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The Effect of Window-to-Wall Ratio (WWR) and Window Orientation (WO) on the Thermal Performance: A preliminary overview

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Abstract
Sustainable aspects of buildings became one of the most crucial aspects of the built environment. The thermal performance can be improved through sustainable design guidelines and, thus, reduce energy consumption. This review covered studies that addressed Window Wall Ratio (WWR) and Window Orientation (WO) and their effect on thermal performance. WWR is a design variable that deals with window design, while the WO as an environmental variable that deals with orientation. The results will help to highlight open issues and research directions in the context of WWR, WO and integrations with other factors in buildings.

Keywords: WWR, WO, Thermal Performance, Energy

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1.0 Introduction

Thermal performance and energy-saving are currently the most critical topics in sustainable architecture. Window, as a building element, is always associated with thermal aspects and energy saving in buildings. Many studies in window design factors have been done to improve the indoor environmental condition, reduce environmental pollution, recover the economy and improve the sustainable aspects for individual and governmental levels. It is essential to study and analyze the green potential of building design elements such as windows in the early design stage. This will help owners and decision-makers to make the proper decision in the early stage of building design for better thermal performance.

According to Alaidroos & Krarti, (2015), buildings are the highest in energy consumption affecting the economy. This is due to the energy demand for cooling or heating the indoor environment for users' comfort achievement (Figure 1.a). Therefore, air conditioning has become an essential part of modern buildings, specifically in a severe climate like hot, dry regions (Bayoumi, 2017). Among the building envelope, as seen in Figure 1.b, windows are the highest in thermal permeability and, therefore, have the highest proportional distribution of heat loss or gain compare with other envelope elements (Grynning et al., 2013).

As the glazed materials, the windows allow or the highest amount of solar radiation, causing high heat gain in a hot climate and heat loss in a cold climate. So this paper will address the essential elements of window design that affect the energy in various climates, especially in hot and dry climates. Despite the importance of this topic, it is difficult to obtain all the factors that influence window design elements, especially with the climate's diversity, so this paper provides an overview of previous studies that addressed this scope. The

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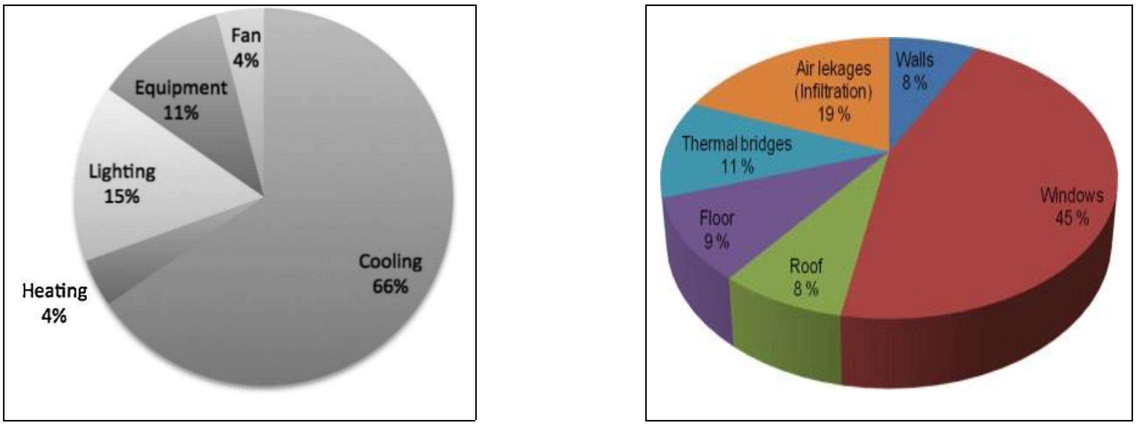
main goal is to clarify the most important window design elements that affect energy savings and improve the indoor environmental condition. This study focuses on window design elements (namely, WWR and WO) on energy saving. The results of this paper will be explored and discussed. Future research work will be highlighted with more interest in the arid climate.



(a) (b)

Figure 1:(a) Distributions of energy consumption in a residential villa; (b) The proportional distribution of heat loss through the different parts of the building envelope of an office building.
(Source:) (a) (Alaidroos & Krarti, 2015) (b)) (Grynning et al., 2013)

1.1 A brief of thermal performance

Thermal performance is a key issue that has been addressed by many studies, including (Méndez Echenagucia et al., 2015), (Pino et al., 2012), (Bano & Sehgal, 2018), (Amaral et al., 2016), (Inanici & Demirbilek, 2000) and (Pathirana et al., 2019).
(Manioğlu & Yilmaz, 2008) notes that knowledge of a buildings energy performance is vital to regulating the amount of heat entering a building through windows and other design elements.
The total energy of heating and cooling is considered the highest energy consumption (around 50% of total energy) in Saudi Arabia. This is also confirmed by (Alaidroos & Krarti, 2015), who have studied energy consumption in several cities in Saudi Arabia (Figure 2).

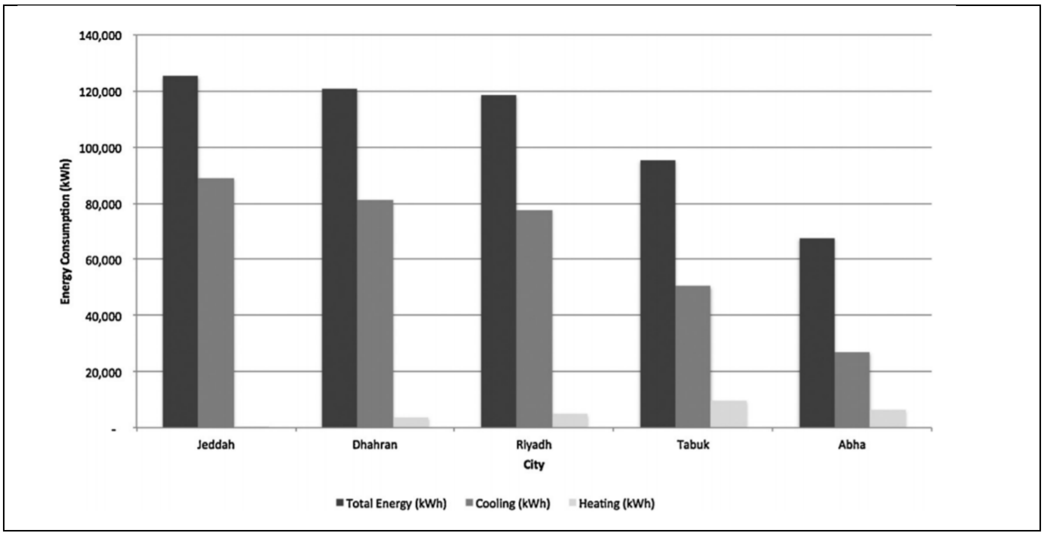


Figure 2: Total energy consumption in buildings in multiple cities in the Kingdom by measuring cooling and heating.
(Source:) (Alaidroos & Krarti, 2015)

1.2 A brief of WWR

The WWR defined as the ratio of the area of clear glass to the area of the wall from floor to floor outside or Window-to-Wall Ratio (Venkiteswaran et al., 2017), (Pino et al., 2012), (Harmati & Magyar, 2015), (Lee et al., 2013a), (Cesari et al., 2018), (Bano & Sehgal, 2018). According to (Amaral et al., 2016), windows are one of the elements that significantly affect buildings' performance, both in terms of thermal comfort and energy consumption for heating or cooling. So it is essential to find an ideal design that will balance their orientation, proportions and shading. (Alwetaishi, 2019) has mentioned that the glazing system is one of the most fragile systems, acquires direct solar gain due to the transparent materials, and stresses that architects and engineers should give it great attention. This is confirmed by research (Marino et al., 2017), as windows design are usually considered the critical component that must be appropriately designed for energy efficiency purposes in light of their function in heat exchange processes and solar energy acquisition management. As studied by (Lee et al., 2013b), Windows are accountable for 20-40% energy loss. In a study conducted in Libya by (Alghoul et al., 2017), the authors emphasized that adding windows to the façade results in an increase in total annual energy consumption by 6-181% for the cases explored in this study.

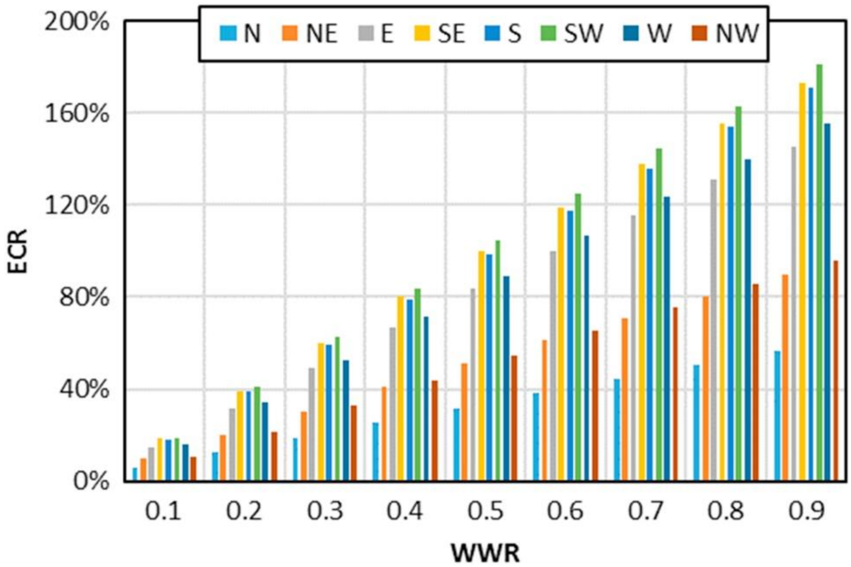


Figure 3:The increase in total energy consumption as a function of WWR
(Source:) (Alghoul et al., 2017)

1.3 A brief of WO

A study by (Gasparella et al., 2011) has confirmed that WWR is not the only influential upon the buildings but WO is also of high importance. (Alshayeb et al., 2015) confirmed that the direction of construction is a significant influence that affects the degree of solar radiation received on the building's facade and the solar radiation, which is a major factor affecting the cooling loads in buildings. Research conducted in Algeria by(Badeche & Bouchahm, 2020), WWR and WO have an essential role in energy consumption and, generally, in various types of climates with all directions, lower glazing ratio has been found to be more efficient.

Badeche & Bouchahm (2020) predicts a semi-arid microclimate in the southern direction, 40-50 % of glazing ratio will be the most efficient. Increasing WWR to 40% or 50% would only increase cooling energy demand and visual discomfort through the glare. Whereas (Asfour, 2020), increasing WWR to 40% or 50% in arid climate will increase cooling energy consumption. (Alwetaishi, 2019) took the trends into account and revealed that the western and southern directions are the worst in obtaining maximum heat in all locations, and the research indicates that glass to wall ratio is recommended at 10% (Figure 4).

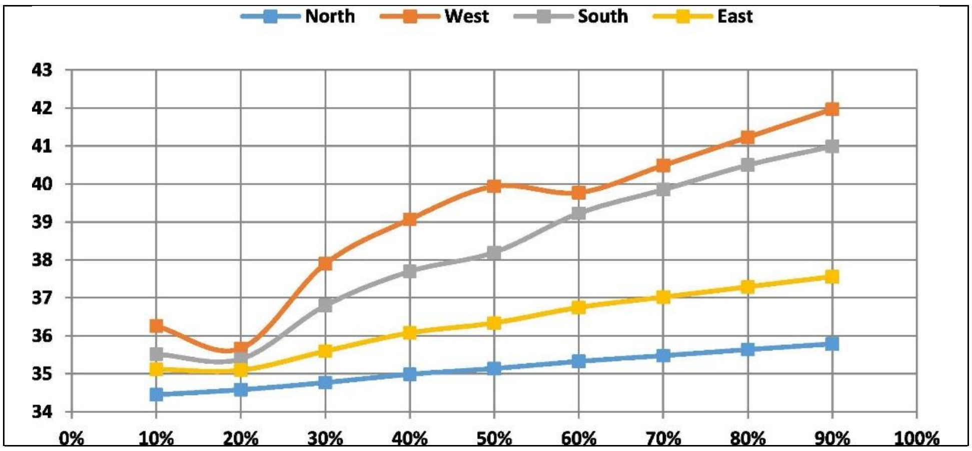


Figure 4: Direct solar gain distribution on exterior walls in every direction in Jeddah (hot and humid climate)
(Source:) (Alwetaishi, 2019)

2.0 Methodology

This study reviews the previous works of building windows and energy consumption (as seen in table 1). It classifies existing studies into three main categories:

1) Those who investigate the WWR.
2) Those who investigate the WO.

3) Those who investigate the WWR or WO with other factors.

Following that, the paper reviews the role of window design factors. The authors of this paper searched through Web Of Science. The keywords terms and inquiries used for the selected studies in this research are as follows:

(TS = (energy, ventilation, heat or daylight, daylight or lighting) and AB = (Saudi Arabia or KSA) and AB = (window, WWR, or glass)).

3.0 Objective

The main objective of this study is to highlight the studies trends in WWR and WO associated with other factors, which affect energy consumption. It is an exploratory study for future work and research gaps.

Table 1: The key papers explored in this study

No	Author, history	Main variables	Climate / region	Testing methods	Building Type	Outcome
1	(Alwetaishi, 2019)	WWR OW	- Different climates - KSA	Simulation Field monitoring	Educational buildings	WWR is recommended to be 10%. South and west orientation gain more heat.
2	(Alaidroos & Krarti, 2015)	WWR, window glazing, window shading	- Different climates - KSA	Simulations	Residential buildings	Optimum window lead design leads to energy savings of 39.5%, 33.7%, 35%, 32.7%, and 22.7% for Riyadh, Jeddah, Dhahran, Tabuk, and Abha, respectively.
3	(Alghoul et al., 2017)	WWR OW	- Hot climate - Libya	Simulations	Office buildings	As the WWR increased, the cooling demand will be increased. But, the heating demand will be decreased.
4	Feng et al., (2017)	WWR OW	-Cold climate - China	Simulations	Residential buildings	The more significant impact of different orientations' WWR on energy consumption order is east (west) > south > north.
5	Marino, Nucara, & Pietrafesa, (2017)	WWR, thermal features	- Italian climate - Italy	Simulations	Office buildings	Climate conditions slightly influence the optimum value of (WWRopt), and the insulation features of the envelope seem to have a low effect on this parameter.
6	Ma, Wang, & Guo, (2015)	Maximum WWR, U-value	- Different climates - USA	Simulations	Office building	Envelope thermal conductivity and ambient temperature amplitude is an essential variable for WWR decision.
7	Cesari, Valdiserri, Coccagna, & Mazzacane, (2018)	WWR, Glazing,	-Humid subtropical climate - Italy	Simulations	Hospital patient rooms	Results show that wider windows with appropriate glazing can lower the heating and cooling energy demand.
8	(Su & Zhang, 2010)	WWR, OW, materials	-Hot summer and cold winter zone - In Shanghai, China	Simulations	Office building	Depending on the window material, the effect is reduced by 9-15%. The environmental benefits associated with the change in the production of envelopes for buildings are mainly due to the high recovery factor of window materials.
9	(Bayoumi, 2017)	Window opening grade	- Different climates -KSA	Simulations	Office building	The results indicate a direct contribution to energy savings by opening windows to specific grades, especially during winter and the intermediate seasons of spring and autumn.
10	Xue, Li, Xie, Zhao, & Liu, (2019)	WWR, external shadings	-Tropical climate -China	Simulations	Residential buildings	The big ratio of WWR can be 0.7 for the WE façade orientation and 0.77 for the SN with a 1.8m extended shading device.
11	(Goia, 2016)	WWR, OW	-Different European climates	Simulations	Office building	0.30 to 0.45 range are the ideal value or WWR. The rise of total energy may occur in the range of 5 to 25 % if the WWR is not considered.
12	(Pathirana et al., 2019)	Building shape, zones, OW and WWR	-Tropical climate - Sri Lanka	Simulation	Residential buildings	WWR change thermal comfort by 20-55%, and the percentage change in lighting electrode due to WWR is only 1.5-9.5%.
13	(Potrč Obrecht et al., 2019)	WWR OW	-Different European climates	Simulation	Residential buildings	38% and 42% of WWR is the optimal design for the southern façade in Ljubljana and Budapest. 0 and 20% of glazing for the ESE orientation and between 0 and 24% for the WSW orientation.
14	(Harmati & Magyar, 2015)	(WWR) and window geometry (WG)	-Moderately continental - Serbia	Simulation	Office buildings	Findings from the dynamic simulations indicated glazing factors on the annual cooling and heating consumption of the multi-zone building model.
15	(Bano & Sehgal, 2018)	Lighting loads WWR plan depth HVAC load	-Compound climate - India	Simulation Field monitoring	Office buildings	Less than 40% of WWR reduces the cooling load and natural light. 15m is the maximum plan depth between external façade
16	(Wen et al., 2017)	WWR Light energy density, WO, interior gain, and building size	-Different climates -Japan	Simulation	Office buildings	A huge ratio of WWR is recommended for buildings in some climate zone in Japan. A rational, moderate size of WWR has to be set carefully according to the façade direction and lighting density.

17	(Chi et al., 2020)	WO,WWR. Daylight factor, air temperature, and air velocity	-Humid subtropical climate -China	Simulation Field monitoring	Residential buildings	The mean maximum indoor temperatures for southeast orientations are lower than southwest orientations with the condition of the glazed walls and south WO intervals.
18	(Wagdy et al., 2017)	Sun-breakers WWR	-Desert -Cairo Egypt	Simulation	Hospital patient rooms	All the WWR scenarios achieved good daylight performance in the wardroom. The cut of angle range between 50° to 54° with the wall. The shading device with horizontal position achieved successful outcome with all WWR scenarios. Cut off angles of shading device performed better than the tilt angle.
19	(Alshayeb et al., 2015)	Effect of building orientation, window shading, and PV panel	-KSA	Simulation	Health centers	The most massive annual cooling load between the eight directions is the southeastern direction, the difference between the maximum and the minimum electricity consumption is approximately 0.38%, and the average saving between the eight directions when the shading ratio to the window is 1: 0.5 is 1,809.97 kWh, which is a decrease. By 1.5%. The ratio of shading to windows 1: 1 showed the greatest energy saving among the eight directions. The saving could be up to about 2.2%.
20	(Alwetaishi & Taki, 2020)	WWR WO, thermal insulation, shading devices	-Hot climate -KSA	Simulation Field monitoring	Educational buildings	This paper showed that minimizing WWR with thermal insulation is important for the current buildings in a dry and hot climate. The best practice for the WWR should be less than 35%, 25%, and 20% for NW, SE, and SW building wall, respectively.
21	(Alqahtani & Elgizawi, 2020)	WWR; wall thickness; thermal efficiency; energy consumption	-Hot climate -KSA	Simulation	Educational buildings	Open 20% WWR cooling 250mm hollow brick in the outer wall, which leads to 33.26% saving
22	(Asfour, 2020)	WWR Daylight and energy	-Hot climate -KSA	Simulation	Office buildings	Use a moderate WWR of 30%, given the use of shading devices. In such a climate, it is recommended to reduce window area and use shading devices in addition to daylight shading elements such as patios and atria.
23	(Gasparella et al., 2011)	WWR, WO, Glazing systems, thermal transmittance, solar transmittance, energy saving	-Climate data were considered for four regions in Central and Southern Europe: Paris, Milan, Nice and Rome	Simulation	Residential buildings	Large bottles improve performance in winter but slightly aggravate peak winter loads. In winter, the use of windows with low thermal permeability is beneficial if they are accompanied by high penetration of the sun. But high sun transmittance leads to a significant deterioration in summer performance;
24	(Hassouneh et al., 2010)	WWR, Energy saving, Kinds of glass, WO	-Climate is that of the eastern Mediterranean region - Amman	Simulation	Residential buildings	It has been found that choosing a larger area facing south, east and west can save more energy and reduce heating costs in winter by using certain types of glass while reducing the area of north-facing glazing can save money and energy by using certain types of glass.
25	(Kim et al., 2016)	WWR, WO, energy load	-Oceanic climate -Canada	Simulation	Residential buildings	The energy simulation result shows that the annual energy load significantly increases as the window size increases regardless of the window position.
26	(Ihm & Krarti, 2012)	WWR, WO, energy load and type of glazing, wall and ceiling insulation levels, lighting fixtures, hardware, heating, and cooling system efficiencies	-Different climates - Tunisia	Simulation	Residential buildings	WO, WWR, glass type, wall and ceiling insulation levels, lighting fixtures, hardware, heating, and cooling system efficiencies. It has been found that the savings in source energy use are up to 59%.
27	(Westphal & Andreis, 2016)	WWR, type of glazing, Facade cover type	-Tropical climates - Brazilian	Simulation	Office Buildings	The opening area causes energy consumption variation up to 27.5% depending on climate and type of glass.
28	(Lee et al., 2013a)	(Orientation, WWR, U-value, SHGC, and Tvis)	-Five typical Asian climates: Manila, Taipei, Shanghai, Seoul, and Sapporo.	Simulation	Office Buildings	Positioning a 25% WWR window in the south face appears to be effective. The north face is a useful location for installing an energy-saving window system in Manila, Taipei, and Shanghai. In cities like Sapporo and Seoul, installing a window in the south can reduce the total energy load.

4.0 Findings

In this section, the main outputs of the reviewed papers will be explained in more details as follows:

4.1 The effect of WWR

There is a unanimous part of the fact that WWR is significantly affected by the climate from several studies in different climates. Based on Table 2, many authors have suggested many recommendations, for instance, (Alwetaishi, 2019) has mentioned that small WWR is recommended for the hot and dry climate with 10%. While in a temperate climate, it is recommended to use 20% of WWR.

(Potrč Obrecht et al., 2019) added that, for temperate climates in the northern hemisphere, a high proportion of glazing in the south is required. However, (Alghoul et al., 2017) found a high ratio of WWR will reduce heating load but increase the cooling load in the hot and humid climate.

On the other hand, for a humid subtropical climate (Chi et al., 2020), the WWR ratio in the north direction is higher than the south direction in general. Concerning the best WWRs, it is recommended 0.39 for NW and 0.4 for SE. (Potrč Obrecht et al., 2019) also found that the optimum share of the primary façade glazing for the oceanic climate is between 38% and 42% of the façade depending on the glass properties of triple-glazed windows. By tilting the main façade, the optimal share of glass should be decreased. For example, between 0% and 20% of the glazed window for the ESE direction or between 0% and 24% for the WSW direction. Moreover, (Bano & Sehgal, 2018) found that less than 40% of WWR reduces the composite climate cooling load.

(Goia, 2016) in different European climates, the perfect ratio can be within the range of 0.30 and 0.45. overall energy usage could be increased if the range between 5% and 25%. (Gasparella et al., 2011) have mentioned that using large WWR improves performance in cold areas. However, (Feng et al., 2017) have stated that 10% -15% is recommended for east and west, while for the south, it is between 10% -22.5% in a cold climate. The results of (Goia, 2016) show that the south-facing façade is more diverse, with the optimum transparent ratio being 0.60 in cold climates and as low as 0.20 in hot climates.

Table 2: The effect of WWR

Author	Climate	WWR	WO
(Alwetaishi, 2019)	Hot and dry	10%	-
	Temperate	20%	Increase the WWR in the S direction
(Chi et al., 2020)	Humid subtropical climate	35%	Applied in S direction
		39% and 40%	Applied in NW and SE directions
(Potrč Obrecht et al., 2019)	Oceanic	Between 38 and 42%	-
(Bano & Sehgal, 2018)	Composite	Less than 40%	-
(Goia, 2016)	Different European climates	(%30 <WWR <%45)	-
(Feng et al., 2017)	Cold	15%-10%	Applied in E and W directions
		22.5%-10%	Applied in S direction

4.2 The effect of WO.

For the orientation aspect, a large number of studies focus on the cardinal directions only. In contrast, the minority focus on the cardinal and intermediate directions. Other studies focused on specific directions and did not consider the rest of all directions (Table 3). A study by (Alwetaishi, 2019) found that eastern and southern orientations are the worst in obtaining the maximum heat, and the research suggested that the WWR should be 10% in both hot, dry, and humid weather conditions. From another angle for a similar climate, (Alghoul et al., 2017) noted that S, SE and SW of windows are the highest in cooling energy consumption.

In education building, (Alwetaishi & Taki, 2020) suggested that the WWR for classrooms facing SW and SE should not exceed 20% and 25%, respectively. Conversely, NW classrooms can have up to 35% WWR in hot climates. (Lee et al., 2013b) have recommended that for windows in each orientation should be minimized in all hot regions. For humid subtropical climates (Chi et al., 2020), under the situation of the glazing walls with the same WWR for south window direction intervals, the mean indoor temperatures for SE orientation are lower than the SW orientation.

In the Eastern Mediterranean climate, (Hassouneh et al., 2010) have found that bigger glazed areas facing south, east and west can save more energy and reduce heating costs in winter, while less north glazed areas can save energy by using certain types of glass. Regarding cold climate, (Feng et al., 2017) highlighted that the most significant impact of different WO on energy consumption could be ordered as east, west, south and north. Adding to that, (Gasparella et al., 2011) confirmed an improved effect in the south orientation, which is better in winter. The energy load increases as the window size increase nevertheless of the position of the window (Kim et al., 2016).

Table 3: The effect of WO

Author	Climate	WO	Outcome
(Alwetaishi, 2019) (Alghoul et al., 2017) (Lee et al., 2013)	Hot, dry, hot, and humid	Southern, southeastern and eastern	Significant increase in cooling demand with reduced heating demand to almost zero.
		Northern	Highest heating energy.
		Southwestern	Highest cooling energy consumption.

		ALL	It should be minimized.
(Chi et al., 2020)	Humid subtropical	Southern, southeastern and southwest	The mean interior temperatures for the southeast direction are lower than the southwest direction.
(Hassouneh et al., 2010)	Eastern Mediterranea	South, east and west	Can save more energy and reduce heating costs in winter.
		North	With less north-facing glass area can save energy.
(Feng et al., 2017)	Cold	ALL	The most significant influence of various WWR orientations on energy can be arranged as east (west), south and north.
(Gasparella et al., 2011)	Cold	South	Better in winter.

4.3 The integration of WWR and/or WO with other factors.

Several studies have added some factors with WWR, WO, such as envelope thermal insulation of walls, roof insulation, thermal mass, window area, sun breakers, window glazing, window shading, and others (Table 4). For instance, (Alaidroos & Krarti, 2015) studied many factors with WWR (as seen in Table 4) and found an average savings of 39% in various climates when considering all of these factors in the Kingdom of Saudi Arabia.

Su & Zhang (2010) have mentioned that 9-15% of energy consumption can be reduced depending on the glazed material. The environmental benefits associated with the change in the production of envelopes for buildings are mainly due to the high recovery factor of window materials.

Results from the study by (Cesari et al., 2018) show that installing wider windows with suitable glazing properties can minimize the cooling and heating energy load. Another research by (Harmati & Magyar, 2015) conducted in a moderately continental climate found that using a suitable type of glass can reduce the heating energy by 83%. (Westphal & Andreis, 2016) that WWR can be increased when more efficient glazing systems are used and, thus, a low impact on energy consumption. (Bano & Sehgal, 2018) indicated that a reduction in WWR will reduce the cooling load. Nevertheless, it decreases the daylight inside the building, which cause increases both lighting and heating load. (Asfour, 2020) used 30% of WWR with shading devices. This results in a better balance between daylight and the decrease of glare. (Hassouneh et al., 2010) asserted that an efficient glazed window can help to maximize the WWR with more flexibility of WO.

Ihm & Krarti, (2012) concluded that WO, WWR, glass type, wall and ceiling insulation and energy efficiency system are among energy efficiency measures that could save energy up to 59%. Moreover, in a tropical climate, a study by (Xue et al., 2019) found that the largest WWR could be set as 0.7 for west-east buildings and 0.55 for south-north buildings with 1.8 m comprehensive sunshades. In the tropical climate (Pathirana et al., 2019), WWR changes thermal comfort by 20-55%, and the percentage change in lighting due to WWR is only 1.5-9.5%.

The results of (Bayoumi, 2017) indicate the direct contribution of the window opening to energy savings by opening windows to certain degrees, especially during winter, spring and autumn seasons in a hot, dry, or humid climate. For the hot and dry climate, an opening of 20% WWR and the use of 0.25 m hollow bricks in the facade, which results in a saving of 33.26% (Alqahtani & Elgizawi, 2020).

Table 4: The integration of WWR and or WO with other factors.

Author	Climate	other factors	Outcome
(Alaidroos & Krarti, 2015)	Hot, dry	Envelope thermal insulation of walls, roof insulation, window area, window glazing, window shading, thermal mass, sun breakers, and others.	Savings of 39% in many climates in the Kingdom of Saudi Arabia.
(Harmati & Magyar, 2015)	Moderately continental	Using the appropriate type of glass.	The demand for heating energy can be reduced by 83%.
(Westphal & Andreis, 2016)	-	Using the appropriate type of glass.	Hat WWR can be increased when more efficient glazing systems are used and, thus, a low impact on energy consumption.
(Bano & Sehgal, 2018)	-	Natural light	This indicates that a decrease in WWR reduces the cooling load. However, it also reduces the availability of natural light inside the building, which increases both lighting and heating load
(Hassouneh et al., 2010)	-	Energy-saving windows	Asserts that if energy-saving windows are used, the flexibility to choose the glass area and orientation.
(Ihm & Krarti, 2012)	-	WO, WWR, glass type, wall and ceiling insulation and energy efficiency system	It could save energy by up to 59%.

5.0 Conclusion

By looking at the various studies, WWR is an essential variable in thermal performance in buildings. However, it must be taken with other environmental factors and aspects. Among these environmental factors is the influence of climate.

It is also noted that whenever the weather is dry (hot or cold), the recommendations for WWR are low, ranging between 10% to 22% at best. However, in temperate and humid weather, the optimum WWR may be increased from 25% to 45%.

Regarding the new WWR technologies, good thermal properties of glass can be applied in large WWR as it will help reduce solar gain through the window. Other design factors can affect WWR, shading device, degree of isolation, type of window frame material, and many more, and all may save energy from 39% to 59%.

For WO, it was found that in the northern direction, WWR could be greater than the southwest direction, which is considered an undesirable direction due to the high solar heat gain.

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Paper Contribution to Related Field of Study

For the last five years, we tried to highlight the papers published in WWR and WO and their effects on the thermal performance with special attention to the hot arid climate. this will help to outline the future research directions and open issues. Through our review of various studies, some gaps can be identified as potential future work, such as 1. The lack of WWR research conducted in hospitals, 2. The lack of published review papers on WWR in the arid climate for the last five years, and 3. The lack of research that relied on field measurements and taking real weather data is very significant for a simulation study.

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