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Hygrothermal Performance of External Wall Systems Under Current Climatic Conditions and Future Climate Projections of Turkey

C. Baş[1], A. N. Türkeri[2] and M. A. Lacasse[3]

[1]Istanbul Technical University, Graduate School, ITU Ayazağa Campus, Building of Graduate School, 34469, Maslak, Istanbul, Turkey, bascana@itu.edu.tr,

[2]Istanbul Technical University, Department of Architecture, 2 Taşkışla Street, 34367 Istanbul, Turkey, sahal@itu.edu.tr

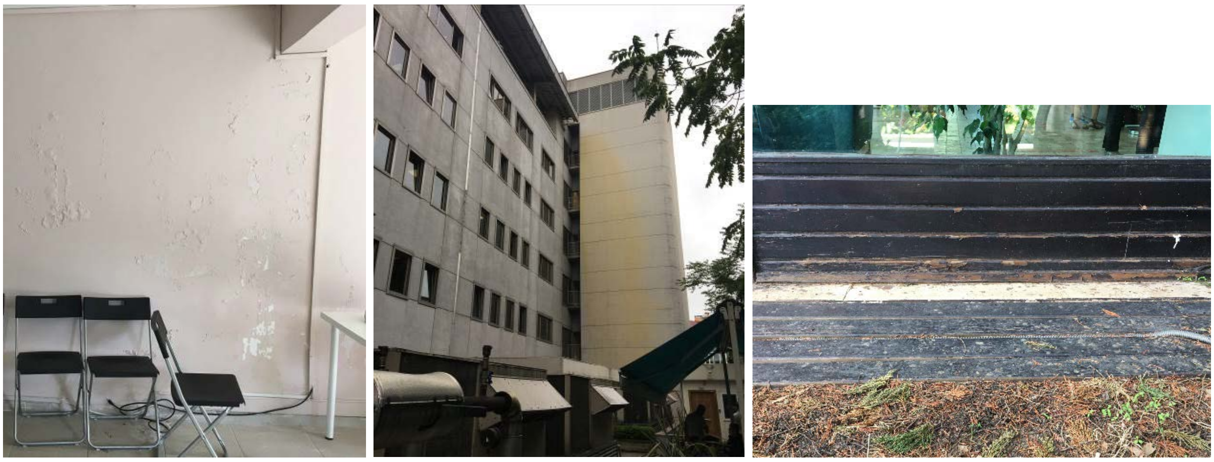
[3]National Research Council Canada, Construction Research Centre, 1200 Montreal Road, Ottawa, ON K1A 0R6, Canada, michael.lacasse@nrc-cnrc.gc.ca

Abstract. *External wall failures caused by rainwater ingress are very common in Turkey. External wall systems that fail to meet the expected watertightness performance may cause premature deterioration of building components, create health hazards for users, and lead to a financial burden for building owners and in respect to the premature deterioration of public buildings, this also has repercussions on the national economy. In addition to the current climatic conditions, thermal and moisture loads that effect the buildings are expected to increase in the future due to climate change. In regards to climate change mitigation strategies, as have been emphasized for the building sector in Turkey, the national government is promoting the use of thermal insulation. However, given that the thermal performance of the most commonly used thermal insulation materials in Turkey are affected by moisture, it is important to evaluate the hygrothermal performance of external wall systems to help ensure the effectiveness and longevity of any proposed measures to mitigate the effects of climate change on building performance. In this paper, the state of the art is presented in respect to investigations of the hygrothermal performance of external wall systems. The research is analyzed based on climatic conditions to which the wall is exposed, the type of external wall assembly investigated, and the method of investigation described in the studies reviewed. The results indicate that the hygrothermal performance of external walls has been extensively investigated; however, there is relatively little research focusing on the hygrothermal performance of external walls subjected to the current climatic conditions of Turkey. In those studies that focused on evaluating the hygrothermal performance of external wall systems under future climate projections, these have been conducted for the cold climate regions of Canada, USA, Norway, and Finland. The hygrothermal performance of external walls under future climate projections for any region of Turkey has not yet been explored.*

Keywords: *Hygrothermal Performance; External Wall Systems, Climate Change*

1 Introduction

Moisture is one of the most crucial external factors that can significantly impact the service life of building elements. Given that the primary function of external wall systems is to provide a barrier between the external and internal environments, the outer surfaces of the external walls are exposed to various environmental degradation factors. If the external walls fail to provide the desired watertightness performance, water intrusion can manifest itself in different forms of damage, including premature deterioration of building elements, and the growth of mold and mildew, which can potentially result in health problems for the building occupants. A recent study was carried out to investigate building facade failures resulting from rainwater ingress based on a literature review and field inspection of 16 public buildings located in Istanbul, Turkey (Baş, Türkeri & Lacasse, 2022). The findings revealed that blistering and exfoliation were the most prevalent issues in stucco-clad facades, whereas staining was often observed in natural stone cladding facades. Detachment of cladding was frequently observed in clay-based cladding facades, and blistering and exfoliation of protective paint were the primary types of damage observed in timber cladding facades (Figure 1).



(a) (b) (c)

Figure 1. The majority of the plastered interior surface of stucco cladding facade suffers from blistering and exfoliation (a), stain on stucco cladding facade caused by water leakage from rusty punctured roof gutter (b), blistering and exfoliation of paint over timber sidings (c) (Baş, Türkeri & Lacasse, 2022).

In addition to the current situation, thermal and moisture loads that effect buildings are expected to change given future projections of climatic conditions due to climate change. In the latest Assessment Report of IPCC (Climate Change 2021: The Physical Science Basis Summary for Policymakers, 2021) it is stated that the average global surface temperature increase for 2081-2100 period is very likely to be 1.0°C to 1.8°C for the very low GHG emissions scenario (SSP 1-1.9), 2.1°C to 3.5°C for the intermediate GHG emissions scenario (SSP2-4.5), and 3.3°C to 5.7°C for the very high GHG emissions scenario (SSP 5-8.5). Global warming will most likely result in heavy precipitation events becoming more frequent and intense in most regions. For each 1°C of global surface temperature increase, extreme daily precipitation is expected to intensify by about 7% at a global scale (Climate Change 2021: The Physical Science Basis Summary for Policymakers, 2021). In a study conducted using the regional climate model RegCM3 to calculate future climate projections for the Eastern Mediterranean region between 2071-2100, it is stated that a significant increase (5%–25%) in winter precipitation is expected over the coastal regions of the Black Sea, whereas a large decrease (20%–60%) in precipitation is expected over the southern and southeastern regions of Turkey (Önol & Semazzi, 2009). A similar prediction can be seen from the calculations of the Turkish State Meteorological Service based on the MPI-ESM-MR global climate model; a general decreasing trend in precipitation is projected for Turkey, whereas an increase of 10%-40% in the winter precipitation is expected in the northern part of the country (Akçakaya et al., 2015). The calculations of the Istanbul Metropolitan Municipality show that the annual average temperature in Istanbul is expected to increase between 1-5°C for different scenarios as compared to the 1986-2005 period, whereas a decrease in precipitation is expected at the end of this century for RCP4.5 of ca. 5%, ca. 8% for RCP6.0, and for the worst scenario, RCP8.5 ca. 12% (Istanbul Büyükşehir Belediyesi, 2018a). Contrary to the expected decrease in precipitation, the total annual precipitation on very wet (R95p) and extremely wet days (R99p) are expected to increase up to 19% and between 19% and 59% respectively for RCP8.5 at the end of this century (Istanbul Büyükşehir Belediyesi, 2018a). This indicates that even though the annual precipitation is expected to decrease in the future, extreme precipitation events are likely to increase.

To mitigate the anticipated effects of climate change as part of a global effort, Turkey became a party to international agreements, including the UNFCC in 2004 and the Kyoto Protocol in 2009. The Paris agreement, which is the most up-to-date international step towards limiting global greenhouse gas emissions to combat climate change, was signed in 2016 and ratified in 2021 by Turkey (Republic of Turkey Ministry of Foreign Affairs, n.d.). In the first Nationally Determined Contribution submitted in 2021, Turkey declared a target of greenhouse gas emission reductions of 21% by 2030, from the business as usual level (United Nations Framework Convention on Climate Change, n.d.). Based on these expected climate change impacts and the binding provisions in the signed international agreements, national strategies were established for 2011-2023 in the Climate Change Action Plan (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2012). Three main objectives are stated related to the building sector in terms of climate change mitigation: increasing the energy efficiency of buildings; increasing the use of renewable energy in buildings, and; limiting the greenhouse gas emissions originating from settlements (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2012). Actions to increase energy efficiency in buildings that are planned and considered an effective implementation of the Energy Performance Regulation in Buildings, include: revision of the minimum requirements in regulations and standards to increase energy efficiency, and; generation of thermal insulation and energy efficient systems that meet the standards (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2012). In parallel to the deployment of national strategies, the local climate change action plan for Istanbul requires that all new buildings be net zero emission by 2030, and all existing buildings be net zero emission buildings by 2050, with renovations to support the goal of being a carbon neutral, and climate change resilient city by 2050 (Istanbul Büyükşehir Belediyesi, 2018b).

The most striking measure regarding the building sector in regard to climate change strategies for Turkey and Istanbul, is promoting the use of thermal insulation to reduce the energy consumption of buildings. Since the thermal performance of commonly used thermal insulation materials can be affected by moisture, assessing the hygrothermal performance of external wall systems is a crucial element to ensure the durability and long-term energy efficiency of any suggested strategies. The aim of this study is to examine previous research focused on evaluating the hygrothermal performance of exterior walls. Through this effort, it will be possible to reveal the state-of-the art in the field and to understand the previous research concerning the exposure of external walls to temperate-humid climate conditions, that are representative of the climate of Istanbul.

2 Research Methodology

A literature review was conducted to permit understanding the hygrothermal performance of external walls of existing buildings and the change in their moisture and thermal performance under future climate projections. The study reflects the preliminary results of a review that was conducted in respect to journal articles published in the last 10 years. For this review, focus was made on examining research articles in which were described the hygrothermal performance evaluation of external wall systems. Research articles based on simulation results or measurements were primarily selected for review, whereas for those studies in which only test methods were employed, these were included in the review provided the climatic region to which the walls were exposed corresponded to the climatic regions of Istanbul or Turkey. Given that such type of analyses were primarily carried out by simulating the hygrothermal performance of an external wall assembly, articles focused on sensitivity and uncertainty analysis or improving the accuracy of simulating future hygrothermal behavior were also included. The research articles investigated in this study was narrowed down following the criteria mentioned above. However, the articles that meet these criteria is not limited to articles investigated in this study since this study reflects the preliminary findings of a review. Data gathered from the review were analyzed under the following headings: climatic conditions to which the wall was exposed[1]; orientation of the wall; wall assembly cladding material and back-up components; research method, and; assessment tool used for hygrothermal simulations. This review permits addressing the knowledge gap with respect to the hygrothermal performance of external walls of existing buildings and the climate resilience of existing buildings exposed to temperate-humid climatic conditions such as Istanbul.

3 Findings and Discussion

3.1 Review of Hygrothermal Performance of External Walls Under Current Climatic Conditions

Articles focused on investigations of the hygrothermal performance of external walls under current climatic conditions constitute the majority of research found in the literature reviewed. The majority of the studies reviewed focused on timber stud walls. Wang et al. (2013) studied the hygrothermal performance of a wood frame wall using on-site measurements, whereas Corcoran et al. (2013) simulated the effect of a construction defect in timber wall assemblies. Amongst the timber wall assemblies investigated by Corcoran et al. (2013), the growth of mold was possible in two wall types that had OSB sheating on the exterior side which, it was observed, limited the drying capacity of the wall. Wang & Ge, (2018) investigated the influence of material properties, boundary conditions, and air and rain leakage on the hygrothermal performance of highly insulated timber walls. Results showed that uncertainties in respect to the moisture content present in wall components have a greater impact on the simulation results as compared to material properties. These studies also determined that timber stud walls having external thermal insulation have a lower risk to mold growth in the case of rain and air leakage

[1] The climatic conditions to which the investigated wall is exposed in the all analyzed articles are classified according to an updated version of Köppen-Geiger climate classification (Beck et al., 2018) based on the given location in the articles.

as compared to timber stud walls with thermal insulation in between studs. When the impact of rain infiltration in highly insulated timber walls was evaluated, it was seen that rainwater deposition causes a significant risk to moisture damage on the exterior or interior surface of the wood sheathing, with the greatest risk being deposition to the interior (Wang & Ge, 2019). These authors also investigated the moisture content of CLT walls under the influence of various boundary conditions, environmental loads, and material properties. It is concluded that the CLT wall with low vapor permeance water resistant barrier has higher risk of moisture problems in the case of rain leakage compared to the one with high vapor permeance water resistant barrier (Wang & Ge, 2016). McClung et al., (2014) evaluated the hygrothermal performance of CLT wall assemblies in terms of drying behavior based on measurements taken from wall assemblies within an envelope test facility and from the results of simulations. It was observed that for CLT wall assemblies, low-permeance materials caused slower drying, however, the presence of high moisture contents, as may cause decay as a result of typical construction moisture, is unlikely to occur in the wall assemblies investigated.

The hygrothermal performance of external brick masonry walls, were the second most widely investigated wall assemblies. Liuzzi et al. (2013) studied the hygric performance of unfired clay composite masonry brick containing bentonite and hydrated lime stabilization. It was shown that this type of brick masonry has a better performance in terms of humidity buffering when used as an interior finishing material as compared to gypsum plaster or acrylic stucco. Kolaitis et al. (2013) evaluated the impact of internal and external thermal insulation systems for brick masonry walls subjected to temperate Oceanic climate conditions, and concluded that incidents of condensation are typically observed in walls incorporating internal thermal insulation. On the basis of field measurements and the results of simulation, Kloseiko et al. (2013) was able to compare the hygrothermal performance of different thermal insulation materials for use in internally insulated brick walls subjected to a cold climate. It was observed that thermal comfort improved in all cases but critical conditions in respect to condensation and mold growth occurred when autoclaved aerated concrete and polyisocyanurate board were used as thermal insulation. Kılıçaslan & Kuş, (2021) investigated the hygrothermal performance of external thermal insulation applications on brick masonry walls of existing buildings. Results showed that when thermal insulation was applied on existing impermeable claddings in the refurbishment process, the wall attained critical levels of moisture content in the winter causing a decrease in thermal resistance, and over the long term, deterioration of building components and as well, mold growth. Kus et al. (2013) was able to show that the thermal transmittance through the hollow portion of pumice aggregate concrete hollow block is greater than that through lightweight solid parts, but as the hollow portion gets wider, there is an increase in convective heat flow that reduces the thermal performance. Edis & Kus, (2014) compared the structure and use of hygrothermal simulation software, and examined the performance of an exterior wall exposed to climatic conditions of Istanbul with WUFI. Wall assemblies that contained 19 cm thick pumice aggregate concrete blocks (PAC) and 4cm exterior XPS insulation, or EPS, were found to have sufficient hygrothermal performance. Kočí et al. (2013) determined the hygric properties of thermal insulation and connecting layer to be used in the thermal insulation systems for autoclaved aerated concrete walls, demonstrating that the materials that meet the required criteria for thermal insulation are hydrophilic mineral wool and calcium silicate, and for the connecting layer, the materials that meet the required criteria for thermal insulation include common lime-cement or lime-pozzolan mortars. Trindade et al.,

(2021) determined the impact of climatic conditions, different type of plasters and thermal insulation on the hygrothermal performance of autoclaved aerated concrete walls, demonstrating that hygric properties of the exterior render has a major impact on the potential for frost damage, and thermal transmittance of masonry. From a broader point of view, Santos & Mendes (2013) calculated heat, air and moisture transfer in likely zones of thermal bridging; these zones included the upper and lower corners of buildings with brick masonry walls and reinforced concrete structures. They concluded that the presence of high values for relative humidity both in lower corner for cold and humid conditions, and in upper corner mainly caused by higher hygrothermal capacity of concrete beam.

Rouchier et al. (2013) investigated the influence of concrete fracture of facade panels on the degree of rain infiltration and thermal performance of building facades. It was concluded that when the cracked concrete panel was exposed to rain events an important accumulation of water in the envelope was present and also, an increase in the moisture content of the insulation layer was observed resulting in a decrease in thermal performance. Iffa and Tariku (2017) studied the effects of location and vapor permeance of membranes on the moisture transport in Insulated Concrete Form (ICF) walls and found that the low permeance vapor barrier used on the exterior prevented drying of the concrete and induces moisture transfer towards the interior of the building.

The uses of relatively new or distinctive building materials in external wall systems has been the focus of some of the more recent studies. Huang et al., (2018) studied the use of bamboo fiber and bamboo charcoal as building materials in terms of the hygrothermal performance of building components, indoor hygrothermal environment, and HVAC demand. Results indicated that usage of bamboo charcoal as a moisture control layer in the upstream side of the moisture flow together with bamboo filler as thermal insulation diminished moisture and heat flow through external walls and thus, enhanced the hygric performance of the wall assemblies. In another study, the authors focused on the optimization of construction design using bamboo as an exterior board (i.e., scrimber), interior board, and interlayer board in buildings located in hot-humid climate regions. It was determined that using bamboo scrimber as an exterior board offered advantages in respect to moisture resistance as compared to brick, whereas bamboo particle board performed best as an interlayer board (Huang et al., 2019). Park et al., (2019) explored the potential of functional gypsum boards (FGB) by adding both porous and phase change materials to gypsum board and found that the thermal conductivity of FGB decreased, and water vapor resistance and water content of FGB both increased without showing any risks of condensation or mold growth in the wall assemblies investigated. In another study, Park et al., (2021) highlighted the potential of biochar-mortar composite material by showing its contribution to humidity control and improvement of hygrothermal performance of mortar in external walls. The hygrothermal performance of thermal aerogel-based rendering was explored by Maia et al., (2021) where it was shown that prevention of moisture related risks through the use of a finishing coating having enhanced hygrothermal properties was important due to the high capillary absorption of this rendering and increase in thermal conductivity in parallel with moisture content. Use of straw bales in exterior wall construction has been studied by Koh & Kraniotis, (2021). In their studies it was demonstrated that the straw bale layer closest to the exterior had the highest level of moisture content and most susceptible to mold growth, whereas wood fiberboard and gypsum board can both be used as sheathing panels to regulate water content within the straw bale.

When the articles were analyzed according to climatic conditions to which the walls were exposed, those walls exposed to the climate of the temperate Group C and continental Group D zones are notable (Table 1). Most of the research was conducted in respect to wall assemblies exposed to a temperate oceanic climate (Cfb) or a warm-summer, humid cold climate (Dfb), whereas only in some studies was the focus on wall subjected to temperate-humid climatic conditions (Csa), this temperate-humid climate corresponding to the climate conditions of Istanbul. Investigated wall assemblies under the effect of temperate-humid climatic conditions (Csa) which corresponds to the climatic conditions of Istanbul include brick masonry core (Liuzzi et al., 2013) (Kılıçaslan & Kuş, 2021) and PAC block masonry core (Edis & Kus, 2014) with render, glass mosaic and ETICS claddings. More studies have focused on south oriented walls, possibly due to south being the direction in the northern hemisphere receiving the highest amount of solar radiation. However, it is seen that the orientation of walls being investigated is dependent on local wind and rain conditions, with the direction receiving the highest amount of wind-driven rain being the most commonly studied orientation.

When the articles were analyzed according to wall assemblies of different materials, it can be seen that all the investigated walls were cladding walls. Of this type of wall assembly, masonry walls of various masonry materials were investigated, as well as timber stud walls, CLT walls and reinforced concrete walls; of these groupings, most of the walls examined were timber stud walls and brick masonry walls (Table 1). The type of cladding material of the majority of the wall assemblies investigated were different types of rendering, these types of rendering being specified as: cement-gypsum, mortar, plaster, or stucco. Walls having brick veneer cladding, glass mosaic, ETICS, and board cladding manufactured from timber, bamboo or fiber cement, were also investigated.

Numerical simulation was used in the research methodology of the significant number of the investigated studies, but it is often supported by another method such as experimental data, field measurements, or numerical calculations to increase the reliability of the results. Wufi seems to be the commonly used simulation tool amongst the analyzed studies, however the number of examined articles should be increased in order to have more trustworthy conclusions on this matter.

3.2 Review of Hygrothermal Performance of External Walls Under Future Climate Projections

The majority of the research focused on having insights on the impact of climate change on the external walls, specifically timber wall assemblies such as timber stud walls, log walls, and walls constructed with CLT. Hao et al. (2020) investigated the moisture safety of the envelope for a representative Alpine historic residential building and concluded that climate change and retrofit interventions would reduce moisture related risks such as increased risk of mold growth in the case of wooden walls, and frost damage in the case of sandstone walls. Choidis et al. (2020) studied the impact of climate change on the risk of biodeterioration for a historical log building located in Tønsberg, Norway. The results from this study revealed that there was no mold risk for the log building under current climatic conditions, whereas for future projections a high mold index was present on the outer surfaces of the log walls where the tar treatment had been removed. A follow-up study by Choidis et al., (2021) on historical timber buildings having

Table 1. Analysis of studies investigating hygrothermal performance of external walls under current climatic conditions.

	Climate											Wall orientation							
	Am	BSf	BSh	Cfa	Cfb	Csa	Csb	Dfb	Dfc	Dwa	no data	N	W	S	E	NE	NW	SE	no data
Kolaitis et.al.,2013				●	●														●
Wang et.al.,2013				●										●					
Rouchier et.al.,2013				●									●						
Corcoran et.al.,2013					●														●
Liuzzi et.al.,2013						●								●					
Kloseiko et.al.,2013								●				●							
Koci et.al.,2013								●						●					
Santos & Mendes,2013											●								●
Kus et.al.,2013											●								●
Edis and Kus, 2014						●											●	●	
McClung et.al.,2014								●							●				
Wang & Ge, 2016								●					●		●				
Iffa & Tariku, 2017					●			●				●			●				
Wang & Ge, 2018					●			●				●		●	●				
Huang et.al,2018	●	●	●	●										●					
Wang & Ge, 2019					●									●	●				
Park et.al.,2019										●						●			
Huang et.al,2019	●	●												●					
Park et.al.,2021										●								●	
Maia et.al.,2021					●		●					●		●					
Koh & Kraniotis,2021				●	●	●		●	●			●	●	●	●				
Kılıçaslan & Kuş,2021						●											●		

	Wall core								Wall cladding													
	timber stud wall	CLT wall	brick masonry	AAC block masonry	PAC block masonry	lightweight concrete block	concrete	straw bale loadbearing wall	brick veneer	cement-gypsum render	thermal aerogel based	biochar-mortar	cement mortar	plaster	stucco	fibre cement board	bamboo board	timber cladding	glass mosaic	ETICS	no cladding	no data
Kolaitis et.al.,2013			●										●									
Wang et.al.,2013	●														●							
Rouchier et.al.,2013							●						●									
Corcoran et.al.,2013	●								●													
Liuzzi et.al.,2013			●							●												
Kloseiko et.al.,2013			●																			●
Koci et.al.,2013				●										●								
Santos & Mendes,2013			●																			●
Kus et.al.,2013					●																●	
Edis and Kus, 2014					●									●								
McClung et.al.,2014		●														●						
Wang & Ge, 2016		●														●						
Iffa & Tariku, 2017							●								●							
Wang & Ge, 2018	●															●						
Huang et.al,2018	●		●	●													●					
Wang & Ge, 2019	●															●						
Park et.al.,2019							●							●								
Huang et.al,2019	●								●								●					
Park et.al.,2021							●					●	●									
Maia et.al.,2021						●					●											
Koh & Kraniotis,2021	●							●										●				
Kılıçaslan & Kuş,2021			●										●						●	●		

	Method				Simulation tool					
	experiment	numerical calculations	simulation	field measurement	WUFI	Delphin	HEMOT	HETRAN	COMSOL	no data
Kolaitis et.al.,2013			●					●		
Wang et.al.,2013				●						
Rouchier et.al.,2013		●	●							●
Corcoran et.al.,2013			●		●					
Liuzzi et.al.,2013	●		●		●					
Kloseiko et.al.,2013			●	●		●				
Koci et.al.,2013			●				●			
Santos & Mendes,2013		●	●							●
Kus et.al.,2013	●									
Edis and Kus, 2014			●		●					
McClung et.al.,2014			●	●	●					
Wang & Ge, 2016			●			●				
Iffa & Tariku, 2017			●						●	
Wang & Ge, 2018			●			●				
Huang et.al,2018	●		●		●					
Wang & Ge, 2019			●			●				
Park et.al.,2019	●		●		●					
Huang et.al,2019			●		●					
Park et.al.,2021	●		●		●					
Maia et.al.,2021	●		●		●					
Koh & Kraniotis,2021			●		●					
Kılıçaslan & Kuş,2021			●	●	●					

log walls supported the earlier findings, whereby it was shown that in the future, there was an increased mold risk for timber buildings, especially for exposed, untreated logs, for horizontal surfaces, and north-oriented vertical or inclined surfaces. Lü et al. (2018) studied the hygrothermal performance of timber material as an interior finishing for external walls. The results obtained showed that climate change leads to rises in humidity levels in indoor air and thus, a corresponding increase in the risk to moisture damage. Nonetheless, given the moisture buffering capabilities of wood building materials, the risk to mold growth can be reduced. Conroy et al. (2021) measured the hygrothermal performance of vertical timber truss panel walls of a building that was built in accordance with the International Passive House standard. The results demonstrated that good hygrothermal performance was predicted under the projected future climate with an increase in the average annual temperatures resulting in lower average relative humidity values within the wall assembly. Chang et al. (2021) investigated the impact of four different thermal insulation materials on the hygrothermal performance of plywood laminated CLT walls. The results showed that the moisture content of the thermal insulation increased under future climate projections causing moisture problems in the thermal insulation, and an increased risk of mold growth, whereas only walls having XPS insulation had no risk for mold growth under future climatic conditions. Wang et al. (2021) provided a different perspective from other work in their studies. They investigated the most effective mold growth risk control strategy for timber frame walls having clay brick cladding. It was shown that the potential for the deflection of wind-driven rain was the most robust control strategy for the risk to mold growth as compared to improving the watertightness or improving cladding ventilation, particularly in future periods.

Nik et al. (2015) and Aggarwal et al. (2022) took a different approach and studied the uncertainty and reliability of simulating the future response of external walls under the impact of climate change. Nik et al. (2015) evaluated the impact of climate uncertainties, WDR calculation methods, facade material and size in the prediction of hygrothermal performance of the building facades. The results indicated that amongst the causes of the variations in the calculation of water content of the facade, selection of Global Climate Model has the largest influence. Aggarwal et al. (2022) studied the reliability of climate-based indices in comparison to response-based indices obtained from simulation results of timber stud wall assemblies under historical climatic data and future climate projections in terms of moisture reference year selection. Their analysis showed that climate-based indices and response-based indices are not consistent, and climate-based indices perform better as an indicator of severity of weather years. As seen in Table 2, in the majority of studies the hygrothermal performance of external walls was investigated under cold climatic conditions, these being classified as Dfa, Dfb Dfc, Dsc, Dwb according to Köppen Geiger climate classification. The most commonly studied climate type was warm summer, humid cold climate (Dfb). For some of the articles, temperate climatic conditions were studied, such as Cfa, Cfb, Csb, whereas in only one of the studies were tropical monsoon (Am) climatic conditions considered. Amongst the studies reviewed and analyzed, none has focused on the hygrothermal performance of external walls under future climatic projections of a temperate-humid climate (Csa). The hygrothermal performance of north-facing walls under future climate projections were commonly investigated, whereas the performance evaluation of south-facing walls, east-facing walls, and walls facing all directions were also available. It was stated that the orientation receiving the least amount of solar radiation, and the orientation receiving the highest amount of wind driven rain were two essential criteria in terms of wall orientation selection (Aggarwal et al., 2022).

Table 2. Analysis of studies investigating hygrothermal performance of external walls under future climate projections.

	Climate									Wall orientation								Wall core					Wall cladding									Method		Simulation tool		
	Am	Cfa	Cfb	Csb	Dfa	Dfb	Dfc	Dsc	Dwb	N	W	S	E	NNW	SSW	SSE	no data	timber stud wall	log wall	CLT	stone masonry	no data	wood cladding	plywood board	brick veneer	concrete board	metal	lime plaster	stucco	no cladding	no data	simulation	field measurement	WUFI	Delphin	no data
Chang et.al.,2021	●	●		●	●		●			●			●							●			●	●								●	●	●		
Aggarwal et.al.,2022			●			●			●	●				●	●	●		●							●				●			●			●	
Conroy et.al.,2021			●			●		●	●	●								●									●					●	●	●		
Nik et.al.,2015						●						●						●					●			●						●		●		
Hao et.al.,2020						●							●					●			●							●				●			●	
Wang et.al.,2021						●				●	●	●	●					●							●							●			●	
Choidis et.al.,2020						●				●		●							●											●		●	●	●		
Choidis et.al.,2021						●				●	●	●	●						●											●		●	●	●		
Lu et.al.,2018						●											●					●									●	●	●			●

Cladding walls were the investigative focus in all studies reviewed. The most commonly evaluated wall type was timber stud walls; this is not surprising given that most of the studies as were reviewed originated from North America and Scandinavian countries where timber stud walls are the commonly used wall type in home construction. Other than timber stud walls, historical buildings having log walls were investigated in two studies, stone masonry wall in one study, and cross laminated timber (CLT) wall in one study. Wood cladding, brick veneer, and plaster were cladding materials of the most commonly studied wall assemblies. In all studies the hygrothermal performance of external walls under future climate projections were investigated using simulations. Five of the nine studies analyzed compared the simulation results of the walls exposed to historical climate conditions to that of field measurements. Delphin and Wufi were the simulation tools that were primarily used in these studies, whereas Wufi was more commonly used than Delphin.

4 Conclusions

In this article the state of the art in the field of hygrothermal performance assessment of external wall assemblies was presented. The findings represent the preliminary results of research articles published in the last decade for the hygrothermal performance evaluation of external walls under current climatic conditions and future climate projections. The articles reviewed were analyzed in respect to climatic conditions to which the wall was exposed, orientation of the wall, the wall assembly cladding material and back-up components, research method, and assessment tool used for hygrothermal simulations. Results indicated that hygrothermal performance of external walls under the current climatic conditions is a widely investigated field compared to the performance under future climate predictions. Timber stud walls and brick masonry walls stand out amongst the wall assemblies investigated. The importance of plaster rendering as a cladding with respect to the hygrothermal performance of external walls were extensively investigated. However, very few studies explored the hygrothermal performance of external walls subjected to the current climatic conditions of Istanbul. The current research on hygrothermal performance of external wall systems under future climate projections mostly concerns the cold climate regions of Canada, USA, Norway, and Finland. The hygrothermal performance of exterior walls has not yet been studied in respect to future climate projections for the temperate-humid climate of Istanbul or any region of Turkey. Understanding the future behavior of external walls is an essential element to permit assessing the thermal efficiency and durability of proposed strategies mitigating the effects of climate change for existing buildings. Further studies will be carried out to complete the review of research literature related to this topic. This will help better understand the current state of knowledge in this field in respect to Turkey, and to address the gap in literature more confidently.

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ORCID (optional)

Canan Baş: https://orcid.org/0000-0002-5761-8405
Nil A. Türkeri: https://orcid.org/0000-0003-4060-6528
Michael A. Lacasse: https://orcid.org/0000-0001-7640-3701

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