Smart and Sustainable Built Environment

Integrated considerations of thermal comfort, daylight comfort and outdoor microclimate in medium density housing (MDH) development

Deependra Pourel, Amirhosein Ghaffarianhoseini, Ali GhaffarianHoseini and Nicola Naismith
Department of Built Environment Engineering, Auckland University of Technology, Auckland, New Zealand

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Abstract

Purpose – Medium-density housing (MDH) development has emerged as a promising sustainable response, as it aims to maintain good quality of life while embracing increased development to accommodate the growing population in urban and suburban areas across the globe. Of the many contributors to quality of life, good indoor thermal comfort and daylight are important aspects; however, research has shown that the microclimate plays a key role in establishing the indoor conditions. Furthermore, an integrated approach considering the nuances between the three conditions is imperative for quality insight. This paper reviews existing research on MDH that discusses the microclimate, thermal comfort and daylight comfort aspects to construct the current knowledge and identify trends.

Design/methodology/approach – A systematic literature review of articles on MDH development that discusses microclimate, thermal comfort and daylight, collectively or in pairs are analyzed. The research papers are synthesized and divided based on themes. The themes are issues, solutions, methodological choices and location. This is followed by analysis on the findings from the themes, supported with wider research to provide critical insights.

Findings – The analysis indicates that multivariate research considering three-way interaction between microclimate, indoor thermal comfort and daylight in MDH is relatively new. Further, huge variance is observed within themes, indicating differences in priorities across geographies. The findings imply the need for more nuanced research undertaking in MDH in the comfort conditions identified, as MDH have evolved into a preferred development model in cities, and it is important that such development support health and well-being considering climate change.

Originality/value – There is no prior research on the nexus of microclimate, indoor thermal comfort and daylight in MDH development. While also contributing to better understanding the current research landscape, this research underscores its relevance to the Sustainable Development Goals, particularly SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

Keywords Medium-density housing, Housing, Microclimate, Indoor thermal comfort and daylight, Systematic literature review (SLR)

Paper type Literature review

1. Introduction

Adequate housing is a fundamental human right (Singh *et al.*, 2022), and as per the UN-Habitat, an estimated 96,000 housing units everyday will be required to accommodate the three billion people by 2030 (UN). Suburban areas expanded, particularly in Europe and America during the industrialization period with accelerated industrialization, to

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accommodate the growing population. It was during this period that medium-density housing (MDH) development was adopted on a massive scale (Hohenberg, 2004). To this day, MDH development continues to be one of the approaches that many countries around the world have embraced in response to the growing pressure of accommodating more people (Allen and Bryson, 2018a; Kupke *et al*., 2015), especially in the suburban region.

MDH is identified as a sustainable densification model that helps densify existing low-density urban areas while maintaining high amenity, livability and quality of life standards (Gibson and Law, 2023). The earliest MDH typology existed prior to the 1919 period in Britain (Pepper and Richmond, 2008). This concept has been adopted across Europe since the early 20th century, and countries from Australasia are borrowing the concept to meet the challenges of the growing population (Birchmore *et al*., 2022). Similarly, in the US, middle housing is being promoted across many cities in previously single-family zones to respond to housing needs and climate emergencies (Zeebuyth and Moore, 2024). Globally, countries around the world are receptive to the concept of MDH, and policies and strategies are in development to support this (Allen and Bryson, 2018a).

The movement for a reformed urban block that ensured improved housing conditions while being advantageous to the city dates back to the houses by Alfred Messel in 1890 (Sonne, 2009). It was also the period that a variety of forms were site-planning led, leading to the invention of courtyards and internal streets to enhance housing condition with priority for light and green spaces. Though researchers have established that indoor thermal comfort and daylight are critical requirements to enhance livability (Allen and O'Donnell, 2020) and that microclimate must be considered simultaneously for holistic improvement (Benincá *et al*., 2023a, b; Haddad *et al*., 2022; LongVu *et al*., 2019) in medium-density housing development, there is limited research applying scientific methods to discuss all three considerations concurrently.

Research on the two-way interaction between building and microclimate is limited for any building type (Luo *et al*., 2022; Lin *et al*., 2023; Pasandi *et al*., 2024) and is a recently emerging research area. This two-way interaction model has been established a s a superior accuracy model to assess the bidirectional building-microclimate interaction (Pasandi *et al*., 2024). However, it has been limited to thermal relationships between the indoor and outdoor. Against this limitation and the emerging growth of MDH development initiatives globally, increased research is warranted. Holistic benefits can be reaped by accounting for the interactions between the outdoor microclimate, indoor thermal and daylight comfort concurrently, as has been discussed earlier. The research intends to draw on the multidirectional relationship beyond thermal comfort and the outdoor microclimate that encompasses daylight for an integrated approach. The consideration of this multivariate relationship will support the holistic development of solutions that complement each other while also fostering systems thinking. Prior studies (Pont *et al*., 2018) have indicated the need for integrated approaches for practical application in real-word scenario. The research acknowledges that there are other IEQ conditions, such as acoustics and air quality that are equally important for indoor environment quality assessment and improvement; however, this paper limits itself to only thermal comfort and daylight while accounting for outdoor microclimate. This research draws inspiration from the research in New Zealand, where people voiced their preference for indoor daylight and indoor thermal comfort in MDH development (Allen and O'Donnell, 2020), and weave it together with emerging research on improving microclimate to set a foundational reference for future research in this emerging field.

This leads to the emergence of three-way interaction. Figure 1 below shows the three-way interaction between microclimate, indoor thermal comfort and daylight as well as the relationship within indoor thermal comfort and daylight. Given the lack of any prior definition for this three-way interaction, this paper sets out to define it as the cyclic multidirectional interaction between outdoor microclimate, indoor thermal and indoor daylight comfort

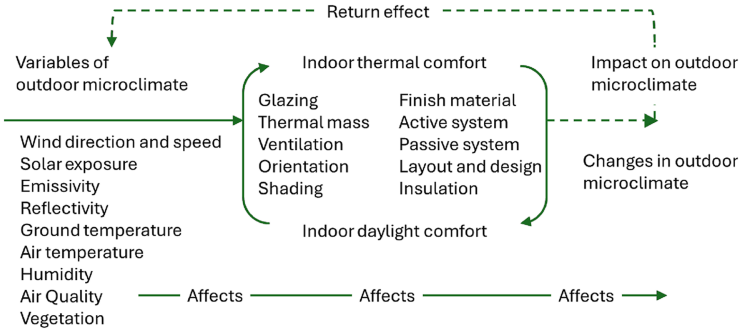

Figure 1. The two-way interaction between outdoor microclimate and indoor condition. Source: Authors' own work

conditions. The figure illustrates the cyclic impact that the quality of indoor thermal comfort and or daylight comfort has on the outdoor microclimate. This new outdoor microclimate changes the variables of the outdoor microclimate, which now impacts indoor thermal and daylight conditions. It becomes a vicious cycle, and while it may not be possible to eliminate this, it can be controlled.

Based on the findings from a regional need, alongside emerging research areas, the research undertakes a systematic literature review against this background with the following objective.

(1) Constructing current knowledge and identifying trends in research articles discussing the multivariate consideration.

(2) To use the findings to support the holistic development of MDH that considers the multivariate consideration of microclimate, indoor thermal comfort and daylight.

(3) Set a reference for furthering the research as countries densify neighborhoods through MDH development to accommodate the growing population.

This research is the first of its kind to synthesize literature on outdoor microclimate, indoor thermal comfort and indoor daylight comfort within the context of MDH housing typology. This contributes to better understanding the sector for holistic development of MDH and establishing a foundational reference for future research in this emerging field.

2. Methodology

The research starts with a bibliometric search based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol. The results are narrowed down based on the screening and eligibility conditions set. It is followed by thematic development that constructs each of the themes. Key findings from the articles are then discussed. Additional articles are inferred to provide deeper insights on the analysis findings, construct the current knowledge and identify the gaps in research undertaking that are necessary to realize a better-performing MDH development.

2.1 Bibliometric search

This paper adopted the process of identifying, selecting, screening and synthesizing research papers based on the PRISMA protocol. Scopus, one of the two largest bibliographic citation databases, is used to access the research papers. The search is limited to Scopus, ensuring only credible articles on the built environment are accessed. Further, strings are developed. Keyword techniques and combining search terms are employed in alignment with the research

objective. Table 1, provides detail of the terms applied in the string development. The first string contains all the relevant words applicable to medium-density housing, the term has been extracted primarily from Allen and Bryson (2018a). The second string is developed to ensure that the results are relevant to architectural spaces. The third string limits the search to scientific research. The fourth string introduces the first multivariate consideration, thermal; the fifth introduces the second multivariate consideration, daylight and the sixth string introduces the third multivariate consideration, microclimate. The last three strings are developed separately to allow search by three-way interaction, as illustrated in Figure 2. Multiple terms in the strings were developed only if it resulted in increased search output. A total of 124 research papers were identified. All articles in the bibliometric search are from Scopus.

The articles were screened for quality by limiting the selection to academic journals, articles and conference papers published up to the year 2023 and in English to include as many articles as possible. No regional or geographical limitations were set. Further eligibility criteria were applied, and each paper was screened to ensure that all research articles with buildings ten storey and higher in height are excluded. This was to ensure that the interpretation of the findings is representative of the all-encompassing definition of MDH. Density, building height and type of building are frequently used to classify MDH typology (Allen and Bryson, 2018a).

Table 1. String development detail

	Purpose	String
1	To broadly account for all literature on medium density housing	"Medium Density Housing" OR "Medium density residential" OR "higher density houses" OR "medium rise housing" OR "mid-rise housing" OR "attached housing" OR "missing middle" OR "medium density neighbourhood" OR "MDH" OR "Apartment" OR "Social housing" OR "townhouse*"
2	To narrow search to architectural spaces	"Architect*" OR "Building*"
3	To narrow search to those where scientific analysis has been adopted on building performance evaluation	"Building performance" OR "Environmental analysis" OR "Indoor environmental quality" OR "simulation" OR "BIM" OR "field study*" OR "survey" OR "Energy Audit" OR" case study"
4	To identify whether thermal comfort is accounted for	"thermal*"
5	To identify whether daylight is accounted for	"Daylight*" OR "Natural light*"
6	To identify whether microclimate is discussed	"microclimate" OR "bioclimate" OR "bioclimatic" OR "Environmental Analysis" OR "Outdoor Environment"

Source(s): Authors' own work

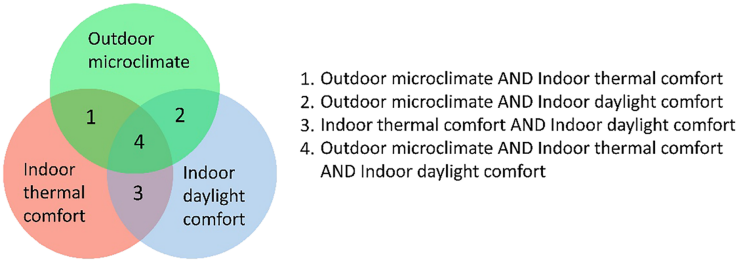

Figure 2. Three-way interaction model. Source: Authors' own work

This led to a final list of 49 research articles for synthesis. The PRISMA protocol applied is illustrated in Figure 3.

2.2 Thematic development

To effectively capture and interpret the findings from the systematic literature review, a thematic framework was developed. Each selected article was critically examined and systematically categorized under the theme most relevant to its content. The four overarching themes identified are (1) issues, (2) solutions, (3) methodological choices and (4) location. The articles were also categorized based on year of publication.

The "issues" theme encompasses the multivariate considerations of outdoor microclimate, indoor thermal comfort and indoor daylight comfort, which together form the basis of the three-way interaction model introduced earlier and illustrated in Figure 2. Research articles were grouped according to their alignment with this model.

The "solutions" theme includes the interventions explored in the reviewed studies. These interventions are broadly classified into building-level, site-level and theoretical approaches, applied either individually or in hybrid forms.

The "methodological choices" theme refers to the scientific methods employed in assessing the built environment across the reviewed literature. Broadly, it was classified under simulation, field measurement, survey and review of documents. Articles were classified based on whether these choices were applied either individually or in hybrid forms.

Finally, the "location" theme categorizes studies based on two criteria: (1) economic classification according to the World Bank (Hamadeh *et al.*, 2023) and (2) climatic

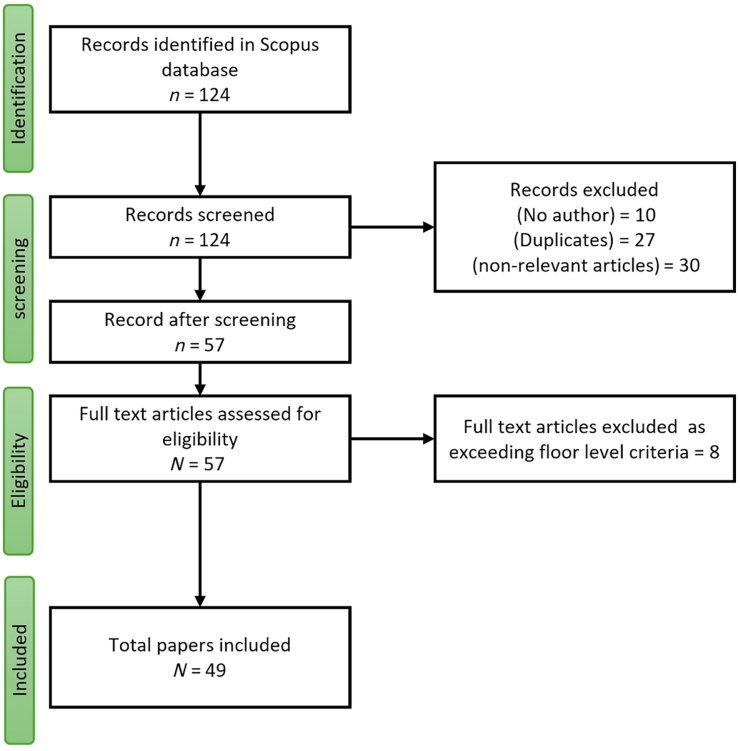

Figure 3. PRISMA protocol for bibliometric search and screening. Source: Authors' own work

classification based on the Köppen climate system (Beck *et al*., 2018). The World Bank classifies countries as upper high income (UHI), upper middle income (UMI) and lower middle income (LMI) countries. The Köppen climate system is used to classify location as tropical, dry, temperate, Mediterranean and polar zones. Additionally, countries are also included in the matrix.

Figure 4 presents a matrix mapping the development and distribution of these themes across the reviewed literature.

3. Findings

The consolidated data based on the thematic distribution matrix was used to present the findings. It was structured on two key dimensions, which are (1) findings by period distribution and (2) thematic findings. The first dimension presents the evolution of thematic focus over time. The latter presents the findings from each of the thematic categories, which are issues, location, methodology and solution. It concludes with a synthesis of key findings.

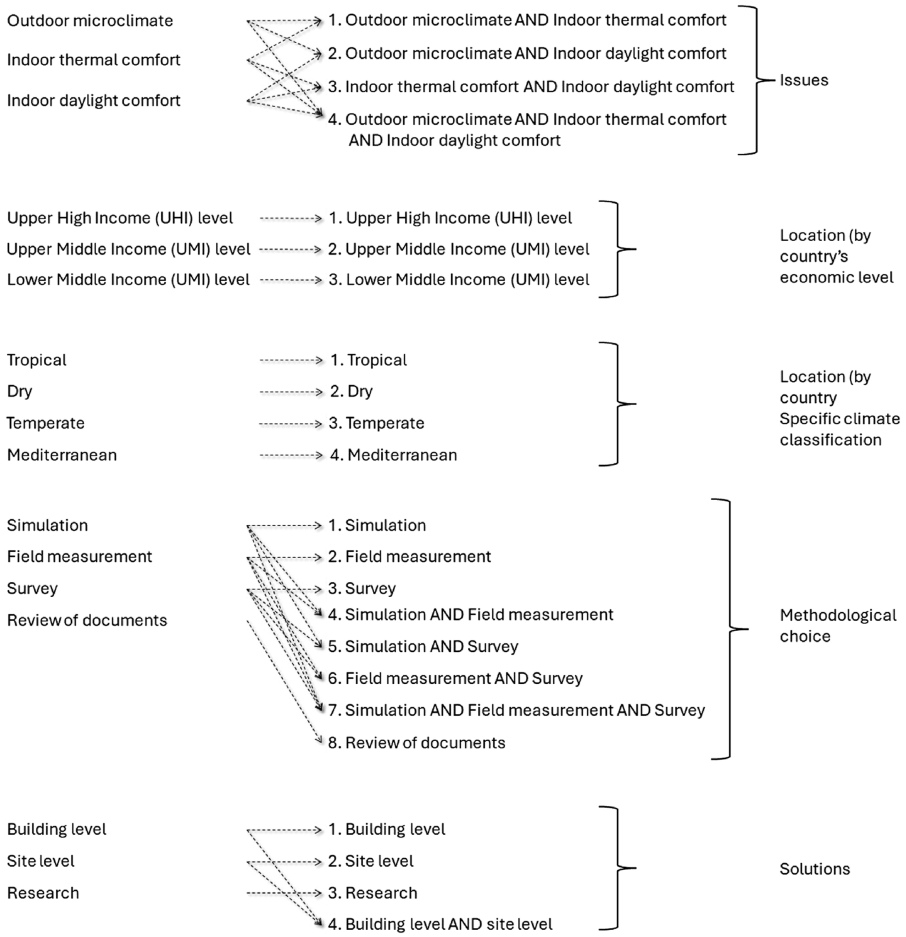

Figure 4. Theme distribution matrix. Source: Authors' own work

3.1 Consolidated finding by period distribution

Below, based on the defined period interval, the changes to the themes observed from the papers are discussed. Given that only two publications appeared in the period 2004–2008, it was grouped with the earliest period. The review period was divided into three intervals: 2004–2013 (earliest), 2014–2018 (second) and 2019–2023 (latest).

In the earliest period the number of publications was the least. The solutions appraised in this period were mostly at the building level, with equal representation from UHI and UMI countries. Further, it was limited to studies that discussed renovation measures in buildings to improve the comfort conditions. The findings brought to light the financial implications of choosing between different options for retrofit and introducing concepts as eco-efficiency. The methodology adopted mostly had the field measurement component. This was probably because the use of simulation tools was nascent at that period.

The second period witnessed an increase in research in the subject area, dominated mostly with articles discussing microclimate and indoor thermal comfort concurrently, of which most of it was in the UHI-level countries. It was also the period when researchers in Europe discussed the implication of interventions on indoor thermal comfort on daylight. While retrofitting remained a research focus, studies at the urban and neighborhood level that included the impact of vegetation were being explored in the UHI-level countries. Interestingly, countries at the UMI-level and LMI-level were also researching on the implication at the urban, neighborhood and site-level on indoor thermal comfort. Field measurement continued to be an approach in the research methodology in the UHI-level countries, while simulation was the preferred method for the rest. The interventions were again mostly limited to the building level, except for LMI-level countries prioritizing site-level interventions. Most of these were in the temperate region.

The latest period had the highest number of articles, which was yet again dominated by research on microclimate and indoor thermal comfort. However, it was almost evenly divided amongst European, Asian and Australian nations in the UHI category. This reflects the growing global interest in MDH development. The solutions are a mix of experimental undertakings, neighborhood-led research and building-level interventions. These solutions appear to be in alignment with international priorities, such as the net zero energy buildings and assessing national policies. The methodology has an almost equal mix of all the methodologies. However, in the case of UMI-level countries, all the articles are from Brazil, disrupting generalization. Here, the researchers focused mostly on building-level intervention, and the preferred method was simulation. This was also a period when daylight was considered together with indoor thermal comfort, but then it was limited to UHI-level countries only. The period also had publications accounting for all three multivariate considerations of microclimate, indoor thermal comfort and daylight simultaneously; however, it was very marginal and limited to LMI countries in Asia.

Figure 5 below summarizes the themes and the distribution following a chronological order of multivariate issues to locations (by country's economy) and methodological choices and solutions over the period 2009–2013, 2014–2018 and 2019–2023. The lone article from 2004 and another from 2006 are grouped with the 2009–2013 period.

Additionally, Table 2: is laid out to show the simplified intricacies between the themes for each multivariate issue. The table was constructed through a structured review process, wherein studies were first grouped by publication period (in five-year intervals from 2004 to 2023). Within each period, entries were categorized based on the multivariate issue explored (MC + ITC, ITC + Da and MC + ITC + Da), followed by classification by economic context (UHI, UMI and LMI), this was followed by Köppen climate classification. Subsequently, methodological choices (simulation, field measurement and survey) applied in the research papers were identified, which were followed by the choice of solution adopted (building level, site level or research level or a combination). Relevant studies were cited for every entry. This layered approach was developed to condense the research findings into a comprehensive layout to support comparative understanding and interpretation. It is important to note the

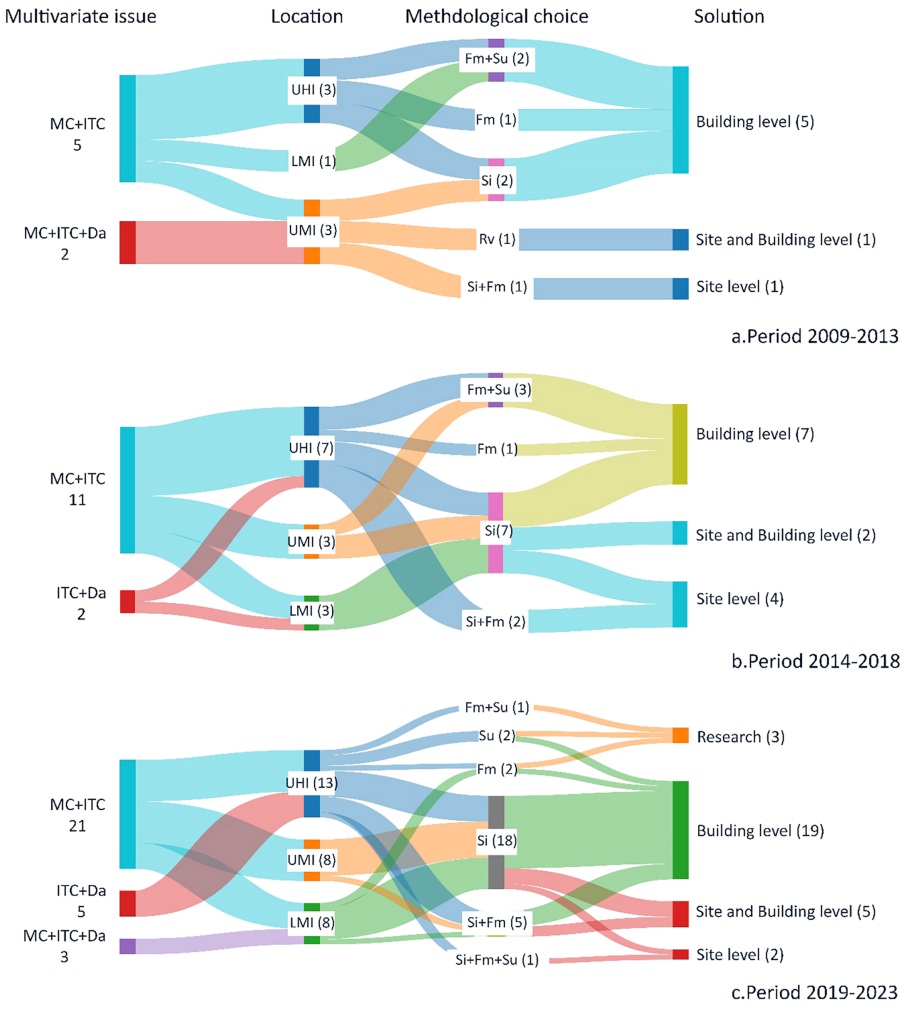

Figure 5. Sankey diagram on distribution of themes over time. *Note:* MC: Microclimate, ITC: Indoor thermal comfort, Da: Daylight, UHI: High-income countries, UMI: Upper middle-income countries, LMI: Lower medium-income countries, Si: Simulation, Fm: Field measurement, Su: Survey and Rv: Review. Source: Authors' own work

limited number of relevant studies for each category in the sorted list, as most categories are supported by a single article.

3.2 Thematic finding

The condensed thematic finding is consolidated in Figure 6, below. This is followed by detailed findings under every thematic group.

3.2.1 Multivariate issue. The analysis of the research articles indicates that most of the research articles assess microclimate and indoor thermal comfort, while the share of articles that includes daylight altogether or with indoor thermal comfort is marginal. Further, our search generated no result of research articles discussing microclimate and daylight concurrently in MDH developments.

Table 2. Simplified matrix of intricacies between themes

Year	Multivariate issue	Location (by economy)	Location (by climate classification)	Methodological choice	Solution	Relevant studies
2004–2008	MC + ITC	UHI	Temperate	Simulation and Field Measurement	Building level	Tenorio *et al.* (2006)
2009–2013			Temperate	Field measurement and Survey	Research	Jurelionis and Šeduikytė (2010)
			Mediterranean	Field measurement	Building level	Dimdiņa *et al.* (2011)
				Simulation	Building level	Kim *et al.* (2012)
2014–2018			Dry	Field Measurement	Building level	Giancola *et al.* (2014)
			Temperate	Simulation	Building level	Nowak-Dzieszko and Rojewska-Warchał (2015)
				Simulation and Field measurement	Site level	Pastore *et al.* (2017), Tumini *et al.* (2016)
			Mediterranean	Field measurement and Survey	Building level	Haverinen-Shaughnessy *et al.* (2018)
				Simulation	Building level and site level	Jung and Yoon (2018)
2019–2023			All	Simulation	Building level	Peng *et al.* (2021)
			Dry	Survey	Building level	Alzahrani *et al.* (2022)
			Temperate	Field Measurement	Research	Balocco *et al.* (2022)
				Simulation	Building level	Rodríguez-Algeciras *et al.* (2021)
				Field measurement and survey	Research	Haddad *et al.* (2022)
				Simulation and Field Measurement	Building level	Marco and Buhagiar (2019)
					Building level and site level	Triana *et al.* (2023)
				Simulation and Field Measurement and Survey	Site level	Diz-Mellado *et al.* (2023)

(*continued*)

Table 2. Continued

Year	Multivariate issue	Location (by economy)	Location (by climate classification)	Methodological choice	Solution	Relevant studies
2004–2008		UMI	Temperate	Simulation and Field measurement	Site level	Chen *et al.* (2004)
2009–2013			Dry	Simulation	Building level	Ochoa *et al.* (2011)
2014–2018			Temperate	Simulation	Building level	Sosa *et al.* (2018)
			Dry	Simulation	Building level and site level	Krebs *et al.* (2017)
			Temperate	Simulation	Building level	Wang *et al.* (2018)
2019–2023			All	Simulation	Building level	Triana *et al.* (2023)
			Tropical	Simulation	Building level	Liaw *et al.* (2023)
			Temperate	Simulation	Building level	Benincá *et al.* (2023a, b), Dalbem *et al.* (2019), Franco *et al.* (2019), Martins and Schmid (2019)
				Simulation and Field Measurement	Building level	López-Escamilla *et al.* (2022)
2009–2013		LMI	Tropical	Field measurement and Survey	Building level	Singh *et al.* (2010)
2014–2018			Tropical	Simulation	Site level	Ahsanullah and Van Zandt (2013), Nugrahanti *et al.* (2018)
2019–2023			Tropical	Simulation and Field Measurement	Building level and site level	Nabilah *et al.* (2022)
			Dry	Simulation	Building level and site level	Saadatjoo *et al.* (2023)
					Building level	Luthra and Sundaram (2023)
			Temperate	Simulation	Building level	Luthra and Sundaram (2023)
					Site level	LongVu *et al.* (2019)

(*continued*)

Table 2. Continued

Year	Multivariate issue	Location (by economy)	Location (by climate classification)	Methodological choice	Solution	Relevant studies
2014–2018	ITC + Da	UHI	Dry	Field measurement and Survey	Building level	Afacan and Demirkan (2015)
2019–2023			Mediterranean	Simulation and Field measurement	Building level	Dolníková *et al.* (2021)
			Tropical	Simulation	Building level	Lan *et al.* (2019)
			Temperate	Simulation	Building level	Roberts *et al.* (2022), Yilmaz and Yilmaz (2020)
				Survey	Research	Foster *et al.* (2022)
2014–2018		LMI	Tropical	Simulation	Building level	Susanto *et al.* (2018)
2009–2013	MC + ITC + Da	UMI	Tropical	Document review	Building level and site level	Bodach and Hamhaber (2010)
				Simulation and Field measurement	Site level	González Couret *et al.* (2013)
2019–2023		LMI	Tropical	Field measurement	Building level	Trihamdani *et al.* (2023)
			Dry	Simulation	Building level and site level	Nait-Taour *et al.* (2023)
			Temperate	Simulation	Building level and site level	Nait-Taour *et al.* (2023)

Note(s): MC: Microclimate and Indoor thermal comfort, ITC: Indoor thermal comfort, Da: Daylight, UHI: High-income countries, UMI: Upper middle-income countries and LMI: Lower medium-income countries
Source(s): Authors' own work

3.2.2 Location. From the search results, it can be deduced that the research in this area is highly varied between countries as well as economies. Individually, Brazil has the highest number of articles, while categorically, countries under the UHI category have the highest number of articles. Brazil falls under the UMI category. In terms of distribution based on climate, most research articles are based on the temperate climate zone.

3.2.3 Methodology. Most studies use post-occupancy evaluation to assess and evaluate building performance. However, simulation for analysis has consistently grown over the years, while analysis by field measurements and surveys is declining. Nonetheless, in the last few years researchers have adopted mixed and diverse methodologies. Over the last few years, the choice for simulation has consistently grown, seconded by mixed methodology by field measurement and simulation. The use of field measurement and survey is declining over the years. Software suites such as EnergyPlus, Rhino Grasshopper suite and ENVImet are the most preferred applications for simulation exercises.

3.2.4 Solutions. Most researchers have limited the solutions to the building level, while some have proposed them at the site level. The least are those solutions in the combination of building-level and site-level interventions. However, recently more researchers have proposed

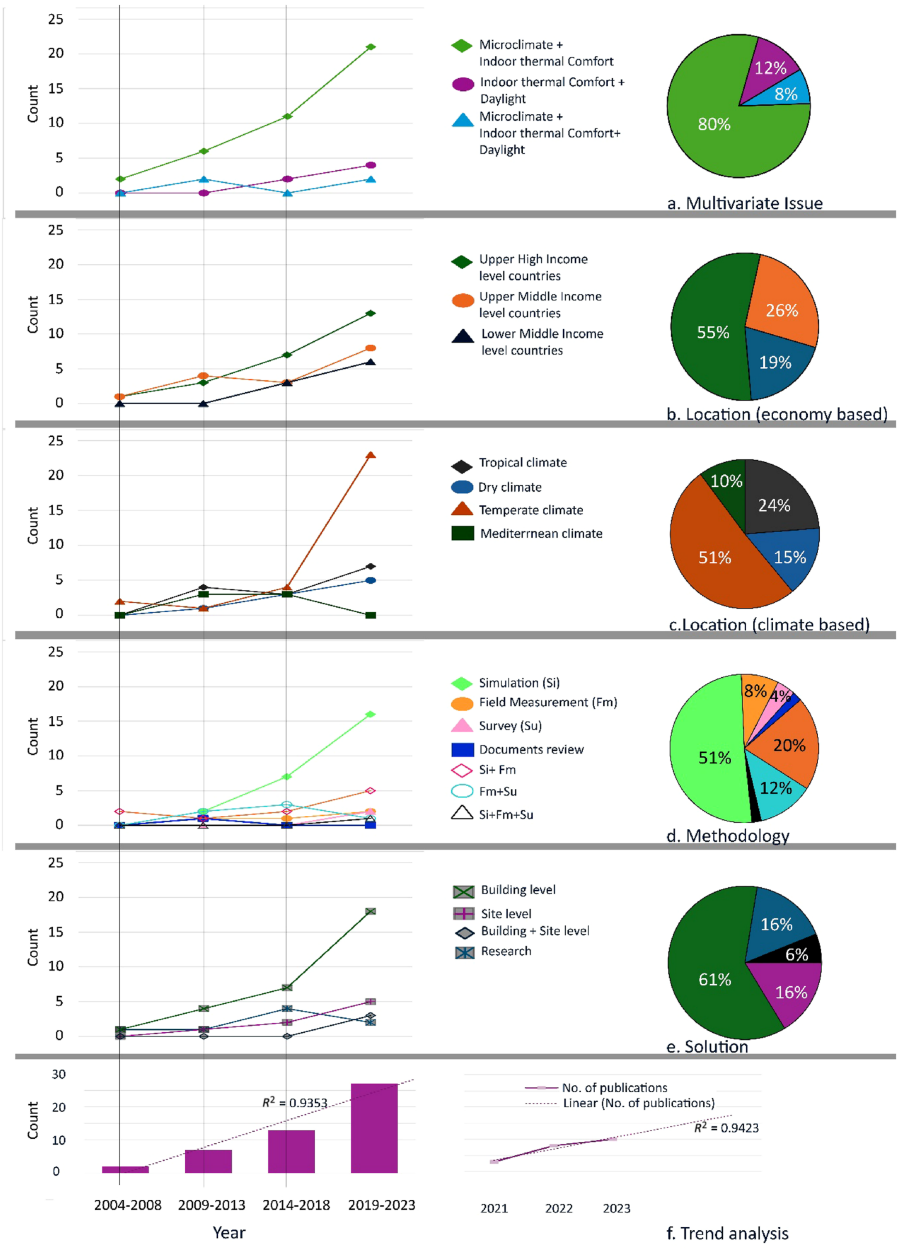

Figure 6. Trend and share of themes. Source: Authors' own work

multiple solutions even within the independent building and site-level interventions, in comparison to a singular solution approach adopted earlier. Accounting for this combination approach, the top three solutions at the building level are insulation, shading and layout and design. The same is not true for the site-level solution, as site planning is the single most

sought-after interventions that has remained dominant and increasingly resorted to since 2009. Overall, from the database it can be concluded that over the years the choice of multiple solutions is on the rise.

3.3 Key findings

Drawing from the findings from the above sections and given the interrelations that exist between the themes and the period of articles included, the following are the key findings, which will be discussed under the next section.

(1) The multivariate research considering three-way interaction between microclimate, indoor thermal comfort and daylight is relatively new in MDH; however, this has increased steadily over the years. This indicates that research into this is expected to further increase in the future.

(2) Research in Europe focused mainly on retrofitting, which can be attributed to the priority on improving the existing housing stock, which also contributes to a higher count of insulation as the most sought solution at the building level.

(3) While UHI-level countries lead on the number of articles, individually Brazil, which is a UMI-level country, has the most articles, almost all of which were published in the last few years. This, coupled with the high variance, skews the observation and hence cannot be generalized.

(4) There is huge variance within themes; most of the articles discuss microclimate and indoor thermal comfort, the majority of articles are from UHI-level countries, temperate regions have the highest representation and simulation is the most preferred methodological choice.

(5) UHI and UMI countries prioritize building-level solutions, while LMI countries consider a more holistic approach, considering solutions at both the site and building levels.

(6) Research including daylighting concurrently with indoor thermal comfort and outdoor microclimate is limited, which provides an incomplete picture of the interactions.

(7) There is no established approach considering the multivariate issue discussed in this paper that has been applied to MDH.

4. Discussion

The research brought to light the current knowledge on MDH, considering the nuances between outdoor microclimate, indoor thermal comfort and daylight comfort. The findings reflect the current stance of MDH in the research domain. Here the findings are discussed in more detail. This will help in arriving at planning for the way forward as MDH development gains increased popularity for adoption.

4.1 Research gaps

Generally, MDH development is being pursued by many countries, and it appears that towards meeting the SDG goals, there is increased research aligned to the research area that this paper introduced. This is substantiated when a search duplicating the same strings earlier discussed in this report and based on the same PRISMA flow chart generated 152 articles on Scopus when the period was set to end in 2024. This is an increase in research articles by almost 28%. While the screening process might yield different results, the fact that the results generated additional articles supports this observation. Furthermore, countries like Australia and New

Zealand have embarked on increased intensification with MDH typology as a preferred approach (Allen and Bryson, 2018b).

The research findings indicate that outdoor comfort consideration does not form an integral part of the indoor assessment in MDH, but interestingly, perhaps this is due to poor research generally in the housing sector (Cao *et al*., 2023; Elsayed *et al*., 2023). It could possibly be attributed to other factors, such as getting access and the cultural values that hinder research in residential development. Nonetheless, this complacency needs urgent attention, as rigorous research into housing must be strengthened, as lifestyle post-COVID-19 has changed the way people live and work, with people spending increasingly more time in houses than the pre-COVID-19 period (Erfani and Bahrami, 2023). While researchers have discussed the impact of climate change on housing (Jalali *et al*., 2023a, b), there are none on MDH typology. There is an urgent need to conduct more outdoor microclimate assessments to arrive at mitigation measures (Hashemi *et al*., 2024). These studies should not be limited to the present climate but should include future predictions to correlate changes to spatial development with microclimate changes.

The other key finding on high variance in article results between countries as well as economies that skews the findings as it limits generalization is due to recent increased research output from Brazil and the continued research by UHI countries in Europe. The high research count from Brazil can be attributed to the ongoing initiatives (Fábio, 2022) by the Brazilian government to increase the housing stock and the growing priority of the country to improve the existing housing stock (Triana *et al*., 2023). In the case of UMI-level countries, given the dominance of research articles from Brazil, the findings cannot be generalized. The high count from the UHI countries may be attributed to the ongoing initiatives to improve existing homes in Europe to meet changing regulatory standards on comfort (Congedo *et al*., 2024). Research at the UHI level has a fair mix of the different multivariate issues with similar approaches to the methodological choices. While the primary focus remains on retrofitting, there is a gradual move toward considering the wider aspects of urban, neighborhood and site planning. However, this is relevant for European countries. In countries like Australia, the concept of MDH is relatively new, given that MDH is currently being widely promoted there (Gibson and Law, 2023). A closer analysis reveals the consistently increasing research output from UHI countries, while the research output from UMI countries has surged in the last few years, mainly attributed to the researchers from Brazil. In fact, the LMI countries, mostly from Asia, have been steadily researching the multivariate area for a longer period than UMI countries, with a noticeable preference for using the simulation method as a methodological choice. While on one hand, the low count of individual papers for most countries indicates that the research area is very much under-researched, on the other hand, the high count of articles from the few countries or, as per economical category, suggests that adequate research is available for generalization.

The distribution by climate differs from the count of countries, given that some research is spread into many locations (Foster *et al*., 2022; Ooka *et al*., 2023; Singh *et al*., 2010; Triana *et al*., 2023). A careful analysis reveals that the climate zone categorization is a result of choice of location, and as most locations are based in Europe, the share of temperate regions is the highest. The findings relevant to the temperate region can be generalized; however, it would best suit only retrofit projects, as research in Europe focused more on retrofits than on new builds. The findings may not be directly relevant to new developments.

4.2 Methodological choices and solutions

Building simulation has emerged as the most preferential method for assessment; however, most of the articles are on retrofit. The evaluation of existing buildings requires post-occupancy evaluation (POE) to assess real conditions prior to simulating. Professional institutes such as the Royal Institute of British Architects (RIBA) have called for increased uptake of POE in the construction industry (Hay *et al*., 2017) as it provides insights, especially

for retrofit projects. However, POE has its own obstacles, especially for daylight analysis, though experiment validation is necessary to develop solutions based on real conditions (Nazari and Matusiak, 2024). Further daylight measurements are also dependent on the sky condition, which can vary within a short period of time (Bellia *et al*., 2018). Daylight studies involve using handheld devices as lux meters to measure and record measured data in time, in contrast to thermal comfort assessment, which requires data loggers that can be placed at strategic locations for data collection and retrieved later for data monitoring at collection, while the time and effort required for daylight studies is probably the main reason for the limited research in residential buildings. Nonetheless, the crucial role of POE cannot be discounted, and there is a need to have strategy and policy support in place to support POE, especially for the retrofit of residential development. The insights are also invaluable for application to new builds. A further assessment of the choice of methodology and its relation to the economic level of the countries indicate that location has an impact on the choice of methodology. UHI countries employ more variety of methodology (Diz-Mellado *et al*., 2023), driving nuanced findings that justifies the diversity of the solutions, though limited to the building level, adopted by these countries. It can be summed up that there is a direct correlation between methodological choices and solutions generated.

Given that insulation at the building level is the most preferred intervention, it merits discussion on its choice and what models it. This increased preference could be attributed to the large share of research from UHI-level countries, especially across Europe, where the focus is on retrofitting existing MDH developments. It could also be due to the contribution of research from Brazil, where the country is researching improving its housing stock to meet national standards, and insulation is by far the most efficient approach to retrofitting (Seifhashemi and Elkadi, 2022). This choice can be attributed to the response to increasing outdoor temperature due to climate change with global temperature rise. This supports the selection of other passive design features such as shading, layout and design and orientation as responses to the higher representation from temperate regions, followed by tropical and dry climatic zones where overheating is an issue. Intervention at windows is also a preferred solution, with a focus on improved ventilation to improve indoor thermal comfort. The UHI-level countries also focus on improved glazing and active means for thermal comfort. Most measures aim to combat indoor discomfort due to increased temperature levels; however, the solutions of choice differs.

Unlike researchers from other UMI countries who adopt only a singular option as a solution, Brazilian researchers identify multiple solutions. In the context of LMI-level countries, the solutions have mostly mixed solutions at both the site and building level. Nonetheless, insulation and shading are the most preferred options, while site planning is the most preferred one at the site level. This increased uptake of multiple solutions at both the site and building levels indicates the rise of holistic approaches to solution generation, given that building performance is a complex system considering various parameters (Hopfe *et al*., 2013; Maslesa *et al*., 2018) and opportunities for improvement are at both the site and building levels. Collectively it can be inferred that while methodological choices determine solution selection, the impact of national priorities, as in the case of Brazil, and the role of climatic challenges and resource constraints, as in the case of LMI-level countries, play an important role in determining the choice of solutions.

4.3 Relevance of outdoor microclimate

Apart from the research article by Pastore *et al*. (2017), none of the researchers selected in this review discuss in detail the impact due to outdoor conditions, despite the known negative impact of natural ventilation from stressed outdoor conditions (Kilnarova and Wittmann, 2017). Recent research has demonstrated that, given the complexity of cities and urban contexts, local intra-urban microclimate zones develop within the same urban context or even neighborhood (Chen *et al*., 2016; Chokhachian *et al*., 2020; Pigliautile and Pisello, 2020).

Established interventions such as natural ventilation, window area and location of openings to improve indoor thermal comfort (Sadeghi *et al.*, 2017) also impact daylight in housing. These interventions are also dependent on the outdoor thermal condition and can be a cause for higher energy consumption. This results in poor adoption of natural ventilation because unfavorable outdoor conditions will only trigger increased energy use as occupants seek to remedy thermal discomfort (Hernández *et al.*, 2024). Across Europe, improving the green index has proven to be an effective solution to mitigate overheating issues (Farahani *et al.*, 2023; Kravchenko *et al.*, 2023). This indicates the complexity of building performance (Hopfe *et al.*, 2013; Maslesa *et al.*, 2018) and highlights the need for a nuanced approach at both the site and building level. The optimization of these microclimate pockets to influence indoor comfort conditions is a missed opportunity that needs to be addressed.

4.4 Holistic overview of MDH

Previous research on MDH has focused on carbon emission and affordability (Hamdy *et al.*, 2011), wherein insulation has been cited as the most effective solution that optimizes cost against thermal comfort solutions. Further, Gao and Lee (2011) also indicated that modification to the outdoor environment is out of scope for architects and planners. These research efforts underestimate the potential of outdoor climate to regulate indoor comfort, probably given that research on outdoor design potential as climate modifiers (Diz-Mellado *et al.*, 2023) was not as advanced at the time. Researchers have also discussed MDH against thermal comfort and energy consumption (Hernández *et al.*, 2024; Ouanes and Sriti, 2024); however, it does not account for daylight, and the solutions identified are limited to the building level.

On a more holistic level, Bunker *et al.* (2020) and Gerrits *et al.* (2023) brought to light the importance of community participation for successful urban transition as cities plan to densify. This is further extended into accessing policy frameworks as determinants to successful public housing by Beattie and Haarhoff (2018), Heinen and Knieling (2022) and Rangiwhetu *et al.* (2020). Others, such as Aflaki *et al.* (2017), Al Haddid and Al-Obaidi (2022), Arriazu-Ramos *et al.* (2023), Hwang *et al.* (2020) and Rañeses *et al.* (2021), cite the impact of climate change and its impact on energy consumption and thermal comfort. This was further discussed from the lenses of well-being. These papers help identify that comprehensive research in MDH development is very much limited and could benefit from the introduction of a holistic approach. It also draws attention to the nuanced approach necessary to provide greater clarity to MDH development. As posited by Afful *et al.* (2021), perhaps the way forward is to ensure that enabling conditions are created to support the integration of indoor environment quality principles into building.

Nonetheless, researchers did reiterate the need to consider microclimate to model impact on thermal performance (Salvati and Kolokotroni, 2023; Wu *et al.*, 2023). Research into façade improvement included windows as the most important building element, while each article on retrofit had different focal issues such as Life Cycle Assessment (Mercader-Moyano and Esquivias, 2020), energy efficiency (Boukli Hacene and Chabane Sari, 2019) and only one focused on daylight and visual comfort (Amoruso *et al.*, 2019). Overall, the findings indicate the importance of building design development considering microclimate for optimized thermal comfort and daylight. This will support future-proofing (Georgiadou, 2014; Georgiadou *et al.*, 2013), which may reduce the possibility of obsolete building design (Buitelaar *et al.*, 2021; Shahi *et al.*, 2020), and this remains true for MDH development as well.

The discussions above highlight the evolving landscape of MDH research in the context of outdoor microclimate, indoor thermal and indoor daylight comfort. It emphasizes the interplay between the themes earlier developed that play a crucial role in understanding the current knowledge in the research context. It can be summed up as while high variance exists within and between the themes, a pattern is also present, especially when it comes to UHI-level countries. It also presents the driving factors that influence research and the solutions that are

arrived at. Factors, such as economic conditions, matters of national or regional priorities and climatic conditions underscore the dynamics of research undertaken in this area of research. Furthermore, it draws on the importance and impact of an integrated approach in terms of issues, methodological choices and solutions. Additional articles are referenced to discuss some of the findings, which further reinforces the need for an integrated holistic approach in MDH development. Moving forward, a more nuanced, context-sensitive and interdisciplinary approach is essential to inform resilient and future-proof MDH development.

5. Limitations

Despite the rigor in article identification and detailed analysis for thematic categorization, the research has its limitations, as it was based on a single database, Scopus, which may restrict the breadth of its findings. Additionally, the findings cannot be generalized given the high variance in article distribution across countries and in the choice of solutions. Nonetheless, this underscores the urgency to develop a nuanced framework that integrates the outdoor microclimate, indoor thermal comfort and indoor daylight conditions for application in medium-density housing (MDH) development.

6. Conclusion

The aim of this research was to construct current knowledge and support the holistic development of medium-density housing development grounded on global trends and historical context. A systematic literature review was undertaken as no prior research was conducted in the domain that accounted for outdoor microclimate, indoor thermal comfort and indoor daylight in MDH. The cornerstone of this research is the development of the themes, which were based on the content of the articles reviewed. Each article selected was thoroughly analyzed to place it within the identified theme.

The findings establish that while significant interactions between themes were absent, there were significant interactions within the themes itself. However, the highly varied and unbalanced distribution of the articles suggests the need for the development of a nuanced approach in MDH development. The research confirms a growing scholarly interest in the multivariate integration of outdoor microclimate, indoor thermal comfort and daylight performance in MDH developments. This study contributes to this expanding body of work by establishing a foundational reference for future research adopting holistic and integrated design methodologies. Furthermore, the findings underscore how national economic conditions and policy priorities shape research agendas, influencing methodological choices and preferred solutions. By highlighting these dynamics, the study underscores the need for context-sensitive, multidimensional approaches to future-proof MDH developments.

In conclusion, this research advances the understanding of MDH by providing insights into the underdiscussed intersection of microclimate, indoor thermal comfort and daylight. The findings have broad implications, from informing designers, researchers and policymakers on these multivariate considerations to encouraging novel approaches for future research. This could realize through policy changes that mandate the inclusion of outdoor comfort analysis in both new designs and retrofit projects or creating awareness among designers and researchers of the choice of solutions and methods applied to assist in their design/research endeavor. It could lead to designers working alongside users to integrate social and cultural values to develop solutions that brings about holistic changes to the way we design and conceive the built environment. The study not only contributes to a deeper understanding of the current research landscape but also highlights the potential of such integrated strategies to advance key Sustainable Development Goals (SDGs). SDG 3, SDG 11,\ and SDG 13 are supported by encouraging climate, and context-responsive design practices. This research supports the creation of livable cities through a multi-objective approach for medium-density housing, thereby enhancing the health and well-being of populations in increasingly stretched and

changing urban and suburban landscapes. This research signals the opportunity to develop a holistic model that optimizes both indoor and outdoor conditions for MDH development.

Ethical statement

This study did not require ethical approval, as no human participants or animals were involved.

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Corresponding author
Deependra Pourel can be contacted at: deependra.pourel@autuni.ac.nz