Courtyard design, a passive approach in residential buildings for reducing direct solar gain

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Abstract— Bylaws followed in existing societies of Lahore, Pakistan are causing more harm than good as the urban fabric lacks the considerable application of passive design building typology in modern construction. These bylaws followed by regulatory authorities are increasing the cooling load of building due to the increase in direct solar gain resulting in more electricity consumption. In this paper minor modifications are suggested in the existing layouts of modern houses by adding courtyard along with veranda as a passive design feature. Among various available passive cooling techniques, the courtyard technique is borrowed from traditional houses like Havelis. The direct solar gain for existing house (no courtyard) is compared with the house having courtyard. Addition of courtyard can result in long term benefits by decreasing the monthly average direct solar gain (Qg) through openings that ultimately reduces the cooling load of a building and significant reduction in electricity bills is seen at larger scale. Implication of this research is to suggest the regulatory authorities to combine the modern houses with traditional one to enhance the effectiveness of residential unit in terms of lesser cooling load. After careful consideration, a residential unit was selected as a representative of modern houses from society of Lahore Development authority. Residential unit with courtyard reduces 52% of direct solar gain (Qg) when compared with the existing house (without courtyard). The simulation results explicate that passive approaches like courtyard and verandas, help in reducing the inside temperature (Ti) and direct solar gain (Qg) in summer. The field survey of Barood Khana Haveli and Sethi Haveli Peshawar was conducted to understand the effective implementation of architectural and passive features of traditional buildings that can be adapted in modern houses to achieve the thermal comfort.

Index Terms— Courtyard, Direct solar gain, Havelis, Naturally ventilated traditional buildings

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1. Introduction

Energy consumption of electric energy in Pakistan is more than its production that is causing load shedding as the production is insufficient to meet the requirement. Global warming all around the world is increasing the hot months throughout the year. An intense increase can be observed in the usage of the air conditioning system and other cooling devices to reduce the temperature of the buildings around the world. The data regarding the economic survey of Pakistan shows that electricity consumption in the domestic sector has been increasing with the 2% growth rate every year [1]. Bylaws followed by the residential societies in Lahore, Pakistan is based on standard operating procedures that are lacking sufficient open space for the circulation of trapped air. Instead of being beneficial, they are not playing an important role to overcome the power shortage in Pakistan. This paper proposes some modifications in bylaws to make it effective in hot climatic conditions. Instead of adapting the bylaws according to local climatic conditions, the typical archetype designed by the residential sector is increasing electricity consumption. We propose that natural passive cooling techniques such as courtyards can help in reducing cooling energy demand. Therefore, this study will quantify the impact of courtyard inclusion in modern buildings typology borrowed from Havelis. Courtyards as a passive cooling technique in modern houses can reduce the net direct solar gain that also has an impact on energy use and thermal comfort in the hot and arid climates. Courtyards found effective in the hot and arid climatic region but not preferred in modern housing trends [2].

The traditional architecture uses different traditional passive elements like courtyards, verandas, jharokhas, galleries, and tehkhanas (like the basement) appears to be more efficient in terms of thermal performance. Among these traditional architectural elements, the courtyard is one of the influential factors. For 5000 years, courtyards have been developed to adapt to severe climatic conditions, particularly in hot and arid climates [3]. So, the focus of this proposed research is mainly the addition of the courtyard and veranda in the current and modern housing society of Lahore. Lahore Development Authority (LDA) is used as a representative society for this research. The courtyard is an open to sky closed or semi-outdoor area encircled by buildings. It was used by the urban civilization of Mediterranean regions, Asia, the Middle East, and South African countries [4]. A courtyard is a cozy zone of a house that is used to offer sanctuary and solitude for a comfortable environment in a house. The efficiency of the courtyard setting can be enhanced by combining it with other economical but beneficial strategies like shading, water bodies, fountains, and vegetation. Shading is an effective method to reduce the solar radiations and improve the indoor thermal comfort in summers particularly in the hot climatic regions [5].

According to existing studies, shading is considered to be one of the most imperative features for reducing the air temperature in a courtyard. Many researchers have studied the shading impact of a courtyard on heat alleviation and compared different shading setups in a hot and arid climate. The results showed that trees provide more reduction in outdoor air temperature among shading meshes [6]. The shaded courtyard helps to decrease the cooling requirement by an average of about 4% that is sufficient value. Recently, the design of courtyards is getting interested in creating a microclimate within a space but still, there is less awareness regarding the courtyard's efficiency in improving the thermal performance of the building, mainly in hot and humid climates. According to researchers [3], the climatic zone highly affects the thermal function of building arrangements. The courtyard is suitable solution for a hot and arid climate but not for hot and humid climate [7]. This research is an effort to improve the thermal performance of residential unit after adding a courtyard and veranda by the reduction of solar gain. The said goal is achieved without any significant modification to bylaws. The required covered areas mentioned according to bylaws are also not much compromised.

There are a lot of factors that increase the energy consumption, one of them is solar gain coming directly or indirectly through windows and building envelope. Solar gain results in increasing the temperature of the material surface that subsequently raises the temperature of neighboring layers of air that will raise the overall building temperature. Consequently, the cooling load of buildings increases, and more cooling devices need to install to achieve the optimum comfort level for humans. These devices ultimately increase the energy demand by electricity consumption. Muhaisen et al. examined that the solar gains have a momentous consequence on thermal conditions within the courtyard that sequentially has a great effect on the thermal performance of the surrounding zones [8]. In both summers and winters, for the proficient courtyard performance, it is essential to make sure the finest quantity of irradiation entering the form as the solar radiations received in the courtyard has a major effect on the resulting heat gains, cooling and heating loads of the building.

Current energy patterns through the extensive use of fossil fuels, 'the socio-economic issues and environmental crisis have increased the challenges of sustainability [9]. Sustainable architecture can best conserve energy resources and can affect the future construction of the urban fabric. The building sector, being a major consumer of energy necessitates critical scrutiny on this aspect. Buildings utilize more than 30% of the global energy demand due to carbon emissions which is the foremost reason for climate change [10], [11], [12]. Rapid construction of domestic buildings and rising living standards are considered to be the main causes of augmented energy demands in Pakistan. The energy shortage results in intimidation of economic growth of a country [13]. Finding a solution for global crises such as carbon emission, climate change, environmental pollution, increasing energy demand, and lack of natural resources is the subject of many studies. In this case, the construction of courtyards is an effective sustainable strategy to control the microclimate and the energy consumption of buildings. As the residential sector is the major consumer of energy the modern houses clearly misses the mark on numerous parts of sustainability [9]. The residential societies of Pakistan’s metropolitan cities like Lahore and other big cities are not much climatic responsive [14]. The methods used for cooling, heating, and ventilation of the buildings previously in early architecture can be analyzed to be more harmonious with nature as compared to the modern one [15]. In the second half of the 20th century, Architecture practiced for building construction is continuedly emphasizing on reconciliation of traditional typology with modern [16]. There are a lot of existing researches that emphasize on the revival of the traditional and vernacular features in modern era dwellings that can enhance the energy efficiency.

This main objective of this research is intended to emphasize the importance of two primal constituents of traditional architectural elements like courtyard and veranda with an integration of modern building design typology of a residential society of Lahore. By adding a courtyard as a passive design feature in modern houses in order to decrease direct solar gain that results in reducing the cooling load of domestic buildings in summers. We achieve this purpose by suggesting a slight modification of the by-laws of an official body of governing the bylaws for the residential sector. This study clarifies the significance of proposed design in reducing energy consumption due to the reduction of the direct solar gain to make it a climate balanced approach. This proposal is more pertinent due to the context of the study being hot and semi-arid region.

2. Literature Review

Courtyards functional units [17] interlink different spaces that provide suitable privacy and visual communication among these spaces at different levels that increases its significance. In traditional courtyard houses, the courtyards are considered to be the main feature for creating a micro-environment within the space [18]. A prime characteristic of courtyard is to generate an intermediate environment that is more private, clean, and quiet as compared to the street environment. With this developed microclimate the adjacent inner zones can interact positively [7]. Among the substantial passive architectural elements' courtyard has a vital role for day lighting and cross ventilation that permits the houses to be heated and cooled naturally [19].

2.1.Courtyard housing

The courtyard is an open area enclosed by walls of buildings completely or partially with openings to permit a connection between the outside and the indoor environment. According to the Cambridge Dictionary, a courtyard is "An area of flat ground outside that is partly or completely surrounded by the walls of a building." Soflaei et al. mentioned that "Courtyard" term is derived from "Curtis" and "Gherdh" which means a structure serving as an enclosure or boundary to protect from harsh climatic conditions. The traditional courtyard housing typology has been implemented over 5000 years ago in the Middle East and China to serve this purpose of protection [2]. Researchers argued that a courtyard is a more sustainable form of dwelling as it allows constant contact of residents with the natural world like earth, sun, fresh air, and rain, the courtyard serves as a conduit or a daylight filter between its surrounding rooms [20], [21]. In the perspective of environment passive cooling within the space can be through prevention, modulation and dissipation of heat gain that is possible by using landscape, outdoor and semi-outdoor spaces, building form shading, solar control, and thermal insulation [22]. A study by Qureshi examined the results of a few contextual investigations on the temperature inside the courtyards is fundamentally cooler in a hot and dry atmosphere [23]. Courtyards with verandas play an important role in decreasing direct solar radiations that ultimately reduce the cooling load of a building. The courtyard as a passive system was mainly developed in response to climatic requirements accordingly. But poor or inappropriate design may create challenges for controlling temperature, glare, and energy consumption due to the collection of solar radiations in a courtyard [24].

In scientific and professional literature, Courtyards are said to be as microclimate modifiers which helps in humanizing the comfortable thermal condition in the surrounding build rooms. Courtyards in general are the part of an architectural language common throughout the history of many regions. According to Meir et al. [25], the courtyard house may be traced from Bronze period Greece, through the Classical, Hellenistic and Roman world, and up to the present [25]. Berkovic et al. [5] have examined that in the hot climate (like Pakistan) for the period of summer season outdoor comfort is primarily reliant on the heat produced due to direct and indirect solar radiations within the space, thus between the wind contribution and shading, Shading is the preeminent resource to get better thermal comfort. Courtyard enhances the air ventilation process. In a research conducted by Al-Hemiddi et al. [26], the authors argued that in hot-arid regions, cross ventilation due to courtyard addition circulates low-temperature air in inner zones of a building that results in heat exchange and hence results in thermal comfort [26].

The basic courtyard model is shown in Fig. 1. At daytime, the direct solar radiation reaches the courtyard that can also contribute to the heat balance at the courtyard surface. Additionally, heat transfer occurs due to the temperature difference between the surface of the courtyard as well as between indoor surface and indoor air when shadow changes in the courtyard. At night, a portion of heat gained by the thermal mass of the courtyard is released and remaining part of the heat transfers (through conduction and natural ventilation) occurs across the sky above the courtyard [27]. Courtyards can provide a cooler microclimate in the summertime even these are used as a passive design strategy in desert climates [28]. However, a balanced design method should be developed with the respective climate conditions. Solar radiation is an effective parameter on outdoor thermal comfort. Few studies have quantified the thermal performance of this building archetype. In most research publications, courtyards have been reviewed without studying the effect of solar radiation.

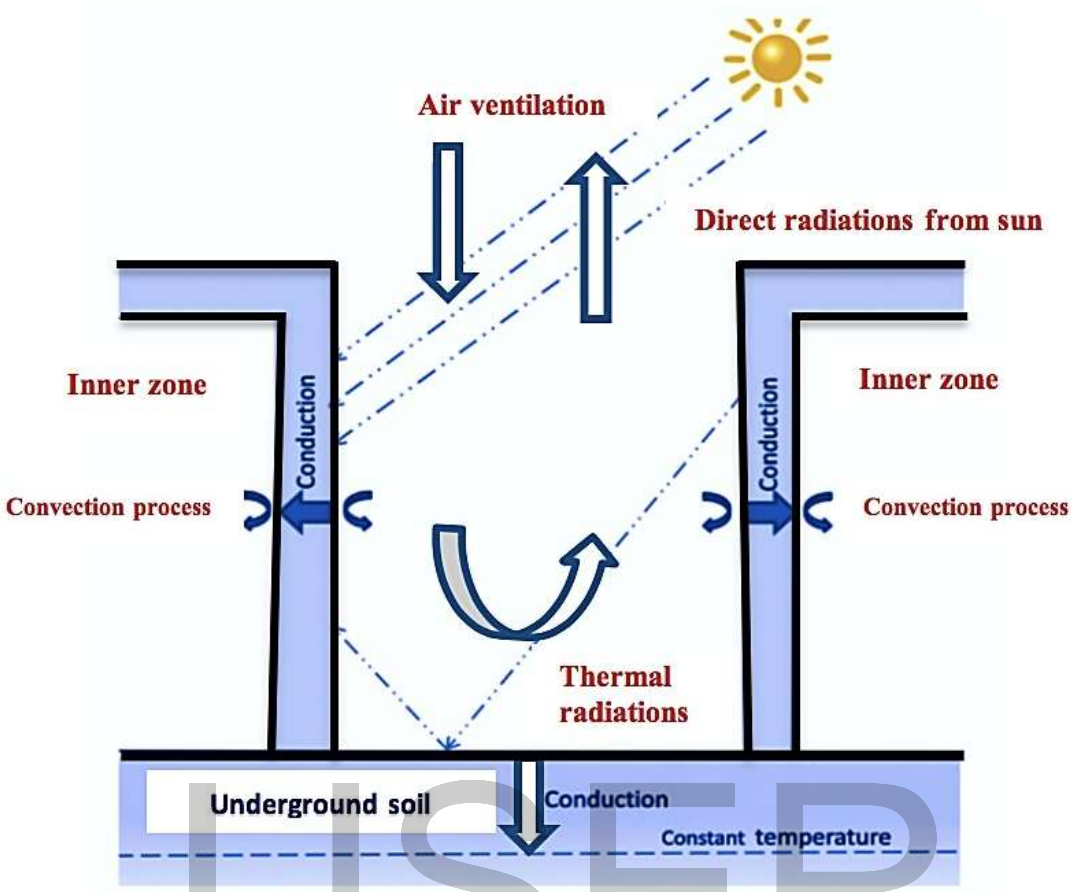

Fig. 1 Natural ventilation process, heat gain and heat transmission phenomenon in a simple model of courtyard [27]

2.2. Direct solar gain

Solar gain is the rise in temperature of a material surface due to the effect of heat gained by the sun. When solar radiation falls directly on any material's surface, the incident energy increases the surface temperature of that material. Under this phenomenon, the temperature differential between the surface and the underneath material also increases [29]. Direct solar gain refers to the collection of solar radiations through windows or other exposed translucent surfaces. Direct solar gain (Qg) is the less expensive method for passively heating the building. Maintaining a strategic distance from Qg is critical in hot regions like Pakistan (Lahore). In many atmospheres, more gain is needed in the winter when the sun is at low altitude while less or none gain is required in the mid of the year. It is also investigated that the orientation of building can considerably change the result when solar gain is under discussion [28]. Courtyard buildings can serve as a shield as well as collectors from the sun based on climate or its orientation. Therefore, the effect of solar radiation must be considered vital by designers for outdoor thermal comfort [7]. The courtyard with water bodies like fountains enhances thermal comfort and daylighting to the building and these strategies can enhance the energy efficiency [30].

The use of courtyard and veranda is examined in detail of two famous and historical Havelis (regional name for courtyard housing typology [23]) of Pakistan in which the practice of these passive elements shows an improved thermal performance in the harsh climate. The survey and analysis of Barood Khana Haveli, Lahore and Sethi Haveli, Peshawar shows that the climate responsiveness for understanding the indigenous responses to handle the issues of environmental comfort in the modern architectural arena of Pakistan is possible by incorporating the main passive features like courtyard in today's houses. This analysis explores the benefits of the vernacular courtyard form of design.

3. Methodology

3.1. Site selection and observation

As mentioned above the modern building construction typology cannot portray the effectiveness of thermal comfort as it was achieved in traditional courtyard housing due to the complex interactions between zones of house and limited open space. The methodology adopted here addresses this problem by adding a standardized courtyard space in modern house. This research focuses on the courtyard addition in 4500 sq. ft residential house and its comparative analysis of direct solar gain with existing LDA residential unit. The research required necessary preliminary study of the traditional passive elements used in old houses of Lahore. The case studies, research papers, journals, and articles depict the courtyard houses of countries all over Asia and deal with the effects of courtyards on the basophilic environment and social setup of the region. For traditional courtyard housing climatic conditions of a region should also be considered. The data of weather and bylaws were collected through surveying the metrological department and Lahore development authority (LDA) from January to May 2020. Among different areas of houses a 4500sq.ft residential unit was selected as a representative sample from the Lahore Development Authority (LDA). In proposed study, a courtyard with veranda is added in the residential unit of LDA society to create a cooling effect that was also observed in survey of Barood Khana Haveli with a combination of modern architecture.

3.2. Climate conditions of Lahore

Lahore altitude lies between the directions 31°15′ to 31°45′ N latitudes and 74°01′ to 74°39′ E longitude [31]. Lahore has a hot semi-dry extreme climatic condition (Köppen climate classification BSh), summers are long and to an extraordinary degree hot and winters are dry and warm. Hottest months are May, June, and July while the coldest months are December, January and February. Maximum temperature for the month of June as 41°C is shown in Fig. 2 [31], [32]. Lahore zone, moreover, experiences rain and dust storms ranging from June to August and passes on generous precipitation to the city. According to a report in 2014 by Walled city Authority Lahore [33], the highest and slightest temperature recorded is 48.3 °C (118.9 °F) in 1944 and −1.1 °C (30 °F) in 1967.

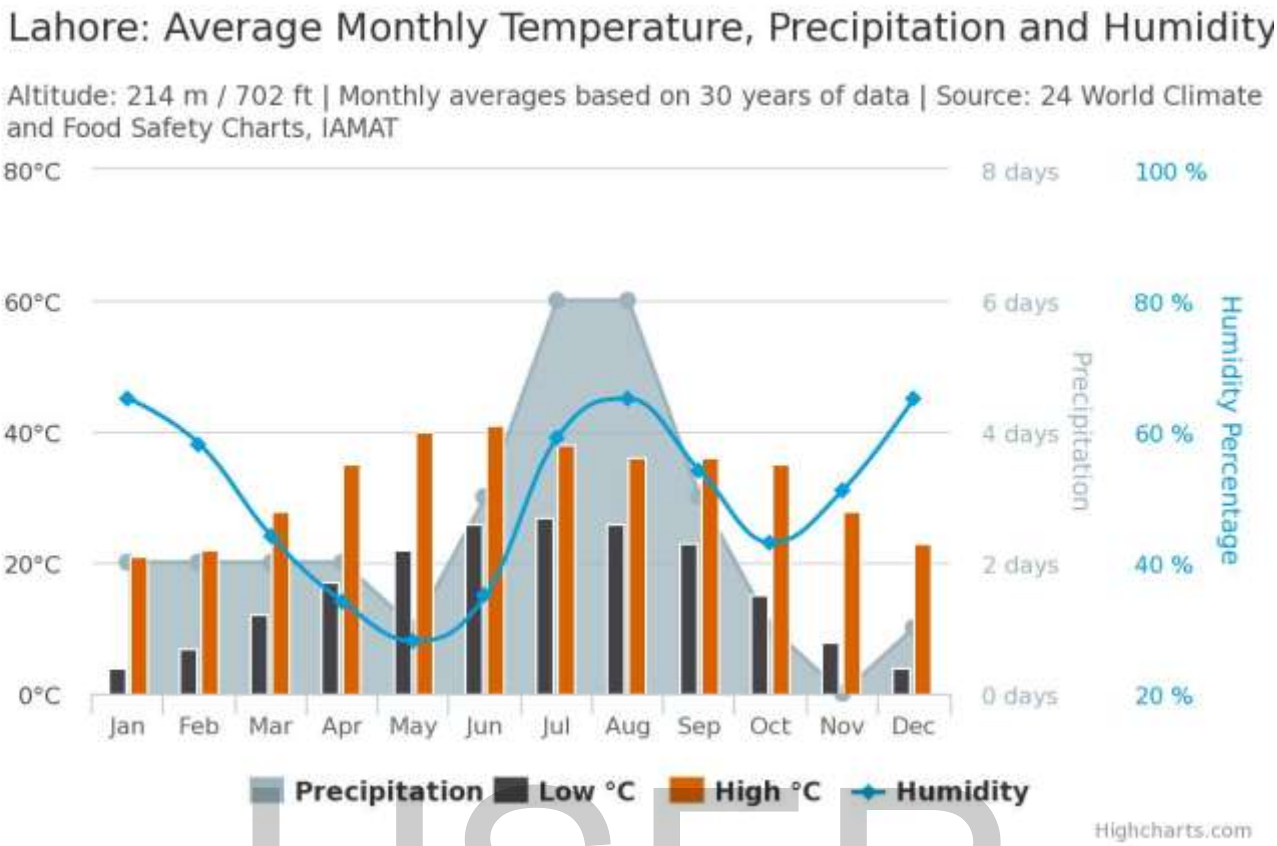

Fig. 2 Climate Information for Lahore, Pakistan [32]

3.3. Features of layouts and Bylaws comparison of existing house with the proposed courtyard design

According to Lahore development authority (LDA) by-laws of covered area and height, ground floor covered area is 65% of the total plot, including car porch while the first floor does not exceed 75% of the total permissible area of the ground floor and the height must not be greater than 38 ft from street level [34]. In today's world the traditional architecture is left behind [35]. For the revival of traditional housing, A standardized 25ft × 25ft wide courtyard including 5ft veranda can be accommodated without compromising the established LDA bylaws. Fig. 3 [36] shows the covered area of existing LDA unit and the proposed design house. The covered area of ground floor is 59% of the plot size and first floor is 72% of the respective ground floor covered area as the required covered areas must not be greater than 65% and 75% respectively.

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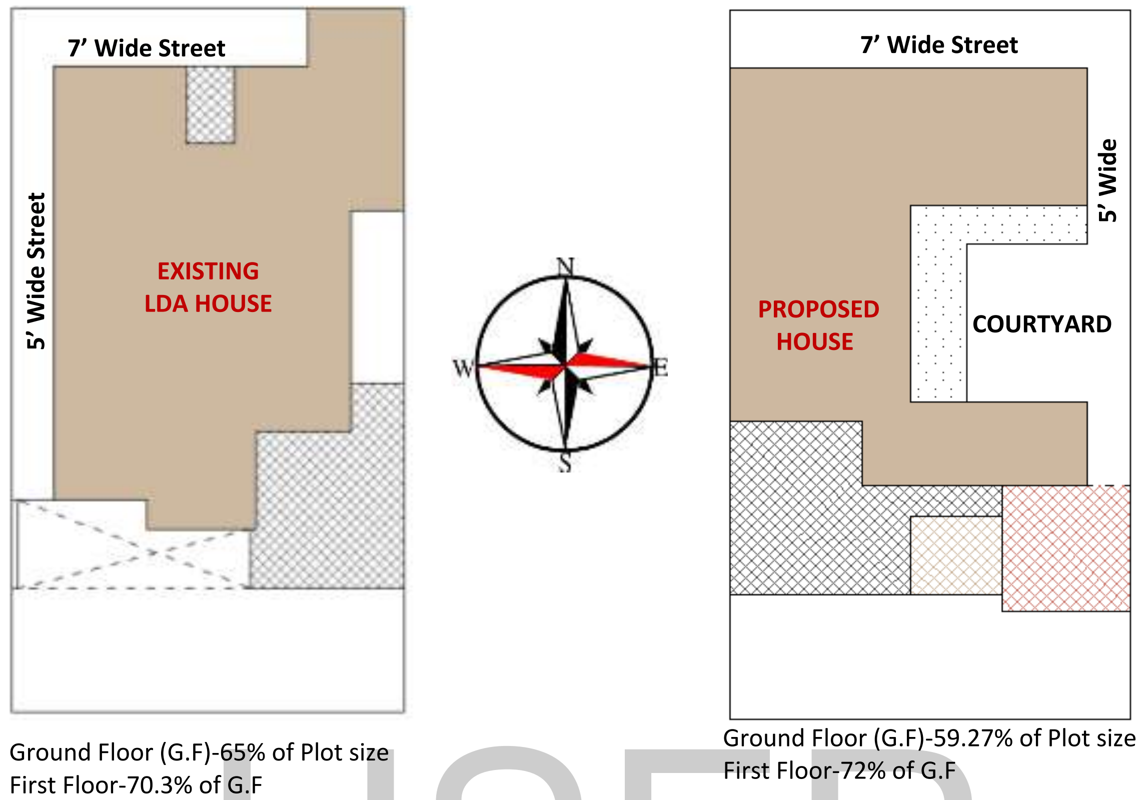

Fig. 3 Covered area with hatch in (a) Existing LDA residential unit (b) Proposed house with courtyard addition

3.4. Measurement of courtyard size according to standards

Different courtyard shapes are being observed in various researches as L-shape, U-shape, inner outer side courtyard and central [17]. The courtyards with D=1 (Fig. (a)) as aspect ratio (D=H/W) the square state of the courtyard permits the production of a roundabout whirlpool which creates numerous air recharges than oval vortexes produced for more wider courtyard with D<0.3. For D>1 (Fig. (b)) where height is much greater than width, the external air inflow is definitely decreased in the lower parts of the courtyard [37]. and

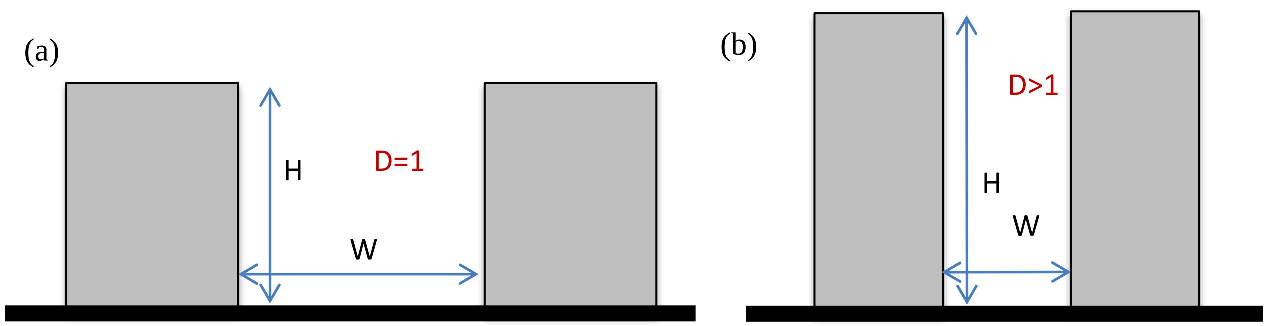

Fig. 4 (a) Aspect ratio (H/W) =>D=1 (b) Aspect ratio (H/W) =>D>1

Tablada et al. examined that the top floor rooms of the thin courtyard with an aspect ratio (W/H=0.33) have higher velocities than the top floors of the more extensive courtyard (W/H=0.66) since they get the majority of the wind current entering the courtyard cavity, inciting that the rooms on the lower floors have much lower velocities. Hence it can be concluded that the higher ratio is more effective for the regions where vertical planning is less at the residential level [33]. The private open space required for each residential unit must not be less than 90 sq. ft. (with a minimum dimension of 6 feet in each direction) [36]. Courtyard aspect ratio should be 1:1 between the width of the courtyard and height of the building so we take 25feet for both width and height of the building. Hence the proposal includes a 25ft×25 ft square courtyard with veranda [14]. Table 1 is taken from the transit zoning code: Architectural standards- building type shows that up to one story no less than 1:1 courtyard is permitted but as we move towards second or third story the ratio tends to decrease as 0.85 and 0.55 respectively [36]. Moreover, the maximum width that we could provide is 55' but researches also recommend ratios like 0.33, 0.66 can also be implemented for residential courtyards sizing having their respective benefits [36]

Table 1 Maximum ratio of each courtyard housing story

Story	Ground floor	2	3	4	5
% of ground floor by story	100%	100%	85%	55%	40%

For better understanding of courtyard housing, two famous courtyard houses (Havelis) were visited. Different sizes courtyards within one house were present to create a microclimate within a space.

3.5. Field Survey of Barood Khana Haveli and Sethi Haveli Peshawar

There are multiple traditional houses found in the heart of the walled city with the traditional architecture that has become the symbol of the city's traditional culture in the region. Field survey of Barood Khana haveli located in the Bazaar Barood Khana, Walled city Lahore and Sethi haveli, Mohalla Sethian, Walled city Peshawar is conducted. Barood Khana Haveli was studied to realize the importance of traditional architecture because today's architecture is more westernized and is unable to provide an energy-efficient environment. Table 2 lists the brief overview of traditional techniques combination and dimensions used in the design of Havelis layout. Courtyard view of both havelis is shown in Fig. 5 (a) & (b). The combination of the veranda with inner courtyards and the main courtyard helps in increasing cross ventilation and stack effect as cross ventilation is an efficient cooling strategy in both Havelis. The openings in the walls are provided at both higher and lower levels that increase ventilation gain and minimizes the indoor temperature. The solar radiations are avoided as most of the windows are present along the north side. Verandas also prevent direct solar radiation from entering through openings. The courtyard houses permit low winter sun in the building and hinder the high summer sun with the help of overhanging roofs.

Table 2 Features and dimension of traditional Havelis observed in field survey

Factors for Architectural and Spatial Patterns	Barood Khana Haveli	Sethi Haveli Peshawar
Total area of Haveli	5 times more than the typical plot size of 4,500sft	Approximately 5333 sqft
Courtyard size	30% of the total area	40' x 40' with a water fountain which is 30% of total Haveli area
Shaded devices	Jharokas (balconies) covered with jalis (screens) and verandahs -South faced windows are shaded by verandah	Open-able 6' wide overhangs to shade windows and the courtyard along its three sides
Height of courtyard	Open to sky - up to one story height	A large two storied inner courtyard
Number of openings	2 or more openings in same wall, windows, ventilators	2 or more openings in same wall
Number of stories	3 stories-Basement, Ground, first floor	3 stories-Tehkhanas (Basement), Ground, first and second floor
Opening area of openings	33%, 40% - 66% of window area to floor area	33%, 40% - 66% of window area to floor area

Fig. 5 (a). Courtyard view of Barood Khana Haveli (b). Courtyard view of Sethi Haveli Peshawar

As per the benefits of traditional courtyard houses in terms of improved thermal performance supported by literature discussed and as observed in field survey, the proposed house with courtyard addition will be an economical and efficient solution to cope with the energy crisis of Pakistan.

3.6. Analysis of direct solar gain

Direct solar gain is figured by determining the amount of energy delivered to any space for a day, month, and a year. Building orientation w.r.t to sun exposure can significantly change the results when direct solar gain is considered [28]. Direct solar gain analysis on Ecotect software is done in a way so that similar exposure to the environment is given for the same orientation of both existing and proposed buildings. The material attributes and orientation of buildings are controlled groups for this solar gain analysis of both buildings. The region on Ecotect is characterized by hot dry summers and cool winters.

Previous researchers stressed either on the courtyard traditional housing benefits and importance in collaboration with other passive techniques through field investigation and analysis through simulation to explore the global and local courtyard designs from the perspective of general research. By contrast, our study stress on how courtyard can be revived in today's dwelling construction and to deal with the thermal comfort issues faced in present architecture of hot and semi-arid regions of Pakistan.

4. Results and Discussions

The LDA existing residential unit and a proposed design with the accommodation of a standardized courtyard are comparatively analyzed based on direct solar gain (Qg). Fig. 6 shows comparative monthly average direct solar gain in summers for both existing and proposed housing units for the hottest month of June. For June, the reduction in direct solar gain is significant in peak hours for proposed house with courtyard. One of the reasons of reduction is may be due to veranda provided around the inner zones of the house that are interacting with the courtyard, acting as a shade.

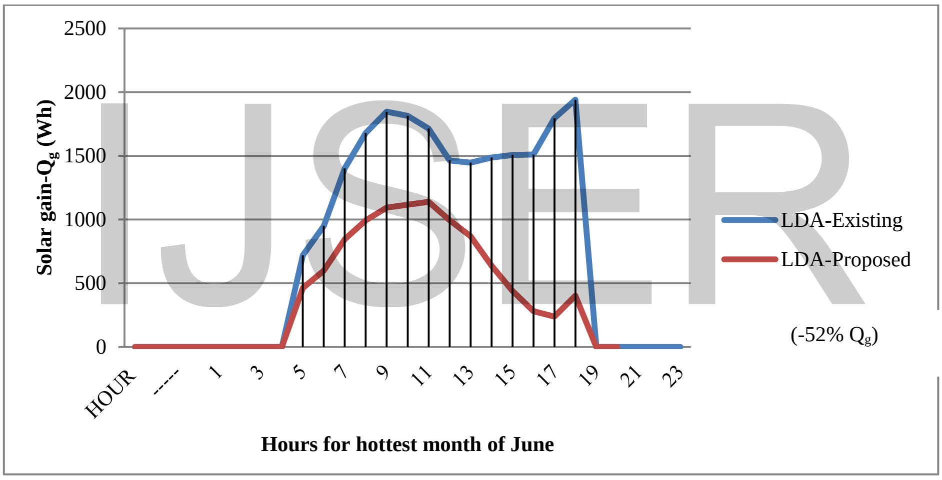

Fig. 6 Hourly difference in direct solar gain (Qg) for existing LDA residential unit and proposed courtyard house

This graph proves that the existing houses in the westernized style are not constructed keeping in view the energy crisis. This paper shows that direct solar gain also has an impact on energy demand just like investigated by Tabesh et al. [24] in which researchers proposed the energy-efficient courtyard design in reference to shape, ventilation, and its performance in terms of daylight factor. To avoid solar radiation, 5 feet verandah around the courtyard (with aspect ratio 1:1) is proposed. As shown in the above graph the courtyard and veranda addition in a residential unit can reduce many watt-hours of solar gain. In a research H. Safarzadeh and M. Bahadori suggested that the other small amounts of energy conservation strategies like improved material of windows, insulation, blinds, and vertical shading devices are if incorporated then they can save the heating and cooling energy requirements of buildings [38].

The bar chart in Fig. 7 compares the annual direct solar gain of each month on a larger scale for the existing LDA unit and proposed courtyard house. For summer months from April to September the existing LDA house and proposed courtyard unit shows the value of solar gain (Qg) varies from 18000-21000 Wh and 9500-11800 Wh even the sun is at high altitude in summers.

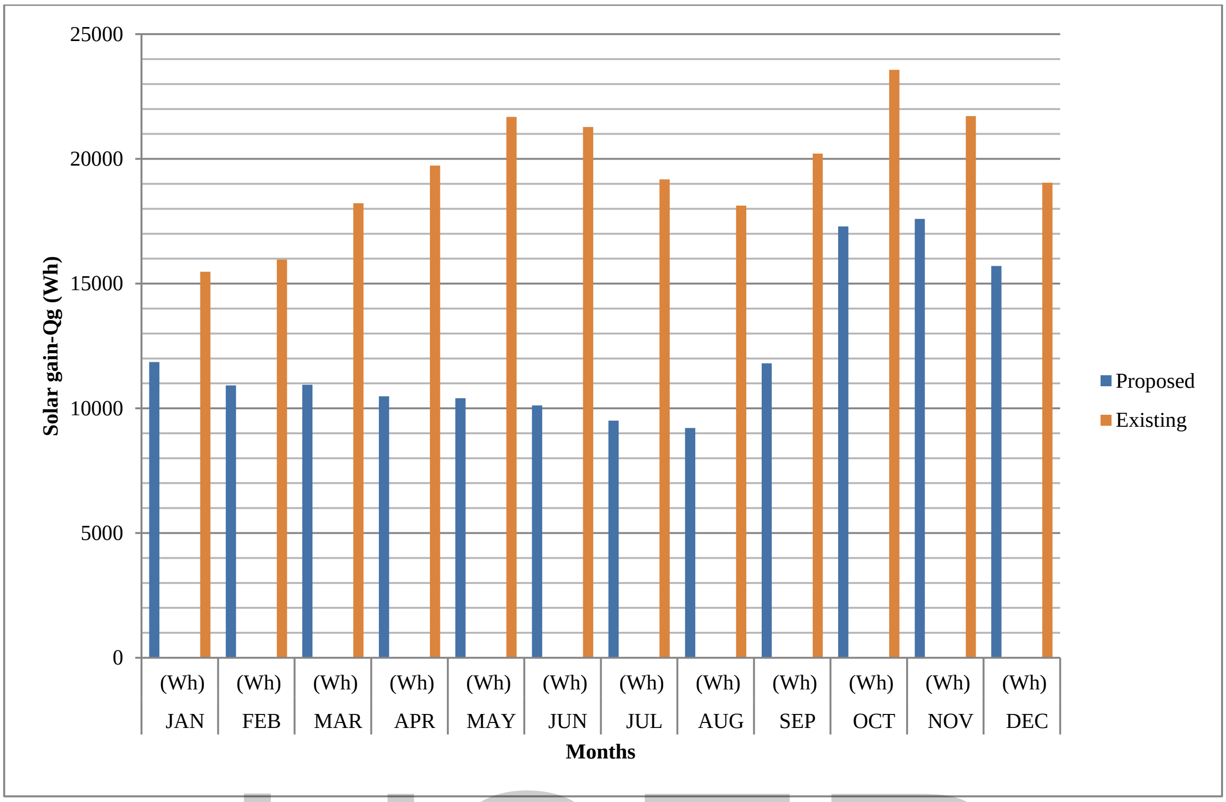

Fig. 7 Annual comparative direct solar gain (Q_g) for both proposed courtyard house with existing unit for each month

Maximum 52% reduction is seen from the graph for critical months of summer season (according to the standard of ASHRAE-55 the discomfortable hours mostly lied from May until September for calculation of indoor thermal comfort for different zones). This reduction is might be due to the the veranda provided in proposed desing along with courtyard.

Courtyard and veranda can reduce a considerable amount of direct solar gain. Similarly, other passive traditional elements like Jaalis, Jharokas, Tehkhaanas, landscape, fountains, and verandas as a shading element can also be employed into the design to make it more effective in terms of reducing thermal loads. The results of a study conducted in 2012 [39] also showed the same result of 54.25% decrease in solar gain for the courtyard form when compared to the usual outline of the house, this reduction is due to the shaded openings positioned around the courtyard. The Courtyard has the potential to save a specific amount of energy when used in a hot climate.

5. Conclusion

In this research, the impact of adding a courtyard in the Lahore devselopement authority (LDA) residential unit on the direct solar gain was simulated subject to weather conditions of hot and semi-arid for Lahore, Pakistan. Ecotect software is used to simulate the results of monthly direct solar gain for a year and specifically for the hottest month of June. Control groups include similar building materials and the same orientation for both existing and proposed design. Proposed design of Courtyard building form in the area of 4500 sq. ft. shows a maximum of 52% reduction in direct solar gain when compared with the conventional form of existing LDA residential unit in the critical months of the summer season. The current research gives an efficient solution towards the fast depletion of World energy resources and augmented energy demand in the hot climate of Lahore in the summer season. The proposal for LDA is more efficient in winters as well as in summers compared to the existing residential unit of LDA, hence it is highly recommended to implement side courtyard design into the respective LDA society to reduce direct solar gain and that will result in low thermal loads without much compromising the bylaws of covered area and setback requirements.

Limitation and future recommendations

Protection of courtyard from solar radiation is mentioned by extant studies, but limited data is available on energy consumption. For future research addition of various sizes of courtyards (including size used in this research) in different plot areas of modern residential housing societies and their impact on energy consumption is recommended. As the scope of research is limited to an area of proportion 50ft. × 90ft. (4500 sq. ft. = 1 kanal), other proportions of one kanal can be worked out as well. The impact of vegetation and shading in courtyards can also be analyzed using this research to improve the effectiveness of traditional courtyard addition in modern housing trends in different climates of Pakistan. Consideration of other factors of thermal performance such as ventilation also needs attention. Optimizing the courtyard orientation and courtyard proportion to simultaneously improve the outdoor and indoor thermal conditions in different regions of Pakistan also need attention.

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Conflict of interest

The authors declare that they have no competing interest.

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