally experiencing a greater and more stringent threshold for comfort.

In addition, the input elements were promptly categorized into two groups, human and environmental, as depicted in Figure 13. Subsequently, they underwent a further summary analysis. The information on the human components was further divided into three categories, namely, anthropometric, physiological, and behavioral data.

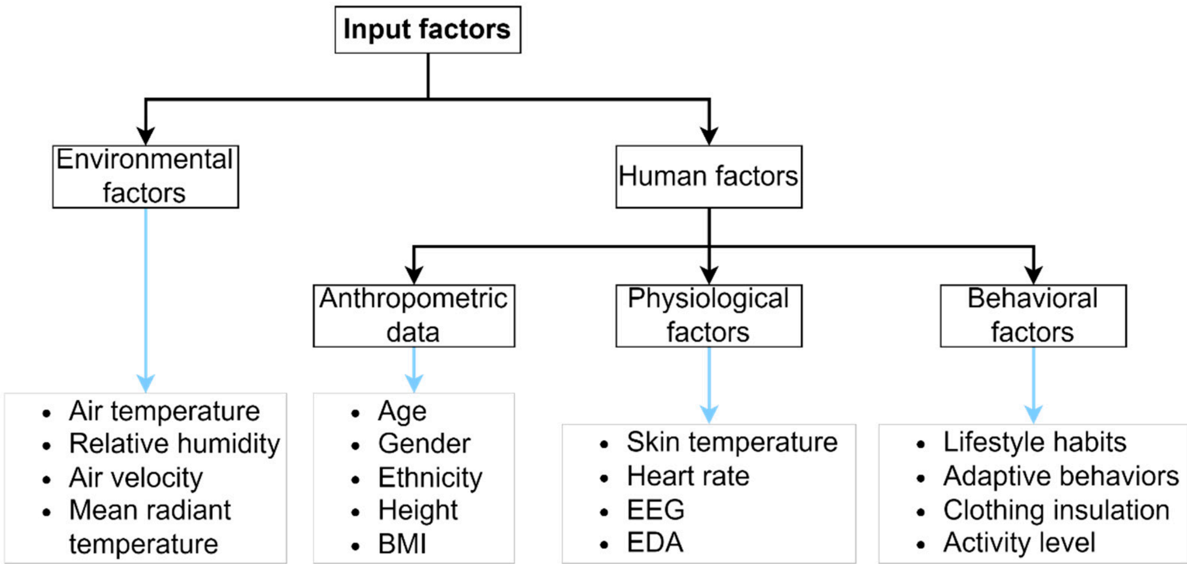

Figure 13. Summary of input factors for models predicting TC. Adapted from Feng et al. (2022) [64].

TC is a critical aspect of sustainability in Great Britain, involving a complex interplay of factors such as the indoor temperature, humidity, and the mean radiant temperature [61]. The evaluation of TC has predominantly relied on the predicted mean vote and the predicted percentage of dissatisfaction models, as evidenced by previous studies [65]. These models consider various environmental and personal characteristics, such as air temperature, radiant temperature, relative humidity (RH), air speed, and subjective feedback, including the thermal sensation vote, TC vote, and thermal preference, which are essential for training and evaluating data-driven TC models [66].

The building automation system plays a pivotal role in enhancing TC by initially regulating HVAC, lighting, and other equipment to reduce energy consumption within the building's grid. It then autonomously adjusts IEQ factors, thereby improving the TC levels of occupants [67]. This process is supported by the thermal adaptation theory, which posits that adaptation encompasses behavioral, psychological, and physiological dimensions [68]. To effectively model TC, it is imperative to gather input data that include both environmental elements (namely, air temperature, radiant temperature, RH, and air speed) and personal factors related to physiological or behavioral responses, alongside subjective feedback. This comprehensive approach enables the categorization of influencing factors into six distinct groups (Figure 14), facilitating a nuanced understanding of TC [66].

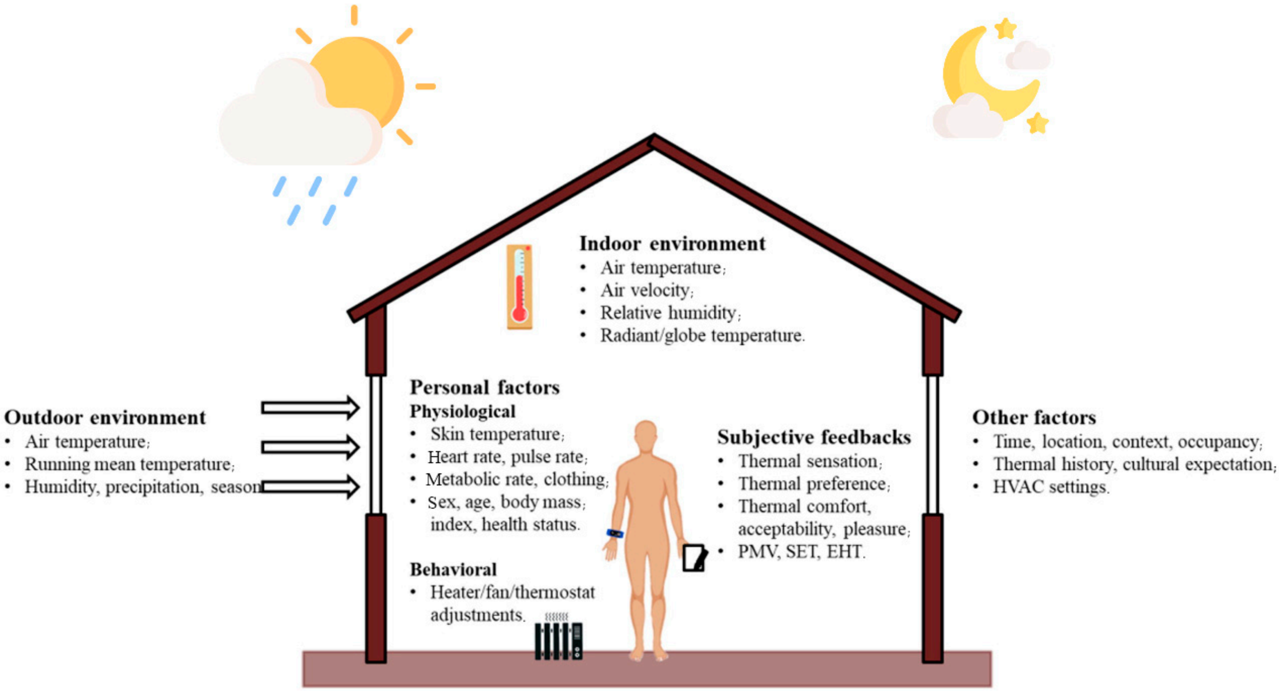

Figure 14. Elements that impact the TC of building occupants. Adapted from a previous study [66].

4.3. The Investigation of Feedback and Sustainability within the Context of POE

Building performance feedback can provide valuable insights for the building industry by facilitating the closure of feedback loops in the design process. As a result, POE could become a prominent source of information for the building sector [18]. Activities related to POE facilitate the collection of crucial data on a wide range of factors, including socioeconomic variables, occupancy and work patterns, transportation, IEQ, water usage, office design, ergonomics, aesthetics, workplace wellness, rest, health and well-being, personality, and overall assessment. The University of Melbourne's Sustainable and Healthy Environments Survey is an example of such an endeavor [69].

Feedback strategies play a crucial role in this context and are classified into five distinct categories, namely, audit, conversation, questionnaire, package, and process [70]. However, despite the acknowledged importance of feedback, the predominant sustainability rating systems for buildings prioritize energy, water, and IEQ metrics but often overlook the necessity of occupant feedback. This oversight suggests that a comprehensive strategy should be adopted when evaluating building performance to truly achieve sustainability goals [15].

Energy certification systems, such as LEED, provides a framework for green buildings. There are >200 U.S. higher education institutions with sustainability agendas that include certified sustainable buildings, with >200 having at least one LEED-certified building on campus [15]. However, several research studies suggest that the LEED certification system may create distorted safety expectations owing to inadequate consideration of OBs and feedback [15].

Research underlines the importance of having feedback and consistent actions from key actors such as owners, designers, tenants, facility management, and residential life personnel for sustainability goals to be achieved [15]. By examining the interaction between user feedback and sustainable practices, the findings from this project can help bridge the gap between sustainability ratings and actual building performance, ensuring that design and operational decisions are informed by comprehensive performance evaluations and feedback mechanisms.

4.4. The Role of POE in Enhancing the Health and Well-Being of Occupants

POE plays a crucial role in enhancing the health and well-being of occupants in buildings. It is a process of assessing the performance of a building environment after occupation and use. POE involves gathering feedback from the occupants, observing the building's functionality, and analyzing various aspects of its design and operation. Preiser [71] suggests that conducting POEs of buildings might mitigate adverse effects on health, safety, circulation, temperature, aesthetics, and maintenance [71].

Disagreements regarding the adequacy of space provided for residents may lead to dissatisfaction with their living conditions [72], which, if persistent, could result in pathological conditions, stress, poor health, delinquency, and maladjustment [40]. An inadequately constructed environment has a detrimental impact on human health and work efficiency [73]. Multiple studies have demonstrated the significant influence of the building environment on health, productivity, well-being, and job satisfaction [11,19,73,74].

The connection between health and well-being and the indoor environment is critical. An inadequate IEQ directly impacts health and well-being, leading to more sick days, a higher incidence of asthma, a greater reliance on medication, and a reduced life expectancy among older individuals [45]. Research has established a clear link between high temperatures and mortality rates, emphasizing the importance of improving a building's IEQ through retrofitting [35,75].

However, the correlations between human health, well-being, and the advantages of improving a building's IEQ are not well supported by real-world information on the effects of building refits [76]. This poses a challenge for the development of highly efficient and healthy buildings. Nonetheless, studies show that most factors related to occupants' happiness and the perceived mental health of occupants exhibit significant impact sizes, with improvements in occupant-reported physical health and self-assessed productivity from before to after occupancy, although the impact sizes were small [11].

Researchers have found that implementing measures to enhance occupants' health and well-being in the workplace can lead to improved physical well-being and ultimately greater job satisfaction [77]. A strong positive correlation exists between workers' perceived well-being, productivity, and happiness at work and their satisfaction levels with "interior use of space" and "physical conditions" [10]. In this context, various studies provide insight into the effects of the building environment on occupants. For instance, Ho et al. (2008) [78] conducted two surveys, namely, using an analytic hierarchy process to investigate building health and safety while evaluating the similarity of perceived selection factors by contacting construction specialists and using input from experts to create an automated decision method to assist school districts in choosing the most appropriate external and building systems. Carnemolla et al. (2021) [43] examined the impact of physical living surroundings on the implementation of residential care for aged individuals with mental health disorders, alongside the viewpoints of the staff. In conclusion, POE is essential for organizations when evaluating employee happiness and possibly even more so when creating action plans to improve workplaces. It offers a structured approach to assess and improve the building environment, ultimately enhancing the health, well-being, and productivity of its occupants.

5. Results and Discussion

This section presents the findings from our review of comprehensive POE feedback on occupant-centric thermal comfort and building energy efficiency. The discussion integrates these findings with the existing literature to highlight key themes, insights, and implications for future research and practice.

5.1. Thermal Comfort Feedback

The analysis of POE feedback reveals a significant emphasis on thermal comfort among building occupants. Most studies indicate a disparity between the design expectations and the actual comfort levels experienced by occupants [29,44,50,65,79]. Occupants exhibit diverse thermal preferences, influenced by factors such as age, gender, activity level, and cultural background, which challenges the effectiveness of a one-size-fits-all approach to thermal comfort [17,20,25,32,65]. The application of adaptive comfort models, which allow for greater flexibility in temperature settings based on occupants' behavior and preferences, has shown promise [28,50,61,66]. These models account for seasonal changes and personal adaptive actions, such as adjusting clothing or using personal fans [50,65,66]. Additionally, several studies highlight the discrepancies between measured thermal conditions (e.g., temperature, humidity) and the perceived comfort reported by occupants, suggesting that objective measurements alone may not fully capture the thermal experience of individuals.

5.2. Energy Efficiency Feedback

Feedback on building energy efficiency is intertwined with thermal comfort, as efforts to optimize energy use can impact occupants' comfort. Buildings designed with energy-efficient strategies, such as enhanced insulation, advanced glazing, and energy-efficient HVAC systems, generally receive positive feedback regarding their energy performance; however, the success of these strategies depends on their proper commissioning and ongoing maintenance [13,42,65]. Occupants' behavior significantly influences building energy performance, with feedback indicating that occupants often override automated systems (e.g., opening windows, using personal heaters), leading to increased energy consumption [8,67,68]. Effective occupant engagement and education are crucial for aligning occupants' behavior with energy efficiency goals. Achieving a balance between thermal comfort and energy efficiency remains a challenge, as overly stringent energy-saving measures can lead to discomfort, prompting occupants to take actions that counteract energy-saving efforts, while strategies that prioritize comfort can sometimes compromise energy efficiency [13,27,65].

5.3. Implications for Building Design and Operation

The findings from the POE feedback provide several implications for building design and operation. Incorporating user feedback into the design process can enhance both comfort and energy efficiency [34,41,59,60,80]. Designing with occupants' preferences and behaviors in mind, and providing adaptive solutions, can lead to more successful outcomes [22,80]. Conducting POE should be an ongoing process, rather than a one-time assessment. Continuous feedback can help identify emerging issues and inform timely interventions to improve building performance [29,31,34,69]. Additionally, advanced building management systems that integrate real-time feedback from occupants with automated controls can enhance both comfort and energy efficiency [17,27,42]. These systems can adapt to changing conditions and occupants' needs dynamically.

POE is an established approach for collecting feedback on the overall performance of a building after occupation. Reviewing and categorizing the papers allowed us to summarize the key characteristics of the analyzed POE research. The components of this study included the research purpose, case study, data gathering methods, collected data, monitoring, research method, and data analysis. Previous research on renovation projects has demonstrated that integrating renewable energy and/or energy-efficient technologies can result in notable energy savings for existing buildings with high energy demands.

The results demonstrate that feedback systems are crucial in influencing occupant-centric TC and the energy efficiency of buildings. Occupants' feedback is essential for understanding their thermal preferences and can be used to make design alterations and operating strategies that improve sustainability. The analysis illustrates a mutually beneficial relationship between the well-being of occupants and the energy efficiency of buildings, highlighting the importance of a balanced and occupant-focused strategy in designing and managing buildings. Moreover, the influence of feedback on promoting sustainable behaviors among those occupying a space was investigated. An understanding of energy consumption patterns, OBs, and their interactions with building systems helps in creating strategies that encourage a more sustainable and energy-efficient building environment.

6. Current Study Limitations and Suggestions for Further Research

While this review highlights valuable insights, several limitations must be acknowledged. The findings from POE feedback are often context-specific, influenced by the building type, climate, and occupant demographics. Caution should be exercised when generalizing the results to different settings. The methodologies used for collecting POE feedback vary widely, affecting the comparability of results. Standardized approaches to POE could improve the consistency and the reliability of feedback. The rapid development of building technologies presents both opportunities and challenges. Future research should explore the impact of emerging technologies, such as smart building systems and wearable comfort sensors, on thermal comfort and energy efficiency.

This study concludes by highlighting the significance of integrating occupants' feedback into the POE process to accomplish complete sustainability objectives. Incorporating occupants' experiences, preferences, and behavior into building design and operation contributes to a more sustainable building environment. This enhances the discussion on occupant-centric TC and building energy efficiency within the broader context of sustainability. Nevertheless, certain constraints need careful attention for future investigations. First, the review may not include all newly developed technologies and design techniques that are important to the subject, which might limit the thoroughness of the conclusions. Moreover, a significant proportion of the examined research was conducted in certain geographic areas, which might have introduced cultural and contextual biases. In addition, in the future, a more thorough examination of the methodological techniques used in this review could be conducted to strengthen the reliability of the results. Future investigations may expand the current review's scope by incorporating a wider array of studies, adopting a global viewpoint, and delving deeper into the methodological aspects of the research. This will facilitate a more in-depth understanding of the intricate correlation between occupant comfort and energy efficiency in buildings.

There has been increasing research on the influence of inhabitants' behavior on buildings, owing to the need to tackle the difficulties engendered by climate change. Considerable research has been conducted on how occupants impact energy consumption in buildings, to reduce the discrepancy between the expected and actual energy usage. Current energy analysis methodologies frequently do not completely account for the active and passive energy behaviors of inhabitants, including window opening, the use of solar shades and blinds, changes in HVAC setpoints, and hot water usage.

Therefore, there is a critical need for energy modelers, researchers, and designers to improve the precision of building energy consumption estimations by including the inhabitants' energy behaviors. However, the main problem is the complex and ever-changing energy behavior of the occupants, which is affected by various internal and external, individual, and contextual elements. Thus, it is crucial to have a thorough grasp of the occupants' motives and reasons and the various aspects that influence their decisions to engage with building systems. A multidisciplinary approach involving sociology, psychology, economics, engineering, and design is required to understand how occupants' behaviors affect a building's energy use.

The significant influence of POE on building energy efficiency, OB, and TC has garnered considerable attention over the last two decades. To gain an extensive understanding of this field, this research employed bibliometric and content analyses to examine 926 journal articles related to POE. POE research has evolved from basic discussions of individual OB to a more systematic and data-driven approach to intricate behaviors. The study identified 30 primary research keywords that form the foundation of POE. Key factors include TC, occupant satisfaction, energy efficiency, building performance, feedback, behavior, sustainability, energy consumption, and IEQ. The primary objective of POE research is to enhance the energy efficiency of buildings while ensuring that their occupants' comfort remains uncompromised.

This research employs a unique approach by combining bibliometrics and a content analysis of the literature to impartially generate a substantial amount of information and fresh insights into occupant-centeredness in buildings. The technique used in this research may be universally implemented and serves as an efficient approach to presenting a comprehensive overview of a particular field of study in contrast to the conventional manual assessment that mainly relies on specialists' subjective judgment. The findings of this study provide valuable insights into the evolutionary trajectory, present state, and prospective trajectory of the research on OB. Notwithstanding these benefits, this study has two constraints.

First, the dataset originated from WoS, which lacked the inclusion of all the significant journals, perhaps resulting in the omission of crucial papers. It is advisable to examine other databases for future studies, such as Taylor & Francis, Wiley, and ASCE Library. Furthermore, although the general identification of clusters is precise, there may be some inaccuracies in categorizing some terms owing to the algorithm's stability. Subsequent research is recommended to enhance the algorithms in bibliometrics.

This study conducted a comprehensive review of >100 publications related to occupant energy behavior in buildings, aiming to identify research gaps for future studies. The key findings are presented below:

- A thorough understanding of the interaction between inhabitants and building systems is crucial for the accurate forecasting and effective implementation of energy management measures. Previous studies have extensively examined several facets of this correlation, such as energy usage, the operation of ventilation systems (or air conditioning), and the utilization of building openings such as windows and doors. Nevertheless, there is scant research specifically on the impact of hot water use on energy usage in various types of structures, particularly in residential environments. Despite being acknowledged as significant, the use of hot water has been subject to little research, highlighting the need for more study. The ramifications of this lack of research are substantial, especially when considering the acknowledged influence of hot water use in certain architectural scenarios. Future studies should prioritize a thorough investigation of the exact dynamics of hot water usage and the exploration of the inter-relations among different energy behaviors shown by renters. Acquiring a thorough understanding of the interaction and influence of numerous energy-related activities is crucial for creating more accurate predictions when estimating building energy use.
- Many studies employ comprehensive methodologies that involve case studies and experiments. These studies utilize various types of qualitative and quantitative data that are collected through surveys conducted before and after occupancy, the monitoring of occupants through sensors or observation, field measurements, and questionnaires. The data are then analyzed using techniques such as Markov chain, Monte Carlo, and logistic regression, as well as simulations. The research results have enhanced our knowledge of how tenants' activities affect energy use in buildings. Currently, the studies have not yet provided substantial progress on forecasting the energy behav-

ior of tenants in buildings. Specifically, incorporating the results of these studies into building energy modeling tools to narrow the discrepancy between anticipated and real energy use in buildings continues to be a major research obstacle in this field.

- With the enhanced accessibility and accuracy of building energy data, there is an opportunity to focus on creating statistical models for the electricity demand, electrical power factor, and domestic water use, including occupancy as an independent variable, and exploring new model forms.
- This systematic research has shown several attributes of the occupant demand in buildings via POE. These factors include the presence of occupants that are only partial in both time and location, the varied and diverse needs of occupants in terms of quality and quantity, and the need for management and adaptation with flexibility. Energy-sufficiency techniques can significantly reduce both energy usage and carbon emissions in response to these demand patterns.

In conclusion, this review underscores the importance of incorporating comprehensive POE feedback into the design and operation of buildings. By prioritizing occupant-centric thermal comfort and integrating energy efficiency measures, it is possible to create sustainable, comfortable, and energy-efficient built environments. Future research should continue to explore innovative solutions and methodologies to address the evolving needs of building occupants.

7. Conclusions

In summary, the current knowledge offers a strong foundation, but there is a pressing need for continued exploration and analysis, particularly in areas that have received limited attention thus far. Through targeted research efforts, we can uncover hidden complexities in occupants' interactions with building systems, leading to more informed decisions in energy-efficient design and management. Furthermore, POE emerges as a powerful tool in the pursuit of creating indoor environments that enhance the health and well-being of their occupants. By systematically assessing various aspects of the indoor environment and addressing concerns, POE contributes to the creation of spaces that not only meet functional requirements but also prioritize the physical and mental health of those who inhabit them. This section highlights the imperative role that POE plays in the ongoing dialog surrounding sustainable and occupant-centric design practices. This research contributes to achieving the SDG of enhancing inclusive and sustainable urbanization by 2030 and seeks to enhance collaborative, comprehensive, and sustainable urban development planning and administration worldwide.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings14092892/s1, Table S1: Summary of literature on postoccupancy evaluation feedback on occupant-centric thermal comfort and building energy efficiency.

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