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A state-of-the-art, systematic review of indoor environmental quality studies in work-from-home settings

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A R T I C L E I N F O

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A B S T R A C T

The COVID-19 pandemic has led to a significant increase in working from home worldwide, making the work-from-home (WFH) setting a crucial context for studying the influence of indoor environmental quality (IEQ) on workers' well-being and productivity. A narrative and visual synthesis of 41 research articles on IEQ in WFH settings was conducted to identify the IEQ factors being measured and their correlations with perceived productivity and well-being. This review shows that the IEQ conditions at home were mainly within the recommended international standards. However, some high maxima were recorded, particularly for metrics related to quality of indoor air partly due to wider availability of evidence, which raised concerns regarding the suitability of indoor conditions while working from home. Despite the presence of these high maxima, workers generally rated all environmental factors highly. This could possibly reflect their lack of awareness of changes in environmental conditions, suggesting that monitoring environmental conditions might be necessary when working from home. Compared with traditional offices, workers seemed to be more satisfied with the environmental conditions at home although some WFH settings were found to be deficient in sound insulation, ergonomic and technological support, leading to multiple health complaints. Several studies have also demonstrated significant correlations between assessments of IEQ and ergonomics and those of productivity, physical and mental well-being. Future IEQ studies in WFH settings should consider using a longitudinal study design and including more representative samples, different seasons, multi-domain analyses, and multicountry and multicultural settings.

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1. Introduction

The work-from-home (WFH) setting has been thoroughly examined for its impacts across sociological, behavioral, organizational, and economic dimensions [1–3]. Some studies argue in favor of separate settings for work and non-work (e.g., domestic) activities, by arguing that working from home may lead to conflict in roles, household distractions [4], feelings of physical isolation and temporal separation [5] due to reduced social interaction [4,6], feelings of loneliness [7] and a lack of sense of organizational belonging [8,9], increase in work-related stress [10,11] or stress of keeping pace with the technological changes, also known as technostress [12–14], which in turn reduces job satisfaction [15]. However, there is also a wide range of studies that focus on the positive and desirable effects of WFH, such as better work-life balance [16], flexibility in work schedules [17], environmental-impact reduction [18–20], efficient use of organizational resources [21,22], better job performance [22], job satisfaction, and reduction in stress [4,23].

Before the COVID-19 pandemic, approximately 8 % of workers worldwide (260 million) worked permanently from home [24]. As infections spread globally and individual countries issued stay-home orders, almost four out of ten employees in Europe started working from home [25]. More specifically, 60 % of employees in Finland; over 50 % in Luxembourg, the Netherlands, Belgium, and Denmark; and around 40 % in Ireland, Austria, Italy, and Sweden were working from home. Based on a national survey of more than 4600 people conducted in Canada between March 29 and April 3, 2020, an estimated 4.7 million people transitioned to working from home during that week [26].

Approximately 18 % of the global workforce works in occupations and lives in countries where they can effectively WFH [27]. Globally, 16 % of companies are now fully remote, and nearly 62 % of workers aged 22–65 claim to work remotely, at least occasionally [28]. A survey of technology companies in 2020 found that approximately 74 % planned to permanently shift to remote work after the COVID-19 pandemic [29].

People spend most of their day indoors [30], but the time spent at home is likely to be relatively longer for a portion of the population that works remotely. Indoor environmental quality (IEQ) is known to impact productivity and well-being [31,32]. Poor IEQ has long been associated with health risks to occupants; the sick building syndrome (SBS) is one such risk [33]. The annual cost attributed to SBS in workplaces is estimated to be between $10–70 billion in the U.S [34]. Nevertheless, WFH reviews have focused on assessing the consequences of moving to a WFH setting without considering the impact of the built environment on the observed changes in productivity and well-being [1–3].

Residential spaces are designed for other activities such as sleeping, relaxing, or cooking, and may not have ideal IEQ conditions for promoting well-being and productivity while engaging in office-type work. In addition, offices are generally held to more stringent IEQ performance standards than residential buildings. Therefore, it is imperative to evaluate IEQ conditions in WFH spaces. The objective of this review is to identify and describe IEQ variables in WFH settings, assess their impact on occupant perceptions, and explore their associations with productivity and well-being. This review aims to compare assessment methodologies across studies, and identify research gaps. Furthermore, it proposes recommendations for future WFH environments from an IEQ standpoint in order to enhance understanding of, and guide improvements in, remote workspaces.

2. Methods

The review process illustrated in Fig. 1 is based on the 2020 version of the "preferred reporting items for systematic reviews and meta-analyses" (PRISMA) schema [35]. The schema was adapted to include the automated processes used during the pre-processing and screening stages. The right-half of the flow diagram documents the

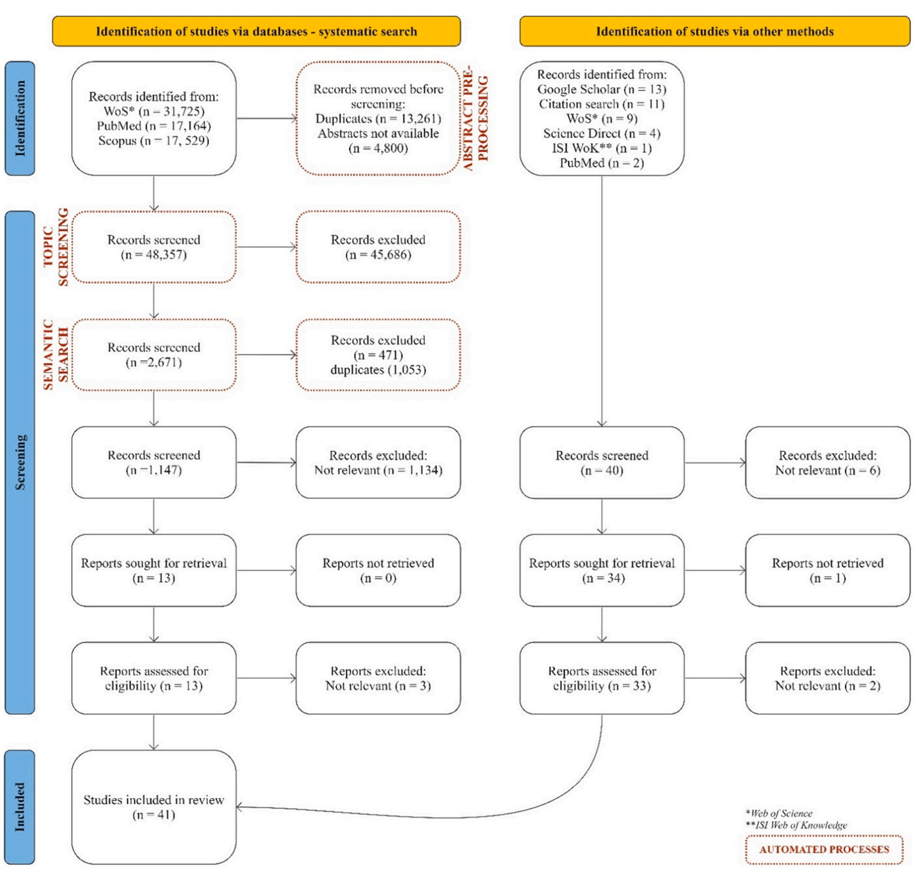

Fig. 1. Review process flow diagram.

'non-systematic' literature search and screening; the conventional systematic process is shown on the left.

This review was limited to studies conducted in WFH settings, specifically in residential spaces. Although one could argue that other environments, such as co-working public spaces, could also be considered because of their similarities in the concept of remote work, the environments of residential and public spaces differ considerably. Therefore, only studies conducted within residential spaces were considered in this review to allow for greater comparability between studies and a meta-analysis of outcomes.

The exclusion criteria for the included papers were as follows: (1) subject outside the scope, (2) languages other than English, (3) unavailability of the full text, and (4) review articles with no additional datasets. In terms of scope, for inclusion in this review, a study had to focus on the assessment of at least one of the four IEQ domains – thermal environment (TE), indoor air quality (IAQ), visual environment (VE), and acoustic environment (AE). In the course of the review, the 'physical environment' (PE) of the WFH context emerged as an important theme in WFH settings and required its own sub-section in the narrative. In this review, PE refers to aspects related to the physicality of WFH environments, such as spatial layout and design, furniture or workstation design, work-related equipment (laptop/computer, monitors, keyboard, etc.), maintenance and cleanliness.

2.1. Literature search, screening, and selection

A search query was created based on terms related to the WFH domain (Table 1). This was used to perform a 'topic' search in Web of Science (WoS), an 'all fields' search in PubMed, and an 'article title-abstract-keywords' search in Scopus databases in August 2021. A total of 66,418 records (Web of Science: 31,725; PubMed: 17,164 Scopus: 17,529) were found.

A semi-automated natural language processing (NLP) workflow was used to process and screen the retrieved abstracts using the pandas Python package in a three-step process. The Top2Vec [36] algorithm in Python was used to perform topic modeling on abstracts from 48,357 records. The algorithm initially pre-processed the abstracts by splitting each sentence into words, removing punctuation, and converting all words to lowercase. Subsequently, a joint embedding (i.e., mapping) of abstracts and words was created in a vector space, and dense clusters of abstract vectors representing the topics were identified. A total of 313 topics were identified and topic words attracted abstracts to their respective clusters. Six authors voted on all topics after assessing their relevance to the scope of the review. Based on this, 13 topics, spanning 2671 records were selected for further processing.

Table 1
Query for database search (literature search) and IEQ search terms used for semantic search.

Query for database search (literature search)	("work* from home" OR "work-from-home" OR "telecommut*" OR "telework*" OR "remote work*" OR "remote job" OR "remote company" OR "work-from-anywhere" OR "work* from anywhere" OR "mobile work*" OR "flexi-work" OR "cyber commut*" OR "home work*" OR "homework*" OR "remote e-work*" OR ″e-work*" OR "self-employed" OR "work* at home" OR "home-based work*" OR "virtual organization" OR "virtual work*" OR "flextime" OR "flexible hours" OR "flexible work schedule" OR "flexible work*" OR "freelance" OR "flexiplace")
IEQ search terms (semantic search)	indoor air quality; indoor environmental quality; indoor environment design; indoor environmental design conditions; thermal environment; thermal comfort; thermal satisfaction; thermal preference; heating preference; cooling preference; visual environment; visual comfort; visual satisfaction; lighting satisfaction; lighting comfort; light comfort; satisfaction with lighting; acoustic environment; acoustic comfort; acoustic satisfaction; occupant comfort; occupant satisfaction

The IEQ-related search terms (Table 1) and the 'query documents' function in Top2Vec were used to conduct a semantic search of abstracts in the saved Top2Vec model which included the joint abstract and word embedding and the abstract text. This function also provides a semantic score ranging from zero (lowest) to one (highest), indicating the relevance of the retrieved documents to a search phrase. The number of documents returned per IEQ-related search term was set to 20 and increased by 20 in each iteration that followed. After the fifth iteration, the mean relevance scores of the documents for all IEQ-related search terms ranged from 0.32 to 0.23, and a cursory examination revealed that the last 20 abstracts were less likely to be chosen. Therefore, the 100 most relevant abstracts, related to the 13 topics, for each of the IEQ-related search terms were retrieved from 2671 records, manually selected in the previous step. This process yielded 1147 records after removing duplicates. Ten studies were selected for inclusion in this review.

However, because the scope of this review encompasses a subject that has recently attracted considerable research attention on a global scale, we expected new relevant papers to be published by the time our review is completed. Therefore, to ensure that our review was updated with the latest research, we conducted non-systematic searches until August 2023 to identify any new publications following the systematic search in August 2021. Additionally, this endeavor aimed to uncover studies that might have been inadvertently omitted during the NLP-based screening process. This process resulted in the identification of an additional 31 records. Therefore, a total of 41 articles were assessed based on a method that is both systematic and state-of-the-art [37].

2.2. Data extraction

The data extracted from all eligible studies were separated into six different sections: (1) general information (e.g., authors, title, year of publication), (2) study features (e.g., study design, sample sizes, monitoring instrumentation, questionnaire items), (3) reference to IEQ factors as independent variables, (4) information on IEQ factors being studied, (5) information on dependent variables (e.g., well-being and productivity), and (6) statistical tests and models.

2.3. Strategy for data synthesis

This review offers a synthesis of the evaluated articles that is predominantly narrative. The review results were categorized according to the IEQ domains investigated in the literature, to explore their effects on perception-related variables pertaining to comfort, well-being, and productivity. In these studies, the assessments were based either on the monitoring of the IEQ conditions (monitoring-based studies) or on the perceptions of participants as gathered by questionnaires (questionnaire-based studies), as is the norm in IEQ studies in general, except for a few studies in which both approaches were used (mixed-method-based studies). The domain of PE was assessed using questionnaires only. In the narrative that follows, *N* indicates the number of studies, *M* denotes mean values, and *SD* means standard deviation. It is also important to note that all measures of well-being and productivity described in the questionnaire and mixed-method-based studies in the narrative below are self-reported.

The narrative is supported by visual summaries of the main outcomes. While there is some consistency in the way the monitoring data are reported across the studies (generally in the form of statistical summaries) the perception-related variables vary considerably, which is common with IEQ studies. However, this also makes it challenging to compare outcomes across studies. This was addressed by identifying and plotting the most widely reported outcomes for each IEQ domain, predominantly in terms of perception of satisfaction with specific IEQ factors. In a few instances, the survey scales and mean vote values were converted to a standard 5- or 7-point format to enable a better comparison. Additionally, semantically similar IEQ factors were grouped together even though they were worded differently across the studies.

3. Results

The final selection of the 41 papers included in this review is presented in Table 2. Most of the studies were conducted at sites located in Europe ($N = 17$), followed by Asia ($N = 11$), and the U.S. ($N = 10$). There was considerable variation in the number of WFH sites and participants across the studies, with those employing questionnaires typically reporting larger sample sizes relative to monitoring-based studies. All the studies were conducted during or after the pandemic, specifically from May 2020 to October 2022. Additionally, the duration of monitoring or surveying across the studies varied widely, ranging from a few days to several months. A detailed summary is provided in Table S1.

Fig. 2 illustrates the distribution of studies across the key themes of interest for this review: the five IEQ domains, productivity, and mental and physical well-being. Most of the studies in this review focused on AE in WFH settings, with VE and PE also receiving considerable attention. A few studies have examined at least one IEQ domain in conjunction with mental well-being.

3.1. Monitoring-based outcomes

Fig. 3 shows a summary of IEQ monitoring data from various studies, focusing on eight main IEQ indicators: temperature, relative humidity, concentrations of CO_2, total volatile organic compounds (tVOC), and particulate matter diameter of 10 and 2.5 μm, or smaller (PM_{10}, $PM_{2.5}$), along with illuminance, and sound pressure level (SPL). While additional indicators, such as standard effective temperature [42], formaldehyde concentrations [41,79], and various particle sizes ($PM_{0.3}$, $PM_{0.5}$, and PM_1) [41], have been reported on occasion, the scarcity of studies on these indicators prevented their inclusion in the meta-analysis.

Aggregating data points that include the maximum, median, minimum, and mean values based on the availability, the evaluation of the eight IEQ indicators spans across multiple studies. These indicators were assessed in the context of selected international standards and guidelines that served as benchmarks within the plots. It is pertinent to acknowledge that, while regional standards might offer more context-specific insights, this meta-analysis opts for international benchmarks to facilitate comparisons across the diverse array of studies. This approach ensures a broader applicability of the findings, providing a cohesive overview that transcends regional variances in IEQ standards.

While four mixed-method-based studies [40–43] monitored temperature, only two reported mean values. Despite being conducted in different climate zones and seasons, the average temperatures reported by both studies were close to 20 °C. There was significant variability in the maximum temperature values, with one study reporting temperatures exceeding 35 °C [40], which surpasses the upper limit advised by international standards such as ASHRAE 55–2017 (19.5–27.8 °C) [80] and the broader World Health Organization (WHO) guidelines (18–24 °C) [81].

Relative humidity measurements were reported in three studies; however, inconsistencies in the reporting of descriptive statistics across these studies precluded the identification of definitive trends in humidity conditions in WFH settings. Nonetheless, apart from a single peak value noted in a Portuguese study [41], all reported relative humidity values fell within internationally recognized acceptable limits, including the 50 % level recommended by the WELL Building Standard [82], 65 % by ASHRAE [83], and 70 % summer ceiling recommended by DIN EN 16798–1:2022 [84].

Six studies included monitoring-based outcomes pertaining to IAQ of which only three reported CO_2 concentrations. While the average and median CO_2 concentrations remained below 900 ppm, the studies indicated noticeable variations in the peak values. The highest of these peaks exceeded 3000 ppm, surpassing the optimal limit suggested by WELL at 800 ppm [82], yet remained below the more lenient exposure thresholds of 5000 ppm set by the United States Occupational Safety and Health Administration (OSHA) [85] and the National Institute for Occupational Safety and Health (NIOSH) [86].

It is important to clarify that while a CO_2 concentration limit of 1000 ppm is often associated with ANSI/ASHRAE Standard 62.1 [83], ASHRAE itself has contested this attribution, asserting that the standard does not specify a definitive limit for CO_2 indoors [87]. The instances of peak CO_2 concentrations revealed in these studies highlight the possibility of intermittent or localized deficiencies in ventilation within these WFH environments. Addressing these issues is crucial for maintaining air quality within the bounds of established health and safety standards.

Two studies within the review reported tVOC concentrations in WFH settings, and only one study reported mean values. These values hovered around or below the 500 $\mu g/m^3$ limit established by the US GBC LEED v4.1 [88] and the 250 ppb limit recommended by the WELL Building Standard [82]. However, similar to the trends observed for CO_2, the peak concentrations of tVOCs surpassed these benchmark levels, suggesting instances of significant VOC presence, possibly due to specific environmental conditions or activities within the studied spaces. The tVOC concentrations in homes in Texas were higher than those in offices [39,43], as was the frequency of SBS symptoms while working from home [43].

None of the studies reported mean PM concentrations, which presents a challenge in identifying distinct trends within WFH spaces. However, reported peak concentrations for both $PM_{2.5}$ and PM_{10} were frequently above the recommended 24-h limits set by WELL [82], WHO (15 $\mu g/m^3$ for $PM_{2.5}$ and 50 $\mu g/m^3$ for PM_{10}) [89], as well as the ASHRAE and US Environmental Protection Agency (EPA) standards (35 $\mu g/m^3$ for $PM_{2.5}$ and 150 $\mu g/m^3$ for PM_{10}) [90]. Such elevated levels of particulate matter suggest episodes of significantly deteriorated air quality with the potential to negatively affect health. In fact, a Portuguese study [41] found significant associations between increased $PM_{2.5}$ concentrations and the occurrence of respiratory and allergic symptoms in WFH settings.

Two studies reported illuminance levels. A field study in the Netherlands [40] reported the average illuminance levels over two separate five-day periods. The average illuminance during the first measurement period was 710 lux, whereas during the second period, it decreased to 342 lux, which is lower than the recommended threshold of 500 lux [91]. However, this study did not elucidate the reasons for this considerable fluctuation in light levels. The second study reported daylight level estimates using simulation techniques and was included in this review because it offered a more objective evaluation than questionnaire-based studies [53]. The findings indicate that summer seasons and multifamily homes typically benefit from higher illuminance levels compared to winter seasons and single-family homes, respectively. Additionally, occupants in historic houses with better VE reported fewer productivity-related issues and less discomfort than those in modern houses. Although the limited sample sizes of these two studies constrain the extent to which these findings can be generalized, a trend emerges, suggesting that better lighting conditions could have a positive impact on performance outcomes.

SPLs were reported in only one study: averaged $L_{A,eq}$ (A-weighted equivalent energy SPL) of 41.2 dB ($SD = 8.4$ dB) (Fig. 3) measured at the participants' main workstations during lockdown in the Netherlands [40]. For reference, an $L_{A,eq}$ of 48–55 dB over long measurement periods (at least 4 h) is presumed to be representative of most open-plan office conditions [92]. However, WFH and open-plan offices represent different acoustic contexts, and SPL is one of several acoustic criteria in offices [92,93] and presumably in WFH situations. In addition, the reported SPL values are likely to be biased because the SPL range [40] spans only the sensor's measurement range [94], excluding out-of-range values. Sound sources and room acoustics were not identified, and other working areas were not measured. However, this methodology [40]

Table 2
A brief summary of the reviewed studies.

Type	ID	Reference	Year of pub.	Study location	No. of WFH sites/ participants (response rate %)[a]	Monitoring/survey period	Type of evaluation (questionnaire)[b]	TE	IAQ	VE	AE	PE	Physical well-being	Mental well-being	Productivity
Monitoring-based	(1)	Kalmár & Kalmár [38]	2021	Hungary	1 WFH site	30–120 min on multiple days (Dec 2019–Jan 2020)			X						
	(2)	Sarnosky et al. [39]	2021	USA	22 participants from 11 WFH sites and 11 traditional offices	5 working days Mon–Fri at each site (April 15 – June 14, 2019)			X						
Mixed-method	(3)	Boegheim [40]	2021	Netherlands	36 participants (100 %)	2 periods of 5 working days (April 2020)	Long-term and short-term (PIT)	X	X	X	X		X	X	X
	(4)	Ferreira & Barros [41]	2022	Portugal	70 participants from 70 WFH sites and 18 traditional offices	30-min continuous monitoring at each site (WFH: Feb–May 2021 -; traditional offices: June–July 2021)	Long-term	X	X				X		
	(5)	Kawakubo & Arata [42]	2022	Japan	198 participants from 190 WFH sites	Feb 15–25, 2021	Long-term	X				X			X
	(6)	Roh et al. [43]	2021	USA	8 participants (female only) from 8 WFH sites	pre-pandemic: May–July 2019; post-pandemic: June–Sep 2020	Long-term	X	X				X		
	(7)	Clèries Tardío et al. [44]	2023	Spain	30 participants from 26 WFH sites	15-day periods during Nov 22, 2021–Mar 6, 2022	Short-term (PIT)	X	X	X	X				
Questionnaire-based	(8)	Guo & Chen [45]	2020	USA	502 (29 %)	May 2020	Long-term	X	X	X	X	X	X		
	(9)	Thapa et al. [46]	2020	India	406	Between 48th and the 71st day of the nationwide lockdown in India	–	X					X		X
	(10)	Andargie et al. [47]	2021	Canada	471 (66 %)	April 16 – May 16, 2020	Long-term				X				X
	(11)	Awada et al. [48]	2021	USA	988	April 27 – June 11, 2020	Long-term	X	X	X	X	X	X	X	X
	(12)	Awada et al. [49]	2021	USA	988	April 27 – June 11, 2020	Long-term	X	X	X	X		X	X	
	(13)	Cuerdo-Vilches et al. [50]	2021	Spain	1170	April 30 – June 22, 2020	Long-term	X		X	X	X			
	(14)	Gerding et al. [51]	2021	USA	843	–	Long-term				X	X	X		
	(15)	Lee & Jeong [52]	2021	UK	183	before lockdown: Mar 27 – May 12, 2019; during lockdown: Mar 27 – May 12, 2020	Long-term				X				
	(16)	Muñoz-González et al. [53]	2021	Spain	838 (72 %)	April 8 – June 7, 2020	Long-term			X			X		
	(17)	Okawara et al. [54]	2021	Japan	5760	Dec 22–26, 2020	Long-term	X		X	X	X			X
	(18)	Salamone et al. [55]	2021	Italy	330	April–June 2020	Long-term	X	X	X	X	X			X
	(19)	Torres et al. [56]	2021	Mexico	970	Aug 7 – Oct 30, 2020	Long-term	X	X	X	X	X			X
	(20)	Torresin et al. [57]	2021	London	464	Jan 18–19, 2021	Long-term				X			X	
	(21)	Xiao et al. [58]	2021	USA	988	April 24 – June 11, 2020	Long-term	X	X	X	X	X	X	X	

(*continued on next page*)

Table 2 (*continued*)

Type	ID	Reference	Year of pub.	Study location	No. of WFH sites/ participants (response rate %)[a]	Monitoring/survey period	Type of evaluation (questionnaire)[b]	TE	IAQ	VE	AE	PE	Physical well-being	Mental well-being	Productivity
	(22)	Yang et al. [59]	2021	USA	648	Sep 14, Oct 1, Oct 4–9, 2020	Long-term			X	X	X			X
	(23)	Amorim et al. [60]	2022	Brazil, Colombia, Denmark, Italy, Poland, and Japan	694	Dec 2020–Mar 2021	Short-term for lighting conditions, long-term for other items			X		X			
	(24)	Bergefurt et al. [61]	2022	Netherlands	1219	Sep 2020–Jan 2021	Long-term	X	X	X	X	X	X	X	X
	(25)	Ekpanyaskul & Padungtod [62]	2022	Thailand	869	May–June 2020	Long-term					X	X	X	
	(26)	Ekpanyaskul et al. [63]	2022	Thailand	869	May–June 2020	Long-term					X	X	X	X
	(27)	Guo & Chen [64]	2022	USA	204	May 2020	Long-term	X	X	X	X	X			
	(28)	Guo et al. [65]	2022	USA	189	May 2020	Long-term	X	X	X	X	X			X
	(29)	Hiyasat et al. [66]	2022	UAE	113	–	Long-term	X	X	X		X			X
	(30)	Matsugaki et al. [67]	2022	Japan	12,774 (38 %)	Dec 22–26, 2020	Long-term	X		X		X	X		
	(31)	Oakman et al. [68]	2022	Australia	964	Sep–Nov 2020	Long-term					X	X	X	
	(32)	Ortiz & Bluyssen [69]	2022	Netherlands	502 (29 %)	Dec 2020	Long-term (one-month recall for description of IEQ conditions)	X	X	X	X	X	X		
	(33)	Torresin et al. [70]	2022	UK	464	Jan 18–19, 2021	Long-term			X	X			X	
	(34)	Torresin et al. [71]	2022	UK, Italy	848	Jan 18–19, 2021	Long-term				X				
	(35)	Umishio et al. [72]	2022	Japan	916	Nov, Dec 2020	Long-term	X	X	X	X	X			X
	(36)	Vasquez et al. [73]	2022	Brazil, Colombia, Denmark, Italy, Poland, and Japan	694	Dec 2020–Mar 2021	Short-term for lighting conditions, long-term for other items			X					
	(37)	Mimani & Nama [74]	2022	India	942	April 2 – June 2, 2022	Long-term				X			X	X
	(38)	Torresin et al. [75]	2022	UK	464	Jan 18–19, 2021	Long-term				X				X
	(39)	Zhang et al. [76]	2022	China	22	–	Short-term for lighting conditions, long-term for other items	X	X	X	X	X		X	X
	(40)	Mura et al. [77]	2023	Italy	521 (study 1); 463 (study 2)	April 2021 (study 1); Dec 2021 (study 2)	–			X	X	X		X	X
	(41)	Park et al. [78]	2023	South Korea	1093	Sep–Oct 2022	Long-term				X				X

TE = thermal environment, IAQ = indoor air quality, VE = visual environment, AE = acoustic environment, PE = physical environment, PIT = point-in-time.

Where possible, independent/dependent variables are categorized into those related to TE, IAQ, VE, AE, and PE, whether they are measured (such as temperature) or perceived (such as sensation). For this table, PE refers to aspects related to the physicality of the WFH environments, such as space layout, furniture or workstation design, work-related equipment (laptop/computer, monitors, keyboard, etc.), space design, colors, cleanliness, etc.

The following papers originate from the same study, but they are listed separately in this table since they focus on different aspects of IEQ/well-being/productivity: (11), (12), (21) | (8), (27), (28) | (20), (33), (34), (38) | (25), (26)

All measures of productivity were self-assessed unless mentioned otherwise.

(15) also included an analysis of the tweets related to noise but the information presented here is based only on the questionnaires that were deployed.

(16) also included simulations of natural lighting but the information presented here is based only on the questionnaires that were deployed.

(13), (18), (34) also included different qualitative methods but the information presented here is based only on the questionnaires that were deployed.

(35) also conducted physical measurements of temperature, relative humidity, CO_2 and $PM_{2.5}$ in traditional office spaces occupied by the participants but that information is not included here since it was not considered

pertinent to this review.
(30), (35) included questionnaire items pertaining to mental well-being, but the papers did not present any analysis on those data.
(39) is an experimental study.
(38) presents qualitative analysis only.
(32), (36) were the only two studies that reported effect sizes. In (36), Cohen's effect sizes were found to be small (based on small effects ranging from ±0.1 to ±0.29, medium effects from ±0.3 to ±0.49, and large effects from ±0.5 to ±1). (32) does not provide significance thresholds against which to evaluate the reported effect sizes.

[a] The values indicate the number of study participants unless mentioned otherwise.

[b] The terminology used to characterize the type of evaluation refers primarily to the recall period required for perception- or response-related assessments. Long-term evaluations entail longer recall periods in weeks or months while short-term evaluations may be instantaneous or based on a few days.

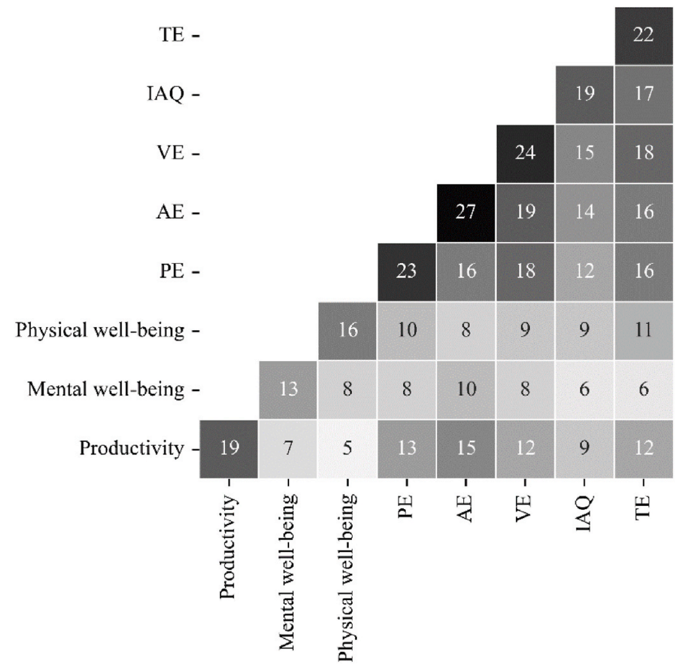

Fig. 2. Heatmap showing the number of studies addressing each IEQ domain, productivity, mental and physical well-being, and combinations of these variables of interest (TE = thermal environment, IAQ = indoor air quality, VE = visual environment, AE = acoustic environment, PE = physical environment).

shows promise and is recommended with a more diverse sample and uniform coverage of the working areas, ideally considering psychoacoustic metrics [95].

In summary, although some mean and median values suggested generally acceptable conditions, the presence of high maxima across several IEQ variables indicated the potential for significant deviations from the recommended standards. These deviations raise concerns about intermittent but severe environmental quality issues that could affect the comfort, well-being, and productivity of occupants.

3.2. Questionnaire-based outcomes

3.2.1. Thermal environment

In the realm of TE within WFH settings, subjective assessments using questionnaire-based studies have provided insights into occupant satisfaction and comfort. Seventeen studies delved into the thermal domain and evaluated occupant experience in terms of satisfaction or comfort (N = 14) [42,45,48,49,54,55,58,61,64–66,69,72,76], thermal sensation (or 'perception') (N = 4) [46,55,56,69], preference [46,55], and the perceived importance [69] and adequacy [50] of TE for work performance. Fig. 4 presents a summary of the most prevalent metrics of occupant perception across various studies expressed in terms of the mean vote and percentage of occupants. It is also important to differentiate between satisfaction with the overall TE and satisfaction with specific metrics related to TE, such as temperature and humidity; we noted the prevalence of both forms in the reviewed studies.

Studies reveal varying levels of satisfaction with TE, with some indicating medium to high satisfaction quantified on a 5-point scale (M = 4.0–4.3) [48,58,64,65]. Others articulate satisfaction in terms of the percentage of satisfied participants, showing a broader distribution, from slightly below 50 % to nearly 90 %. This disparity highlights that, while mean satisfaction scores may suggest an overall positive sentiment towards TE, individual satisfaction percentages reflect a more nuanced and varied occupant experience.

TE was associated with overall mental health, physical activity, distractions while working, occurrence of new physical and mental

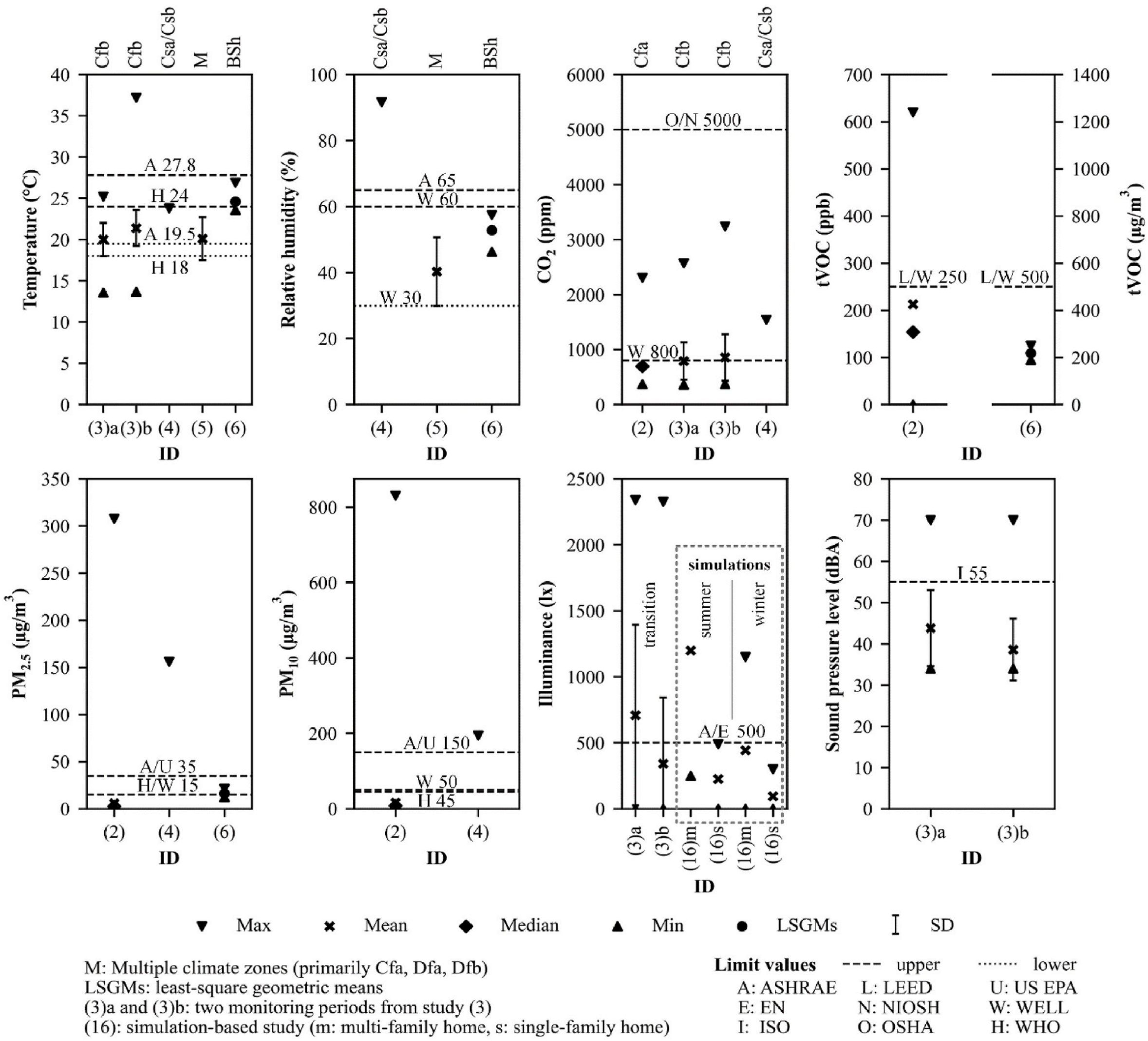

Fig. 3. Summary of monitoring-based data from IEQ studies in WFH settings.

health issues [58], and productivity [48,65], although the nature and strength of these associations varied across the studies. One study reported that satisfaction with temperature and humidity had a significant effect on severe 'work functioning impairment' [54], while regression analyses in other studies did not support any direct effect on physical or mental well-being [58] or productivity [65,72]. The lack of significant findings in this respect may be attributed to the timing of the survey, which was conducted shortly after the transition to WFH in the U.S [65].

The mean satisfaction votes for temperature indicated medium to high levels of satisfaction, as measured on both 5-point ($M = 3.7$–4.3) [45,49,55,61] and 7-point scales ($M = 5.2$–6.0) [44,66,69,76]. Satisfaction with temperature varies according to work-related activities [45], income levels [49], and housing type [66]. Nearly 46 % of the 321 point-in-time responses in a Netherlands-based study were 'neutral' on the sensation scale, and the participants who felt 'slightly cool' reported higher satisfaction than those feeling 'slightly warm' [40]. This was different from other studies where most participants felt 'neutral' to 'slightly cool' [55,69]. Although thermal sensation is a well-known perception metric for TE, it was less commonly used in the reviewed studies.

The review of questionnaire-based studies pertaining to TE reveals a complex picture of occupant satisfaction, which is influenced by a variety of factors, including the specific environmental parameters being assessed, climate zone, and assessment method used. Although there is a general trend towards satisfaction with thermal conditions, the extent of this satisfaction is not uniform and is subject to fluctuations based on the aforementioned variables.

3.2.2. *Indoor air quality and ventilation*

This section provides a summary of the studies that have investigated subjective satisfaction, perception, and preference pertaining to IAQ, as well as correlations with productivity and well-being in WFH settings. Most of the mixed-method- and questionnaire-based studies ($N = 17$) assessed IAQ in terms of perceived satisfaction ($N = 12$), on different scales such as 'very dissatisfied' to 'very satisfied' [40,45,55,61,64,65, 72], 'strongly disagree' to 'strongly agree' [66], importance [69] and other perception-related scales, such as 'very good' to 'very bad' [50, 56], or 'not smelly' to 'very smelly' [55]. A summary of the main findings is shown in Fig. 5.

The collective findings from the reviewed literature emphasize a generally positive occupant perception of IAQ. Satisfaction was frequently reported on various scales, with a majority of participants expressing content. Satisfaction ratings on a 5-point scale averaged between 4.0 and 4.3 [45,48,49,55,58,61,64,65], while a 7-point scale reflected slightly higher satisfaction levels, with the mean ranging from 5.3 to 5.6 [66,69]. These scores reflect a positive overall response, suggesting that the majority of occupants were fairly satisfied with the IAQ in their home offices. However, the standard deviation bars indicate

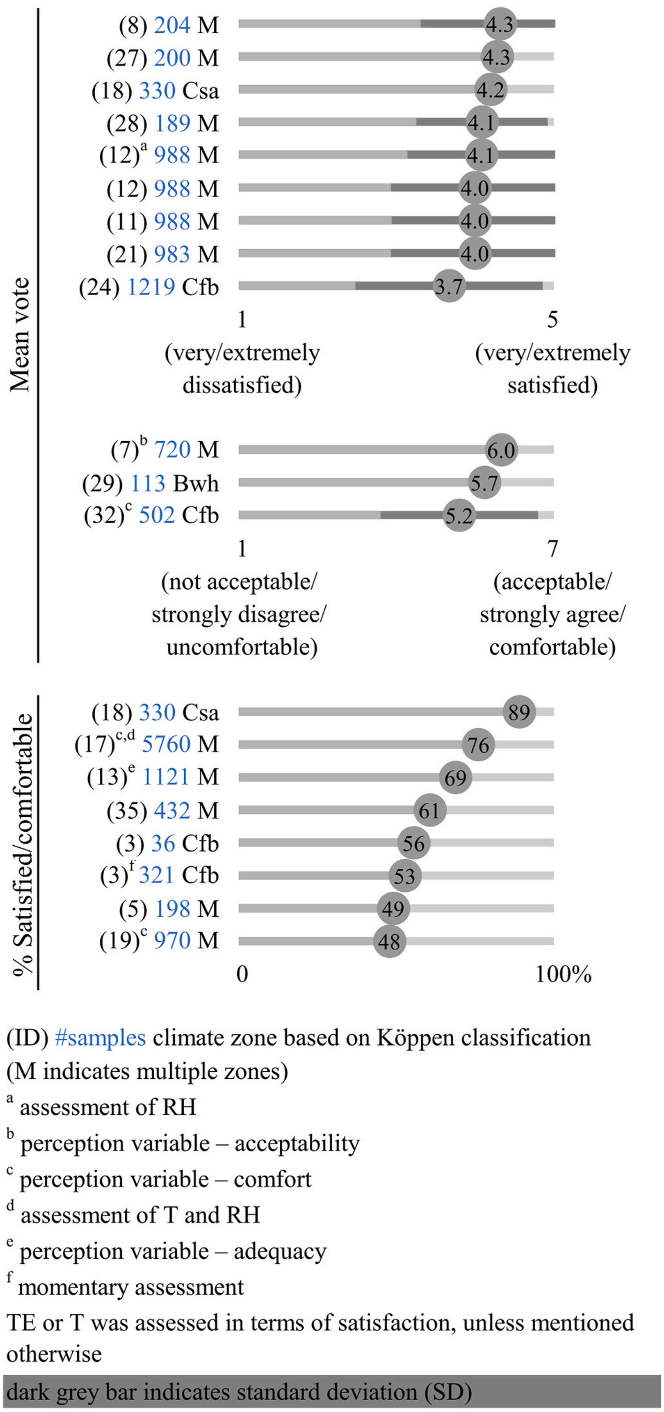

Fig. 4. Summary of questionnaire-based outcomes related to the thermal environment in WFH settings.

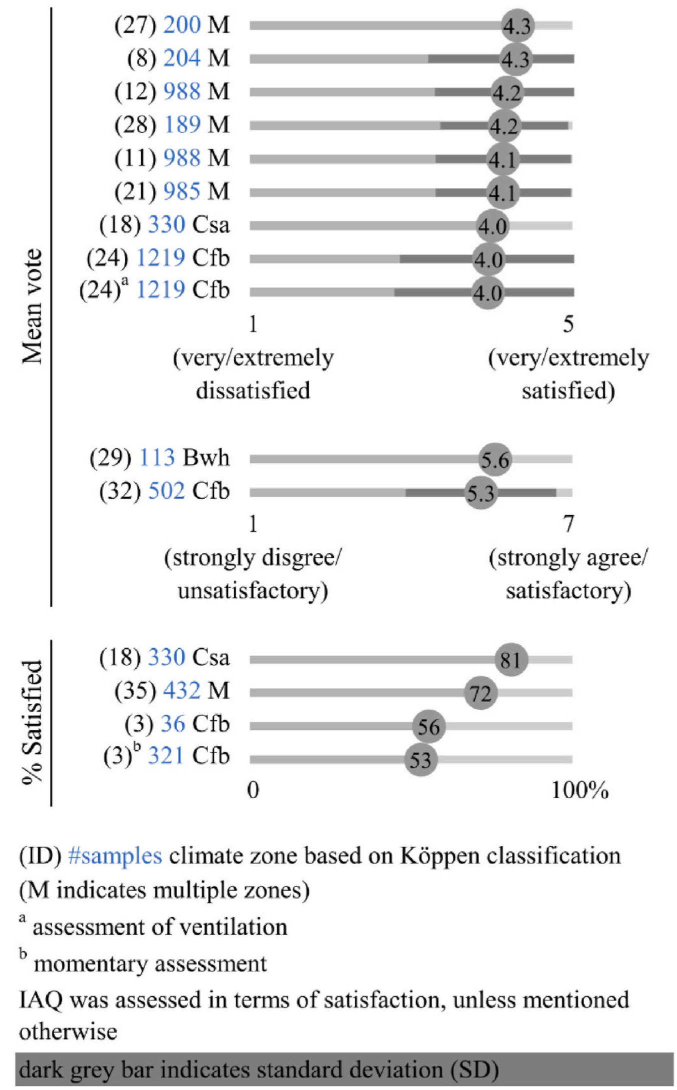

Fig. 5. Summary of questionnaire-based outcomes related to the air quality in WFH settings.

the variability in the responses within each study, showing that not all occupants shared the same level of satisfaction.

The proportion of participants satisfied with the IAQ was fairly wide across studies, ranging from 53 to 81 % [40,55,72]. A few studies have reported outcomes suggesting that occupants in WFH settings tend to report a higher sense of satisfaction with IAQ than those in traditional office environments [45,64,72]. Specifically, detached homes had higher mean satisfaction than apartments and students reported greater satisfaction than other occupational groups [66].

Diving deeper into demographic correlations, gender differences emerged, with females often reporting higher satisfaction levels [64,66], although this is not a universal finding [49]. Age appears to play a role, with an increase in IAQ satisfaction as age increases [49,64], suggesting that different age groups may have varying expectations or sensitivities to IAQ. Satisfaction with IAQ was also found to be associated with income [49] and number of children in the household [66].

To summarize, although overall satisfaction with IAQ in home offices appears positive, the nuances revealed by the different scales and assessments underscore the complexity of measuring IAQ satisfaction. The interplay between objective IAQ measures and subjective perceptions highlights the importance of a comprehensive approach for evaluating and improving IAQ to meet the diverse needs and preferences of occupants. Studies assessing IAQ in terms of satisfaction, without any specific mention of the IAQ factors evaluated, generally showed a positive trend. However, this could obscure the importance of individual IAQ components such as CO_2 levels, particulate matter, and VOCs.

3.2.3. Visual environment

Most VE studies focused on subjective assessments ($N = 23$). Questionnaires were used to investigate participant satisfaction with VE ($N = 15$), its adequacy ($N = 2$), and the need to improve it ($N = 1$). Satisfaction was most commonly assessed using a 5-point ($N = 8$) or a 7-point Likert scale ($N = 4$). In some studies, VE was considered in general terms ($N = 6$), whereas others specifically addressed access to daylight, electric lighting, glare, and visual privacy ($N = 7$). Additionally, two of the 15 studies asked the participants to evaluate lighting conditions in both WFH and traditional office settings. A summary of the main findings in shown in Fig. 6.

Participants were mainly satisfied with VE while WFH, scoring it on average between 3.5 and 4.3 on a 5-point Likert scale [45,48,49,55,56,58,61,64,65], and 4.7–6.4 on a 7-point Likert scale [60,66,69,72]. In other studies, 64–88 % of participants reported satisfaction with VE [50,55,56,73]. Having access to daylight, 'good electric lighting,' shading tools, and 'nice views outside' the window were considered important in a WFH setting [50,56,60,69,73]. A 'window view of vegetation' was associated with improved well-being [70].

The data revealed the climatic influences on satisfaction with VE in WFH settings. For example, a mixed-method-based study in Spain found that despite participant complaints of inadequate lighting, photographs of WFH spaces showed mostly natural and sufficient lighting [50]. By contrast, issues such as glare were more commonly reported in areas with sunnier climates, such as Los Angeles [49]. Despite these regional differences, the predominant theme across studies was a high level of satisfaction with VE in home offices.

In a WFH setting, individual differences in perceived needs emerged, such as cultural variations across continents in the 'desire to change electric lighting' [64]. Additionally, gender influences on visual satisfaction were observed, with males reporting greater satisfaction in WFH settings than traditional offices, an outcome that is not as pronounced among females [66]. Gender and the number of children at home were also found to affect the participant satisfaction with the 'amount of light reaching' their workspace [66].

In summary, the analysis underscores the significance of VE in WFH settings, with high overall satisfaction, marked by individual preferences, cultural differences, and the availability of natural light and views. In regions with limited external daylight, insufficient light was linked to impaired work functioning, whereas in areas with abundant natural light, participants reported mostly adequate lighting.

3.2.4. Acoustic environment

This section presents the findings from the 27 studies included in this review that primarily addressed acoustics-only aspects [47,52,57,70,74,75,78] or acoustics among several factors [40,44,45,48–50,54–56,58,59,61,64–66,69,71,72,76,77]. Questionnaires were used in all the 27 studies. These studies referred predominantly to WFH during pandemic-induced lockdowns, except those with additional data including retrospective assessments of pre-lockdown conditions [45,47,52,54,64,69,72]. Lockdowns had a major impact on environmental noise, with substantial SPL reductions worldwide [96]. Therefore, the reviewed studies may not represent typical environmental (e.g., traffic noise) or indoor (e.g., cohabitants during WFH) acoustic conditions for non-pandemic WFH. Yet, these studies present a timely and developing account of acoustic environments as experienced during WFH lockdowns and raise relevant acoustic issues for the future of WFH.

The data from the studies indicate a broad spectrum of occupant experiences in terms of satisfaction, with mean satisfaction votes on a 5-point scale ranging from 3.2 to 4.3, suggesting that while some found their AE satisfactory, others experienced discomfort, as can be seen from Fig. 7. The participants' ability to WFH was affected by annoyance related to overall outdoor and indoor noise [47,52]. In a pre- and during-lockdown comparison in London, 'noise' complaints increased significantly for environmental, and air- and structure-borne sounds [52]. This indicates that despite (or rather because of) reduced environmental noise SPLs, WFH may be subject to acoustic disturbance due to existing and/or additional sources. Hence, local sounds and their effect on WFH may require judicious assessment in general, as well as during lockdowns and quieter times.

The findings indicate that indoor soundscapes with 'high comfort' and 'low content,' relating to 'higher privacy and control,' were perceived to be more appropriate for WFH [57,70]. WFH 'suitability' (i.

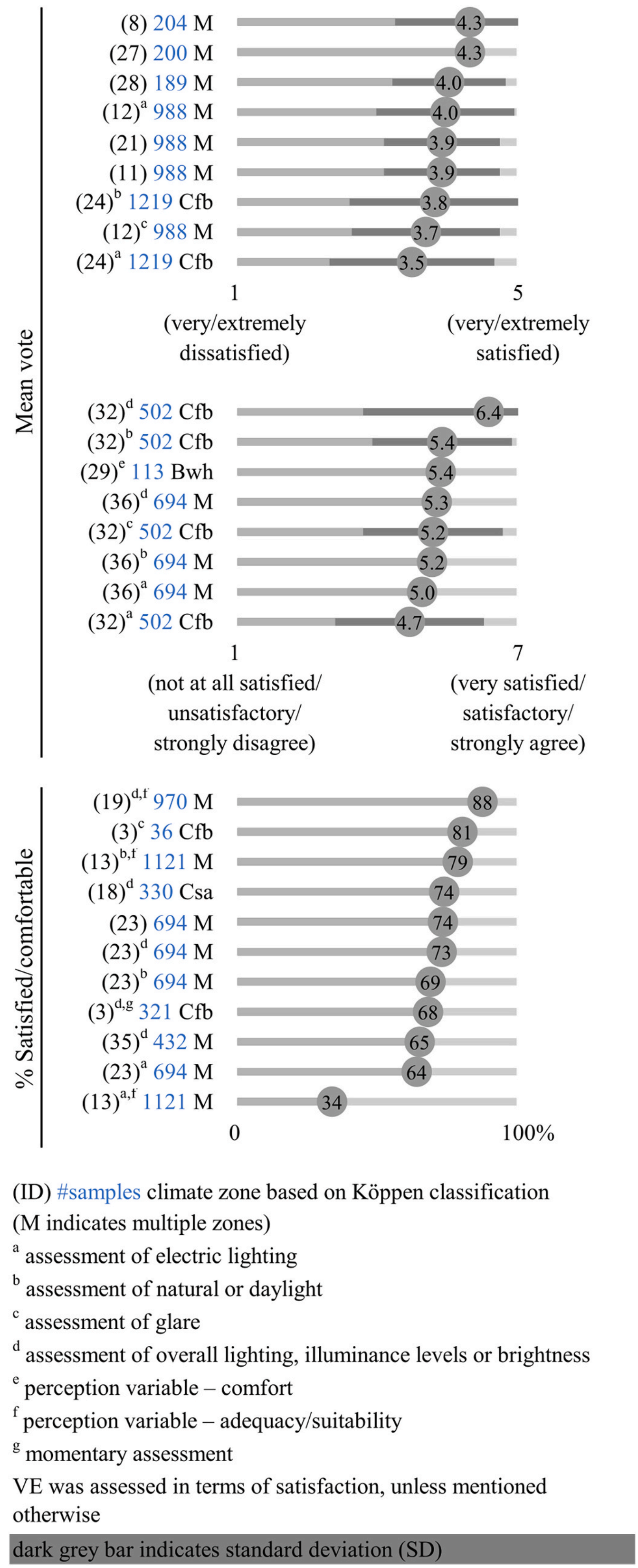

Fig. 6. Summary of questionnaire-based outcomes related to the visual environment in WFH settings.

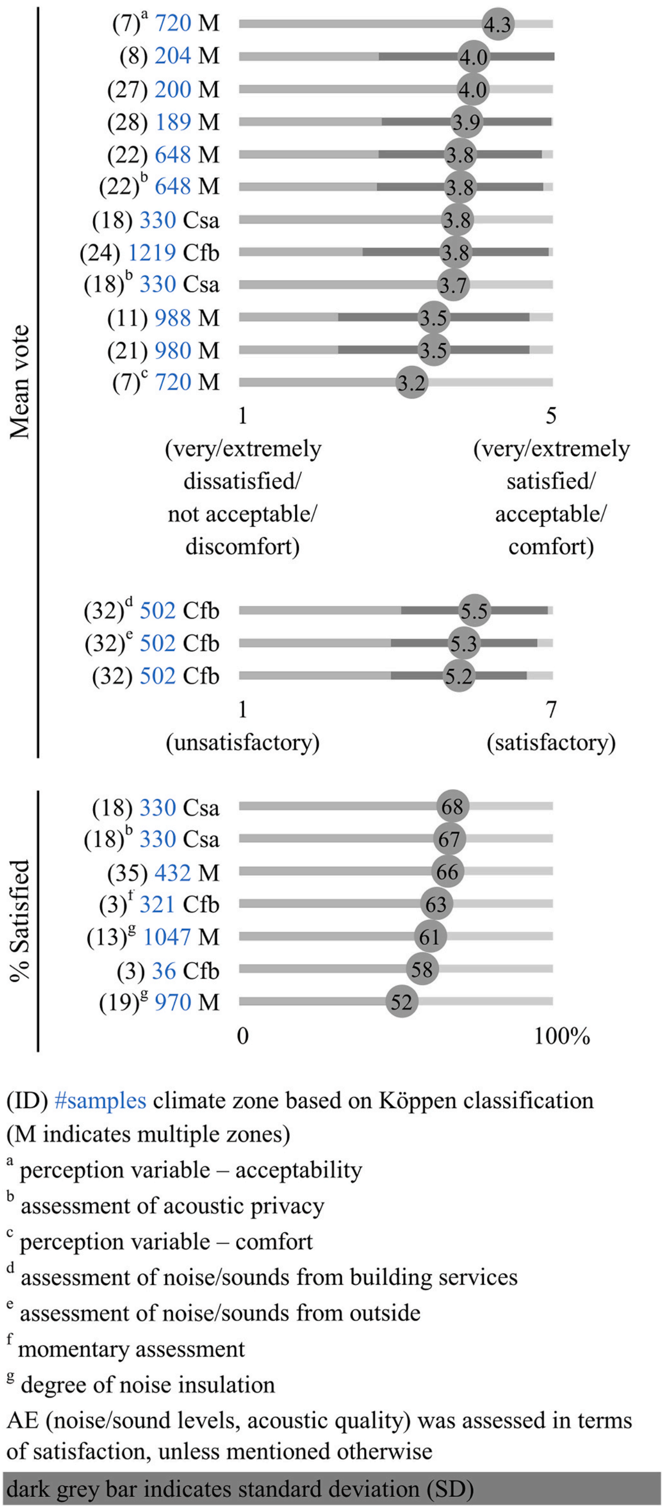

Fig. 7. Summary of questionnaire-based outcomes related to the acoustic environment in WFH settings.

e., ability to work pleasantly) positively affected the perceived satisfaction with the noise level [40]. IEQ and psychosocial preferences appeared to be situation- and gender-dependent [69], as with other IEQ domains, although this cannot be generalized. Age-related trends suggest that older participants have higher noise satisfaction [48,64,70].

The analysis also considered the influence of building features such as HVAC systems and window behaviors on AE satisfaction. Window-opening behaviors, while not significantly affected by factors such as participants' noise sensitivity, showed a tendency towards natural ventilation [71] and implied the importance of less dominant HVAC sounds in WFH [47,52].

Most studies with multiple IEQ domains that also reported satisfaction with acoustic aspects rated the acoustic environment as either the lowest [48,65], or close to the lowest [55], although this may not relate to poor overall satisfaction, since some absolute ratings were high. Accordingly, satisfaction with 'noise insulation' was not very high [50, 56]. Since general findings suggest high IEQ satisfaction during WFH, recommendations include investigating personal control over IEQ in WFH versus office situations while emphasizing standardized noise-control evaluation methods [48], which was echoed across other studies [47,52,70].

The survey items in these studies used terms in a colloquial sense – such as 'noise environment,' 'noise,' 'sound environment,' and whether the environment is 'quiet,' provides 'acoustic comfort,' etc. The intention was for participants to report their broad *perceptual* assessment(s) of the *physical* 'acoustic environment.' However, the use of some terms may be counterintuitive depending on the context. For instance, broadband 'noise' (e.g., from HVAC operation) at a reasonable SPL and spectrum can provide beneficial sound masking [97] and may not be detrimental 'noise.' As a corollary, overly 'quiet' workplaces can sometimes be detrimental due to inadequate masking from irrelevant sounds, or due to individual preferences [98]. However, it is assumed here that the term (s) used per paper were consistent with the study design and were unambiguous for the participants.

3.2.5. Physical environment

This subsection reports the findings pertaining to the subjective assessment of the PE in WFH settings from 23 questionnaire-based studies that included assessments related to the nature or type of workspace, available features and equipment, design, furnishing, layout, cleanliness, and maintenance. A summary of the main findings is presented in Figs. 8 and 9.

Satisfaction with [50,55,72] and importance of [69] the spatial work environment were important themes in the literature, in addition to correlations with productivity [56,66,72]. General satisfaction with PE ranged from 3.4 to 4.2 for assessments on a 5-point scale and between 4.8 and 5.8 on a 7-point scale. At least 50 % of participants expressed satisfaction with PE [50], with figures as high as 90 % [72].

The type of workspaces available to individuals during the pandemic appears to have significantly impacted their WFH experiences. Fig. 9 shows that the availability of a dedicated workspace in WFH settings varied considerably across studies, ranging from 9 % to 75 %. There are a few instances where not having this feature may have resulted in lower satisfaction with the WFH environment [50,55]. More women than men worked in spaces with 'frequent interruptions' or were relegated to using spaces that were accessible [68]. More professionals than students had exclusive rooms for work, and professionals in South America were more likely to have dedicated spaces than those in Europe [60]. These findings highlight the diversity in WFH arrangements across demographics and geographies.

Spatial aspects of the work environment, such as room size and layout, have emerged as critical factors influencing WFH satisfaction. While satisfaction with the room size was generally high, there were notable differences among the countries. For example, Italian workers reported higher satisfaction with the size of a WFH room [55] than their Spanish [50], Dutch [69], and Japanese counterparts [72]. The mean satisfaction with layout and cleanliness ranged between average [69] and high [65].

Ergonomics and technology are vital themes in PE assessment. The availability of specific ergonomic features varied considerably across studies. For instance, more than 90 % of the participants in a US-based study did not have an ergonomic chair [59], whereas nearly half of the participants in Japan did [54]. Furthermore, 'furniture adequacy,' internet connectivity, and access to ergonomic equipment are all

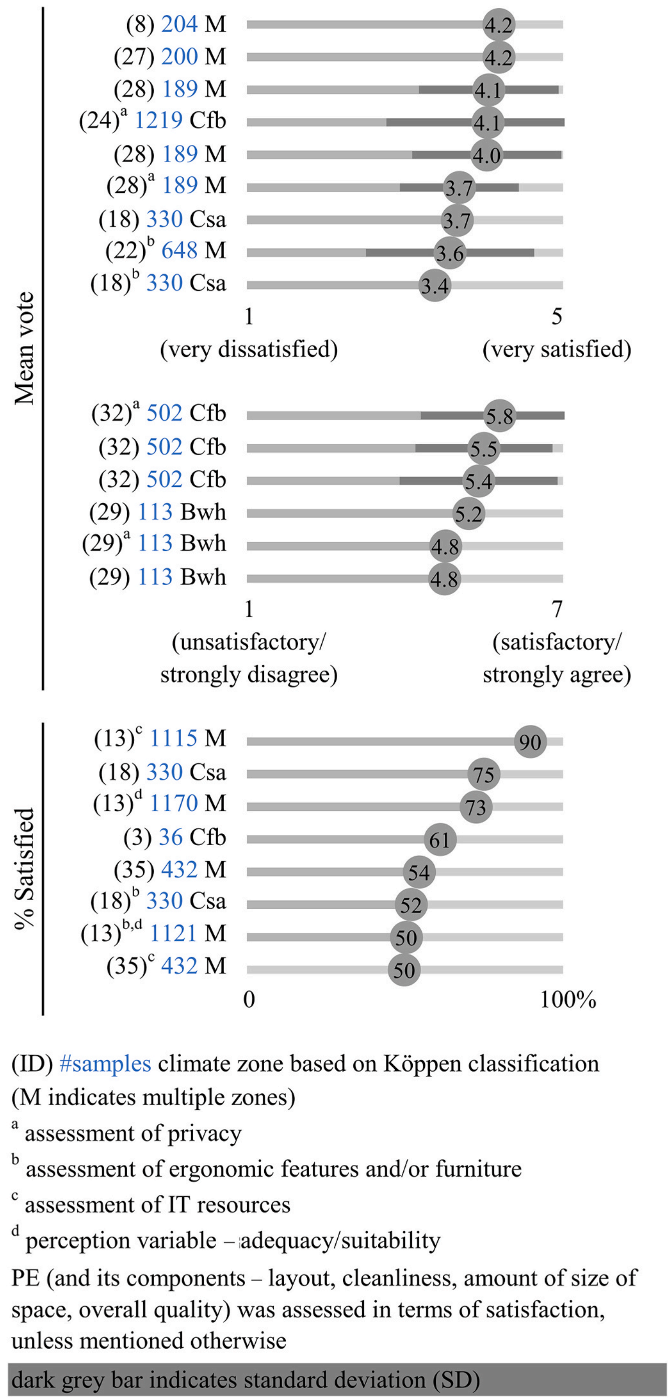

Fig. 8. Summary of questionnaire-based outcomes related to the physical environment in WFH settings.

significant contributors to the WFH experience. Satisfaction with these features ranged from average [50,55,72] to high [45,64,65,69] (Fig. 8), indicating the importance of better-suited furniture and technology for WFH.

This review indicates that PE, which encompasses workspace type, ergonomics, and spatial design, is the cornerstone of a successful WFH experience. The observed variations in satisfaction across studies underscore the importance of personalized and adaptable PE solutions to a range of preferences and requirements, with the ultimate goal of enhancing well-being and productivity in WFH settings.

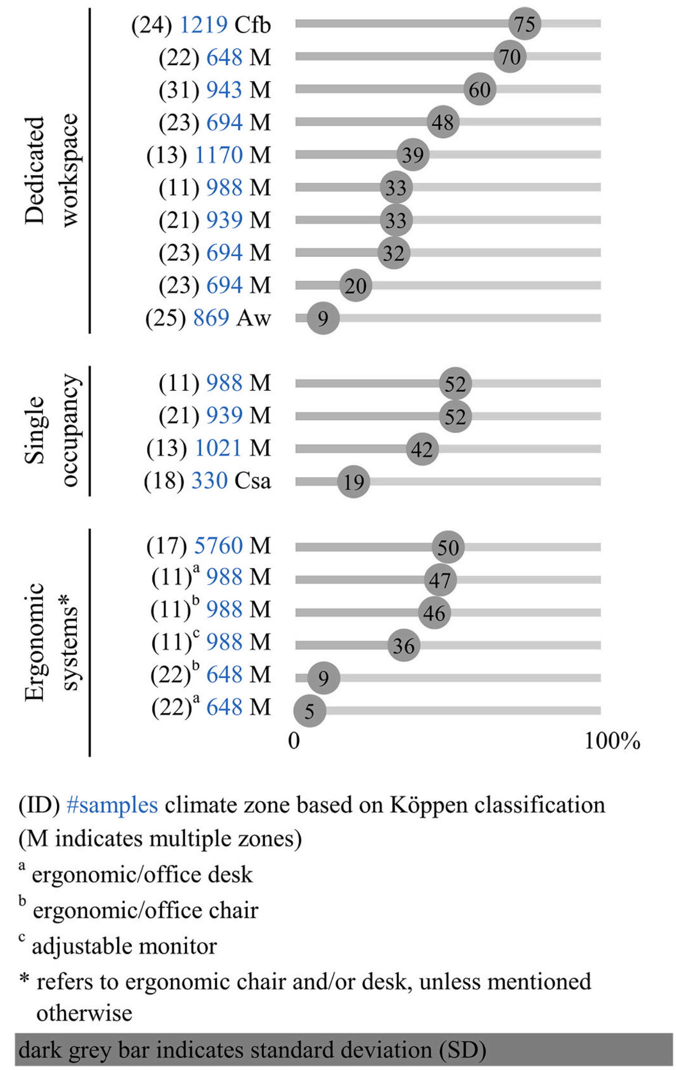

Fig. 9. Summary of availability of features deemed important in WFH settings.

3.3. Associations of IEQ with well-being and productivity

Associations between IEQ and perceptions of well-being and productivity were examined in multiple ways across the reviewed studies. This section presents a narrative synthesis of these associations. The majority of studies used different statistical tests for this purpose, such as the *t*-test, ANOVA, chi-square, Mann-Whitney, and Kruskal-Wallis. Several other studies used different forms of regression analysis. Some of the less common analytical methods used were path analysis, factor analysis, cluster analysis, structural equations, and thematic analysis. However, the Pearson and Spearman correlations were the easiest to compare across the studies. Only six studies reported the outcomes for the variables that were of interest to us, and they are visualized in Fig. 10.

Satisfaction with TE was associated with overall mental health, chances of reporting two or more new mental health issues [58], and productivity [42,48,65]. Satisfaction with temperature was found to correlate with stress [40]. While path analysis indicated that satisfaction with temperature was not significantly related to mental health [61], regression analysis demonstrated a significant impact on overall mental health [49] and revealed a negative association between satisfaction with temperature and the number of dependent children [66]. Low satisfaction with temperature was linked to the prevalence of symptoms related to 'trouble concentrating,' 'maintaining attention,' or 'focusing,'

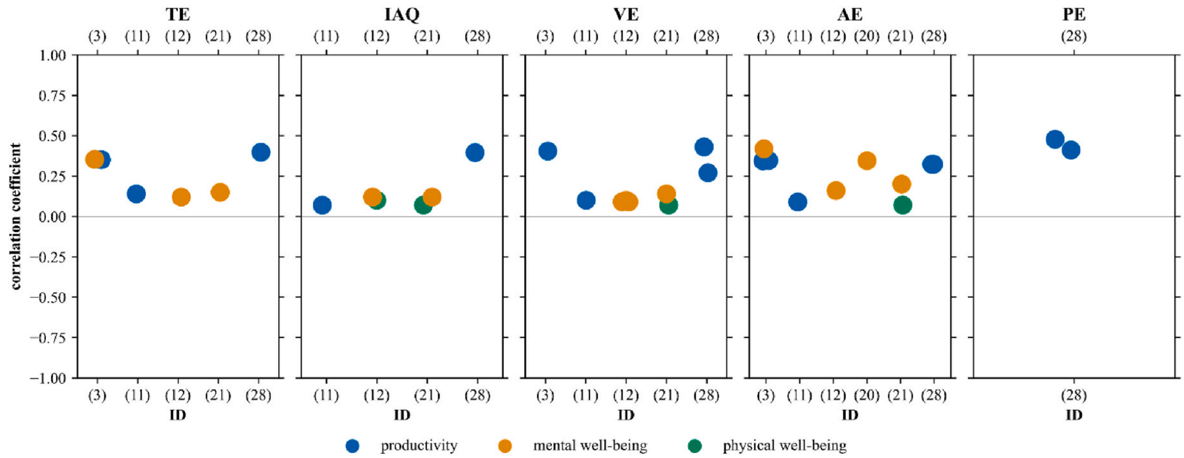

Fig. 10. Correlations (significant) between the IEQ domains and productivity, mental and physical well-being in WFH settings (TE = thermal environment, IAQ = indoor air quality, VE = visual environment, AE = acoustic environment, PE = physical environment).

and dissatisfaction with humidity was associated with nose/throat- and skin-related symptoms [49].

Satisfaction with IAQ was found to be significantly correlated with overall physical health [49] and SBS symptoms [43] while working from home. Participants who reported higher IAQ satisfaction also reported a lower incidence of new physical health issues after transitioning to WFH [58]. Mental-health correlations, although significant in some studies [49], show that IAQ is not a consistent predictor of well-being [61], indicating the need for a nuanced understanding of the psychological impacts of IAQ. A few studies have reported a positive association between IAQ satisfaction and productivity [48,65,72], although this was not consistently observed across all productivity subcategories or studies [55]. Satisfaction with IAQ has also been linked to higher workplace satisfaction [40,55], with notable relationships to visual, thermal, and acoustic environments [58], indicating a multi-sensory dimension of occupant satisfaction in WFH settings.

Although visual comfort is considered the least influential IEQ factor in predicting overall WFH satisfaction [55], satisfaction with VE has a significant effect on productivity [65] and mental health [49,61]. VE also correlated with 'healthy' and 'unhealthy' food intake, 'distractions' while working, general physical and mental well-being, and 'ease of communication' [58,72]. The effects of VE on physical health were limited to the eye-related symptoms [49]. Well-illuminated workplaces were associated with higher 'engagement' and 'concentration' [55,65], and having insufficient light was associated with the highest 'work functioning impairment' in a Japanese study [54]; although this was not supported by another Japanese study in which the lighting conditions were found to have no effect on 'concentration', 'creative tasks', and the 'ability to refresh with ease' [72].

SPL and satisfaction with noise were significantly correlated with workplace mental health concepts and the suitability and level of distraction at home [40]. Further, $L_{A,eq} > 58$ dB resulted in increased 'mental tension' and diminished satisfaction with the noise level. Being satisfied with the noise level increased 'concentration', self-reported well-being, 'engagement', and reduced 'tension' [40]. Low noise satisfaction (lowest among IEQ factors, but high in general) was a medium-to-strong predictor of several mental and physical symptoms [48], and increased noise satisfaction lowered the chances of workers experiencing new health issues after the WFH transition during early phase lockdown [58]. A higher dominance of sounds from cohabitants was associated with lower well-being [70].

Comparing WFH with offices, we found mixed results with a few studies reporting high satisfaction with AE and better productivity in WFH [54], although it was only for certain age groups [64], or depended on the type of work being done and the degree of control over noise [59]. Other studies reported that the sound environment was not important for productivity while working from home [61], but it was the most important productivity factor in offices [72]. Access to separate WFH rooms/spaces may partly account for lower proportions [54,59] and/or importance [61] of acoustic issues in WFH settings since this resembles access to separate office room(s) in offices, which is crucial in increasing workplace satisfaction [99].

Dedicated spaces for work activities led to higher productivity levels [48,59], increased time spent in the WFH workspace compared to the traditional office setting [48,73], and improved general satisfaction and work-life balance [59]. Participants with allocated workspaces reported fewer physical and mental health issues after transitioning to WFH [58]. On the other hand, a lack of a place/room for WFH was significantly associated with severe 'work functioning impairment' [54]. Satisfaction with the PE [72] and cleanliness [65] were significant predictors of productivity.

Physical pain or discomfort in WFH settings [68], sometimes owing to inadequate ergonomic support, was a prevalent issue [51], with data showing correlations between the lack of ergonomic features and severe 'work functioning impairment' [54]. On the other hand, access to ergonomic furniture and equipment and telecommunication/internet quality had a significant relationship with general satisfaction and productivity [59].

In summary, each of the five IEQ domains has small to moderate positive correlations with productivity, mental well-being, and physical well-being in WFH settings. The strongest correlations were observed with productivity. This meta-analysis suggests that enhancing these environmental factors could significantly improve WFH experience across all three measured outcomes. However, the variability in the strength of the correlations with the mental and physical well-being suggests that individual preferences and other unmeasured factors may also play a significant role. This review reveals a notable lack of research regarding the connection between PE and well-being. Similarly, research on the relationship between TE and physical well-being in WFH settings is scarce. This indicates the need for further investigation into the impact of these environmental factors on the well-being of occupants in the context of remote work.

4. Discussion

This review examined 41 research articles focusing on IEQ in WFH settings. Despite the great and growing body of literature addressing WFH settings since the pandemic, these were the only articles that met our inclusion criteria as they specifically address the topic of IEQ. The primary objective of this review was to identify and describe the IEQ variables measured in WFH environments, explore their impact on occupant perceptions of these settings, and determine their association with productivity and well-being levels. An additional objective of this review was to offer recommendations for both immediate and future considerations of WFH from an IEQ standpoint and to appraise the methodological approaches employed in the reviewed studies.

In general, studies focusing on WFH settings demonstrated that IEQ conditions were within the thresholds provided by most international standards, although maxima were presented in all IEQ domains. Preliminary conclusions can be drawn only for the IAQ parameters, for which more data is available within the literature. IAQ seemed to vary considerably above the upper limits. The presence of high pollutant concentration peaks in some studies demonstrated the need to implement monitoring processes in WFH settings. Variations in IEQ conditions within WFH settings are likely to be influenced by a variety of factors, including occupants' awareness levels of changing IEQ conditions, associated behaviors, and knowledge of how to monitor and regulate them. The lack of awareness of changing IEQ levels could also partly explain the high satisfaction rates presented by WFH participants across all IEQ variables, which is not supported by monitoring-based studies. Additionally, the scarcity of monitoring-based studies in WFH settings could be responsible for the misalignment between objective data and the subjective perception of the participants. While most participants reported high satisfaction with the IEQ conditions in WFH settings, there were notable minor variations, with some individuals expressing lower satisfaction levels. These satisfaction levels could be attributed to individual differences among WFH workers. The analysis revealed positive correlations between IEQ factors, and outcomes such as productivity, and mental and physical well-being, underscoring the critical importance of monitoring IEQ conditions in WFH environments. Despite the distinct nature of the different IEQ domains, their associations with these outcomes were consistent, suggesting that a holistic approach to understanding their combined impact on productivity, and mental and physical well-being could offer more significant insights.

All the studies included in this review were conducted either during the COVID-19 pandemic or just after the pandemic. Therefore, they represent unique instances of WFH settings, particularly in terms of AE as the pandemic marked a quieter global period. Future studies could compare subjective and objective IEQ conditions during and after the pandemic to determine whether there were any changes in IEQ conditions or perceived satisfaction with the IEQ.

Although only a limited number of studies in this review directly compared the IEQ conditions of traditional offices to those of WFH settings, they suggested higher overall satisfaction rates with the IEQ in WFH settings. This higher satisfaction may stem from the greater sense of control individuals have over their environmental conditions at home, rather than the actual IEQ conditions themselves. This is supported by objective measurements indicating that air quality in WFH settings sometimes exceeded the recommended thresholds.

4.1. Thermal environment

Studies pertaining to the thermal domain have suggested that home workplaces can provide acceptable thermal conditions that meet regulatory standards and are perceived as satisfactory. However, linking the thermal environment and its perception to well-being proved difficult, and the correlations found were small in magnitude. The relationship is likely to be mediated and moderated by a multitude of factors, including situational circumstances, personality traits, and preferences. Such factors need to be considered before deciding the feasibility and potential success of WFH (in terms of well-being and productivity). It may also be necessary to link satisfaction with thermal conditions to energy usage. Such a link adds another evaluation criterion to the holistic comparison between WFH and office settings. More studies have focused on the influence of thermal environment on productivity and mental well-being than on physical health, highlighting an important gap in the literature.

4.2. Indoor air quality and ventilation

In the IAQ domain, there was a discrepancy between the subjective and objective data. While the subjective ratings were mainly positive and attested to satisfactory IAQ perceptions, measurements of CO_2, PM, and tVOC concentrations revealed elevated and often problematic concentrations of these pollutants. To a considerable extent, subjective satisfaction with the IAQ at home may be explained by a high degree of control over window operation, whereas the absence of regulations in residential environments appears to place WFH environments at a higher risk of pollutants than traditional office environments. Positive correlations of IAQ satisfaction with work performance and well-being have been reported but have not been unanimously confirmed. Closer inspections by the authors of the studies revealed, for example, that IAQ satisfaction is correlated to overall satisfaction as well as other comfort domains, and that personal belief matters (perception that IAQ improves productivity). This finding supports the assumption that IAQ is not evaluated in isolation and should be viewed and evaluated as part of a holistic IEQ perception.

4.3. Visual environment

More than half of the reviewed studies included an assessment of the visual environment. Two studies included objective measurements and found associations between illuminance levels and productivity-related metrics [40,53]. However, the limitations of their study designs (small samples and limited geographical representation) restrict the conclusions that can be drawn regarding the impact of the visual domain on well-being and productivity. The questionnaire-based results indicated that the lighting conditions were acceptable, although glare has occasionally been described as a reason for complaint. As with IAQ satisfaction, visual satisfaction was related to a variety of other factors, such as the ability to refresh, ease of communication, and even food intake. However, no conclusive link was found between lighting in WFH settings and either productivity or well-being. Future studies could investigate the impact of lighting conditions on performance outcomes. Measurement-based lighting profiles that include daylight access, light levels, duration, artificial-lighting capacity, and view quality in the home workplace, are required. Future studies should collect data from different types of residential buildings across a wide range of socio-cultural, economic, programmatic, and temporal contexts. Furthermore, no direct comparisons between the participants' actual lighting exposure in their home workplaces and regular offices have been reported.

4.4. Acoustic environment

Studies on the acoustic environment indicate that lockdowns do not necessarily translate into quieter WFH environments, and that air-borne, structure-borne, and impact sounds might be a consequence of more people working at home in multi-dwelling buildings, thereby shifting the noise source from traffic to in-house. Several studies analyzing acoustics as one of the many IEQ domains report that people's ratings of acoustics or noise are among the lowest compared with those of other domains. This could partially be attributed to a ceiling effect, meaning that the absolute ratings altogether were at a higher level of satisfaction, and acoustics only 'underperformed' relatively. Noise perception was correlated with age and gender, underscoring the contingent nature of annoyance ratings and the necessity to evaluate WFH on a person- and situation-specific basis. Insufficient sound insulation was observed in homes for WFH, highlighting the importance of assessing indoor soundscapes in terms of comfort, control, and appropriateness for WFH, while accounting for demographic effects. The need to improve the acoustic planning of residential spaces for WFH is also highlighted.

4.5. Physical environment

Studies focusing on subjective assessments of the physical environment of WFH have shown a scarcity of suitable working equipment and technology, leading to reports of neck or head pain, eye irritation, or increased tiredness. People with access to a separate room or a dedicated space for WFH reported higher self-rated productivity. The studies reviewed in this paper often displayed improvised and rushed use of spaces to work at home during the lockdown phases. At the same time, we still want to highlight this somewhat dismal ergonomic situation to prevent maladaptation to insufficient WFH ergonomic structures and utilities. Additional data from future studies are required to support the assumption that WFH workers are sufficiently supplied with the proper office equipment.

In addition, several results reported above suggest that the economically weak who do not have access to a separate WFH space at home will benefit less from WFH conditions than those with access to a private and dedicated WFH space, raising questions with respect to the inequality of opportunities related to the future of WFH.

4.6. General discussion points

Overall, the research methods used in most studies were predominantly questionnaires, relying on subjective reports of satisfaction with different environmental domains without sufficient details on the indoor environmental conditions to which the participants were subjected. This approach poses problems in assessing the impact of IEQ on productivity or well-being, as it relies solely on reported predictor (e.g., thermal comfort) and target (e.g., perceived productivity) variables without considering potential common methodological bias [100]. Moreover, most studies used non-validated questionnaires. Alleviating the issue of self-developed, non-validated survey items is easily achievable in terms of rapid and easy study improvement. Many scales and standardized items already exist and are codified in standards [101]. Although they may not be tailored to every specific study context, these questions are pre-tested and strongly increase comparability of the study results. As a compromise, highly standardized item versions can be used with study-specific survey items on topics not covered by standardized items.

Even when environmental conditions were measured, basic parameters were assessed, and some studies on the thermal environment ignored the fact that thermal comfort depends on factors other than air temperature, such as radiant temperature, air velocity, clothing insulation level, and activity level. Similarly, the acoustic properties were reduced only to the sound pressure level.

Additionally, owing to the heterogeneous study properties in terms of methodology and geographical origin, discordant results were observed, limiting the possibility of drawing clear and quantifiable conclusions about the general drivers of well-being and productivity in WFH settings. Only a small number of monitoring-based studies have gathered IEQ data from WFH environments while also studying occupant-related productivity- or well-being metrics. Although a few studies have found meaningful relationships (particularly in the visual and acoustic domains), they are often limited by small and homogeneous samples, narrow geographical coverage, and short study periods. Beyond the intricate interactions among various IEQ factors, certain studies have emphasized the role of intangible elements (such as office furnishings, ergonomics, or biophilia) and personality traits in influencing the perception and assessment of IEQ [102,103], which further complicates the identification of replicable patterns. In the absence of an easy solution to this complex problem, ecological models such as Bronfenbrenner's bioecological model [104], originally developed to analyze child development, provide a structured and coherent approach to analyze and integrate the influences of a complex environment. This specific model has already been adapted for use in the IEQ domain [105].

To overcome these limitations, future studies should consider more representative samples, different seasons, multi-domain analyses, and multicountry and multicultural settings. Notably, most studies were conducted directly after the start of WFH mandates in the countries studied; therefore, their findings likely do not capture the long-term adaptation effects of working from home. This may explain some of the inconsistent correlations reported by different studies. Therefore, a longitudinal analysis is suggested as part of future research to ensure that the WFH solutions and recommendations derived from early lockdown periods and studies are adapted to the current and post-pandemic stages.

5. Conclusion

This study reviewed 41 research articles focusing on indoor environmental quality (IEQ) in work-from-home (WFH) settings. The findings indicate that the IEQ conditions, on average, met the thresholds from the relevant international standards, and workers were generally satisfied with the thermal, air quality, and visual conditions in the WFH settings. However, given the presence of high maxima in all IEQ domains, and more specifically based on available evidence for CO_2, particulate matter, and total VOC concentrations, it is essential to further investigate these IAQ indicators in future IEQ studies specific to WFH settings and potentially other indicators associated to the other IEQ domains, which lack extensive monitoring outcomes. The acoustic and physical environments were sometimes reported to be inadequate owing to insufficient sound insulation in residential spaces and a lack of ergonomic and technological support, which can be investigated further. Although correlations between IEQ conditions and perceptions of well-being and productivity were reported, they were not strong enough or consistent across studies to establish any conclusive links between the dependent and independent variables. This review also highlights the need for more high-quality studies with larger sample sizes. A debate is needed on the quality criteria of such studies, as recently published for multi-domain studies [106], to better understand the complex relationships between the indoor environment and occupants. It is essential to address aspects that not only decrease productivity and well-being in WFH settings but may even be harmful to human health.

CRediT authorship contribution statement

Sanyogita Manu: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Tobias Maria Burgholz:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Data curation. **Fatemeh Nabilou:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Data curation. **Kai Rewitz:** Writing – review & editing, Supervision, Funding acquisition. **Mahmoud El-Mokadem:** Writing – original draft, Validation, Investigation. **Manuj Yadav:** Writing – original draft, Validation, Investigation. **Giorgia Chinazzo:** Visualization, Validation, Methodology, Investigation. **Ricardo Forgiarini Rupp:** Visualization, Validation, Methodology, Investigation. **Elie Azar:** Writing – original draft, Methodology. **Marc Syndicus:** Writing – review & editing, Writing – original draft, Methodology. **Abdul-Manan Sadick:** Writing – original draft, Software, Methodology, Formal analysis. **Marcel Schweiker:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Sarah Crosby:** Writing – original draft, Methodology. **Meng Kong:** Writing – original draft, Investigation. **Donna Vakalis:** Writing – review & editing. **Adam Rysanek:** Supervision, Conceptualization. **Dirk Müller:** Writing – review & editing, Supervision, Funding acquisition. **Janina Fels:** Writing – review & editing, Supervision, Funding acquisition. **Christoph van Treeck:** Writing – review & editing, Supervision, Funding acquisition. **Jérôme Frisch:** Writing – review & editing, Supervision. **Rania Christoforou:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

All data used for this review is already presented within the manuscript.

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Appendix A. Supplementary data

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