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Exploring the Role of Intelligent Facades in Enhancing Energy Efficiency in Educational Buildings: A Scoping Review

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ABSTRACT

Recent advances in digital technologies have greatly influenced construction and architectural design, highlighting the importance of intelligent technologies for sustainable architecture. Facades, which serve as barriers between interior and exterior spaces, play a crucial role in energy efficiency and thermal comfort. Despite the importance of improving energy efficiency in university buildings- Since students spend about a third of their day in it, accessing the intelligent facades for optimizing energy efficiency in university buildings is still an area of study that is rarely researched. This paper aims to identify the state of the art of the intelligent facade technology and its role for energy efficiency in the educational buildings. Through scoping reviews, the research seeks to inform architects and Decision makers about the importance of intelligent facades for energy efficiency. Findings indicate that intelligent facades can significantly reduce energy consumption, contributing valuable insights to promote energy efficiency in educational environments.

Keywords: *Intelligent facades; energy efficiency; sustainability; educational buildings*

1. Introduction

In order to achieve the current targets of constructing high performance buildings that approach nearly ZEB, it is essential to persist in the progress achieved in the design, technology, and materials utilized in construction. Integrating intelligent solutions into the buildings can enhance the indoor environmental comfort for occupants and minimize energy consumption [1]. Enhancement of energy efficiency is essential in educational buildings. There is a correlation between the architectural environment and people who live, develop, or interact within it. A quality environment can help meet the objectives of an educational project [2]. Authors believes that intelligent facades will have a major role in enhancing energy efficiency in buildings, as they are the envelope that separates external influences from the internal environment, especially since there are challenges that cannot done by designers for various reasons. So, Understanding and applying strategies of IFs that enhance energy efficiency in buildings for educational purposes is of crucial importance. In addition, increase energy efficiency and reliance on renewable energy is the strategy of Palestinian authority- as one of Mediterranean countries- to solve this problem [3].

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Numerous studies have primarily focused on the development of IF technologies that are only able to evaluate its effect on the sustainability aspects. Many researches have been done about efficiently in using energy [4]. In contrast, through review of the existing literature, few studies have examined the energy efficiency of IFs in response to environmental conditions in education buildings. Analyzing the existing literature has highlighted a gap between the research problem of the study and the current state of the art. Therefore, this study aims to bridge this gap by addressing intelligent facades in education buildings to increase their energy efficiency to improve sustainability. Therefore, the paper aims to identify the state of the art of the intelligent facade technology and its role in enhancing energy efficiency in the educational buildings.

2. Methodology

2.1 Materials and Methods

The reporting of this scoping review was prepared in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analysis Protocols Extension for Scoping Reviews (PRISMA-ScR) guidelines [5] . All articles written in English up to 2019 addressing the use of Intelligent Facades to enhance energy consumption with the objective of exploring the relation between intelligent facades and energy efficiency. Multiple sources of information were selected to develop a search strategy as thorough as possible. Four databases were searched to identify all potentially relevant documents on the topic of this review. The databases consulted were ScienceDirect, Google Scholar, IEEE Xplore, and Emerald. The search was performed on title, abstract and keywords. Three groups of terms were searched by combining them with Boolean operators: *("intelligent facade" OR "intelligent envelope" or "smart facade" OR "adaptive facade" OR "kinetic facade" OR "solar facade" OR "double skin facade") and (“sustainability” OR “environmental sustainable” OR “reducing energy consumption” OR “generate energy” OR “efficient building” OR “energy efficiency”) AND (“smart school” OR “school building” OR "university building” OR "smart campus" OR "education building"*").

The first group includes terms related to IFs, the second group includes terms related to energy efficiency, and the third group includes terms related to educational building. As IF-related terms, *“"adaptive facade", "kinetic facade", "solar façade"* was chosen because they are popular types of intelligent facades, and “envelope” because it includes the building facade. As for the terms in the second group, in addition to the synonyms of energy efficiency in the terms *“generate energy”*, *“energy consumption”*, they define the meaning of efficiency.

After the search, all results were organized in a bibliographic reference manager, and duplicates were eliminated. Identical references were removed automatically, while similar ones were manually reviewed for removal or merging. The titles, abstracts, and keywords of the remaining articles were then examined and classified into three categories: Included, Excluded, and Unsure. Articles categorized as "Unsure" were those where, after reviewing the title, abstract, and keywords, it was still unclear whether they were relevant to the topic of the current review.

Therefore, the full text of the articles labeled as Unsure was read to determine whether they should be included in the review. After selecting the articles included in the review, the research team created a data sheet and exported the general data for each article (author, date of publication, title, keywords, type of document) from the bibliographic reference manager. Next, the following items were included in the data sheet: intelligent type; building type; intelligent technology; research method; evaluation method; environmental variables; relevant results; additional comments.

2.2 Intelligent Facades
2.2.1 Intelligent facade technologies

The Intelligent Building Institute defines an intelligent building that optimizes four key elements, structure, systems, services, and management along with their interrelationships to create a productive and cost-effective environment. These buildings enable owners, property managers, and occupants to achieve goals related to cost efficiency, energy management, comfort, convenience, safety, long-term flexibility, and marketability [6].

From the literature review, the Authors can summarize the definition of Intelligent Facades as: "The external envelopes as an essential& high-performance part designed to react to environmental conditions maintaining quality indoor environment & efficiency of the building which enhance the well-being and productivity of occupants".

Intelligent facade consists of a set of systems that integrates with each other to perform a protective layer that can increase the users' comfort while reducing power consumption. According to Al-Qaraghuli *et al.,* [7] technologies of intelligent facades separated into three categories techniques appearance levels, artificial intelligent techniques, intelligent facades components as shown in Figure 1.

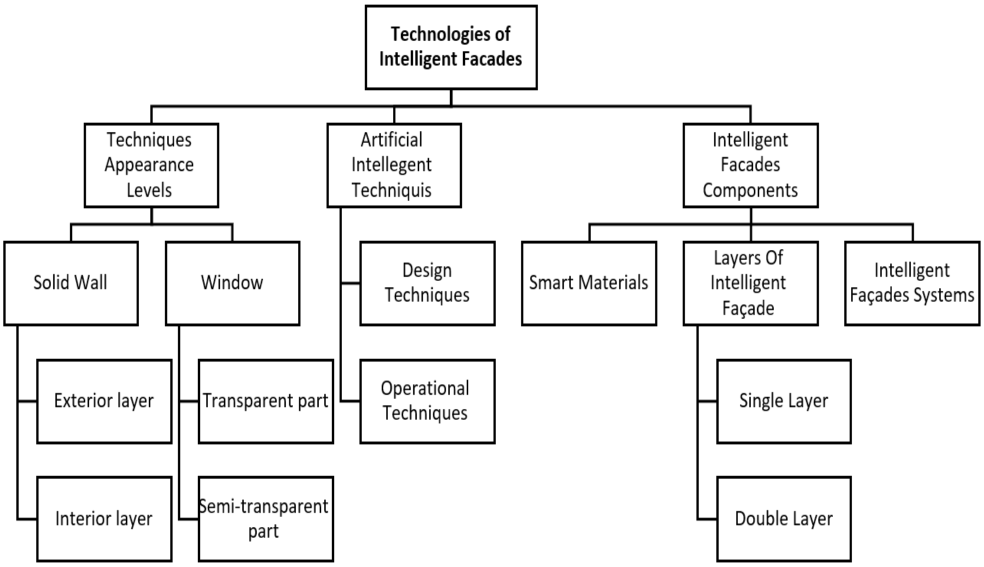

Fig. 1. Technologies of Intelligent Buildings [7]

2.2.2 Types of intelligent facades

Several researchers in the field of AFs have helped to classify IFs into sub-groups with shared characteristics. In addition, many review papers have been published on the different categories of IFs. [8]. Intelligent facades have been studied and applied in various ways, with differences based on technology, materials, and facade locations. Classifications exist for specific groups of facades that share common characteristics, as well as for distinct types that each focus on a specific concept.

In 2024, ICONARP proposed a new classification of intelligent facade systems, which is divided into five categories: mechanical technologies, electro-mechanical technologies, information technologies, passive technologies, and integrated technologies [9] as shown in Figure 2.

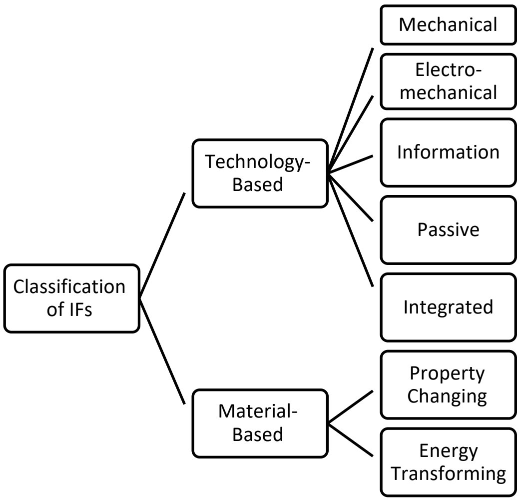

Fig. 2. Classification of Intelligent Facades Systems [9]

According to Habibi *et al.,* [8] there are many qualified types of IFs implemented in various buildings (Table 1), as Vertical Green.

Table 1
Qualified types of intelligent façades

IF type	Legend
VGS	Vertical Green System
DSF	Double Skin Façade
ETFE	Ethylene Tetrafluoroethylene Cushion
Wind-wall	Wind-WALL
PBR	Photo Bio-Reactor
BIPV	Building Integrated Photo Voltaic
BIST	Building Integrated Solar Thermal Syst.
TiO2 façade	Titanium Dioxide
Auto-blinds	Auto-BLINDS
Electro active	Electro ACTIVE

System, Double Skin Façade, Ethylene Tetrafluoroethylene Cushion, Wind-Wall, Photo Bio-Reactor, Photo Bio-Reactor, Building Integrated Photo Voltaic, Building Integrated Solar Thermal System, Titanium Dioxide, Auto-Blinds, Electro Active. There are pictures showing the shape of these facades as shown in Figure 3.

According to Ahmed *et al.,* [4], Intelligent Façades fall rather comprehensively into five categories (Figure 4.). Each of these categories includes many types of intelligent facades which have the same characters and technology.

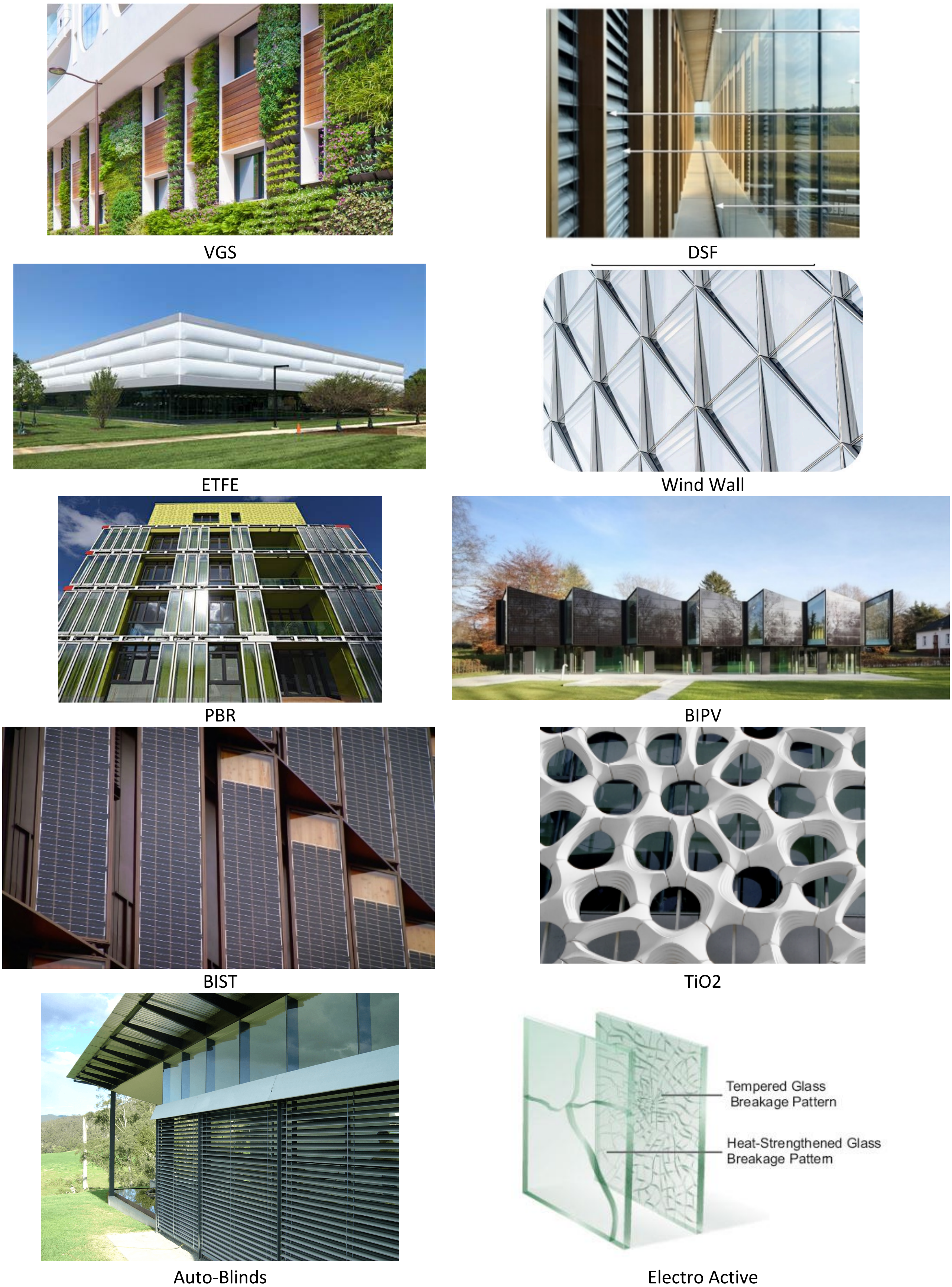

Fig. 3. Qualified types of intelligent façades

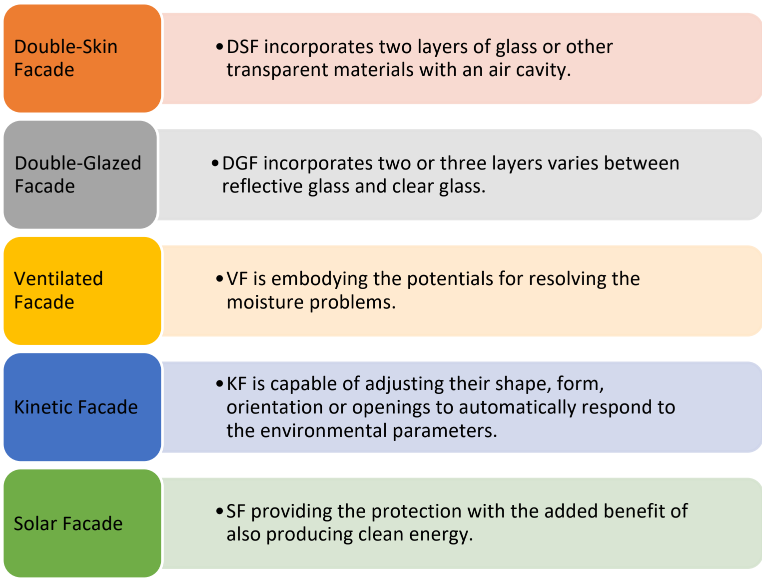

Fig. 4. Various types of intelligent facades [4]

2.3 Intelligent Facades and Sustainability
2.3.1 Intelligent facades towards achieving sustainability

The intelligent facades represent a key aspect of smart systems integrated into architectural design. Smart facades can interact with climatic variables and effectively address issues that result from their environmental interactions [10]. Furthermore, an intelligent facade represents an effective approach to managing the building envelope, aiming to minimize heat gain in the buildings. Nonetheless, the dynamic façade-as one of the intelligent facades- acts as a secondary skin for the building, can adjust its shape, orientation, and positioning in response to environmental conditions. This system promotes energy efficiency, potentially reducing consumption by 40% to 60% while enhancing thermal comfort [11].

According to Habibi *et al.,* [8], the article confirms that IFs are able to achieve sustainability in its three main aspects as shown in Table 2.

Table 2
IFS towards achieving sustainability [8]

Sustainability Aspects	IF Qualification
Economic	-Provide IF dismantling strategies and investigate reuse materials acceptance; -Clarify contributions from producers, suppliers and researchers in the total fabrication cost of IF products; -Comprehensive economic analyses of wind harvesting technologies; -Define the main economic potentials of inflating façade; -Investigate harvesting equipment and their high-cost challenges
Environmental	-Review strategies to extend the energy efficiency of IF systems; -Explore the high amount of waste, their reusing potential, and their increased life time. -Explore environmental contributions and recommending worldwide extension; -Carry out analysis of different mechanical equipment in IF technology.
Social	-Explore injuries and harm possibilities in IF development processes. -Post-occupancy analyses considering stakeholders' and users' satisfaction on the built environment; -Study labor working hours and required professionals for each alternative.

2.3.2 Intelligent facades towards achieving energy efficiency

The facade is the single most important factor in the energy efficiency of the structure. The facade's efficiency is significantly dependent on the building's location and orientation to the sun, as well as the materials and construction methods used in the façade [12]. As Intelligent Façade, a responsive facade system is considered a major component of high-performance building envelope that is capable of responding to environmental stimuli and aims to improve occupants' comforts and energy consumption [13]. The significant results according to Bui *et al.,* [14] confirm the capability and effectiveness of adaptive façades system in reducing the energy consumption and enhancing the energy efficiency of building, and concluded that AFs is a potential solution to enhance the energy efficiency of buildings, and it can reduce the energy consumption by 14.2–29.0%.

According to Ahmed *et al.,* [4], there are main potentials towards the sustainable design of low energy buildings, that is divided according to the type of intelligent façade as shown in Table 3.

Table 3
Sustainable potentials embodied in types of if [4]

Type of IFs	Main Potentials Towards the Sustainable Design
Double-Skin Facade	-Energy efficient (Decreasing solar heat gains) -Energy efficient (Receiving optimized daylight) -Energy efficient (Ensuring proper air ventilation) -Sound insulation -Enhanced aesthetic feature -Improved thermal comfort
Double-Glazed Facade	-Energy efficient (Decreasing the level of heat transfer) -Improved thermal comfort
Ventilated Facade	-Flexibility -Adaptability -Customizability (Shape & Color) -Energy efficient (Resolving moisture problems – air ventilation) -Improved thermal comfort
Kinetic Facade	-Energy efficient (Interactive and responsive to the -environmental attributes) -Adjustable & Adaptable -Improved thermal comfort
Solar Facade	-Energy efficient (Source of renewable energy) -Contributive to cooling and heating purposes -Visibility
Parametric Pattern Facade	-Energy efficient -Wind direction & provide shade -Adaptable & Responsive

2.3.3 Studies & case examples of intelligent facades and its impact on energy efficiency in educational buildings

The paper conducts a scoping review for the existing studies, that are extracted from different scholarly databases in an attempt to present the linkage between the intelligent buildings technology and the energy efficiency focusing on intelligent façades in educational building. Also, this review finds the assessment methods and tools used to determine the impact of intelligent facades on sustainability & energy efficiency. Ultimately, the outcomes will provide a close relationship between smart facades and achieving energy efficiency in buildings in their various aspects (Table 4). These points had been taken into consideration, most of the case studies have been constructed in a climate like Mediterranean climate (warm & rainy winters and hot & dry summers), and Case studies will be selected so that more than one type of intelligent facades is presented, regard to environmental stimulation.

2.4 Applications of Intelligent Facades in Educational Buildings

In today's world, as the intertwined challenges of increasing energy consumption and climate change, educational institutions are emerging as leaders in the pursuit of sustainable development. Implementing Energy Efficiency Systems in these facilities marks a significant turning point in moving toward a more environmentally friendly and energy-conscious future. Through these systems, educational institutions can significantly aid the global effort against climate change while also serving as instructional hubs that provide essential lessons on sustainability. In addition, the investigation of energy efficiency can motivate educational institutions to instill a sense of environmental responsibility among both students and educators [15].

2.4.1 Benefit from improved energy efficiency in educational buildings

According to the findings of Almasri *et al.,* [15], the Study show that adopting energy efficiency and renewable energy offers significant technological, economic, and environmental benefits. Higher education institutions that invest in energy-efficient technologies can lower utility bills and save costs in the long run. This shift also reduces reliance on fossil fuels, decreasing greenhouse gas emissions and promoting sustainability. Additionally, enhancing energy efficiency in educational settings provides students with valuable hands-on experiences with sustainable technologies.

Improving energy efficiency in educational buildings offers several benefits for university campuses, as outlined by the University of California [16]. These include:

i. Controlled Environment: Campuses can efficiently allocate resources within their structured settings.
ii. Environmental Awareness: Many schools have motivated students, faculty members and staff to implement energy-efficient solutions.
iii. Innovation Hubs: Campuses act as experimental spaces for energy conservation, utilizing advanced technology and exploring zero-net energy.

2.4.2 Educational buildings and intelligent building strategies

The increasing dependence on technology in smart schools highlights the need to prioritize energy efficiency to lower operational costs and reduce environmental impact [17]. Various strategies can be implemented to enhance energy efficiency in smart schools and reduce overall energy consumption [18]. Optimizing HVAC systems is particularly important, as they are a major source of energy consumption in smart schools [19].

Educational buildings should incorporate advanced technologies, including automated systems and architectural skins, along with well-designed spaces and features that serve as active bioclimatic solutions. Understanding and implementing strategies that enhance indoor environmental quality is essential, particularly in educational settings [20]. One active strategy employed in these buildings is the use of architectural skin as an advanced technology that protects facades from climatic challenges and helps regulate indoor temperatures. By implementing a responsive skin, buildings can adapt to changing needs through both passive and active strategies, significantly impacting their overall performance [21].

2.4.3 The implementation of intelligent facades in educational buildings

The next generation of building façades features multifunctional and highly adaptive systems, where the physical barrier between the interior and exterior environments can modify its functional characteristics or behavior over time. This responsiveness to changing performance demands and boundary conditions aims to enhance the overall efficiency and performance of the building. Educational buildings are designed to meet all modern requirements of the educational process, providing the flexibility to continuously adapt to evolving needs and standards [22]. To identify modern trends in educational façade design and the application of innovative technologies that meet essential requirements while adapting to ever-changing requirements, an analysis was conducted on the design and construction of educational building façades. One promising direction in the architectural and construction practices of educational facilities is the use of transformable, adaptive, and responsive systems in building façades, which effectively address all necessary design criteria.

Table 4
Studies & case examples of intelligent facades and its impact on energy efficiency in buildings

	Intelligent Façade					Type of IF							Sustainability aspect	Energy performance/ responsive function				
ID	**Reference**	**Treatment system**	**Location**	**Climate**	**Building type**	**Double Skin**	**Façade, Double Glazed**	**Ventilated Façade**	**Kinetic Façade**	**Solar Façade**	**Parametric Facade**	**Evaluation Methods**		**Energy generation**	**Reject heat**	**Collect heat**	**Energy**	**HVAC Loads**
1)	***Bashy & Alchalabi, 2023***	Temperature and air	Mosul/ Iraq	hot	Educational building "hostel"	•						surveys &meetings Grasshopper / DesignBuilder	Thermal comfort		•		•	•
2)	***Fakourian & Asefi, 2024***	Temperature. light	Kolding Campus/Denmark	Mild climate	Educational building "hostel"		•		•			Ecotect	Environmentally sustainability		•		•	•
3)	***El-Darwish & Gomaa, 2017***	Solar radiation, temperature	Egypt	Hot Arid	Educational building		•					Case study, Design Builder-Energy Plus	daylight		•		•	•
4)	***Webb, 2022***	temperature	--	various	Educational building						•	Modelling, TRNSYS	Energy efficiency, thermal comfort				•	•
5)	***Yoon, et al., 2021***	Solar radiation	South Korea	humid	Educational building				•	•		Revit, modeling	Energy efficiency, thermal comfort	•				

The mechanisms and materials of these façades can address design requirements by fulfilling functional needs, addressing sustainability concerns, and meeting aesthetic considerations [23]. Through the literature review, it has been shown that most of the educational buildings use various types of intelligent facades to achieve many functions toward environmental sustainability, most of which are focused on achieving energy efficiency, enhancing daylight, providing thermal comfort or achieving indoor environmental quality (IEQ). The intelligent facades used in these building varies between double skin façade -with either fixed, adjustable or moveable panels, double glass façade, kinetic facades, solar facades as shown in Figure 3 and Figure 4. These types are gradually used in terms of the method of movement, the type of materials used, the percentage of their use in buildings, and the purpose of their installation. Thus, in the educational institution modern buildings design the technologies systems in conjunction with sustainable technologies are applied.

Fig. 3. Kinetic façade in University of Southern Denmark and the Royal Veterinary College's [23]

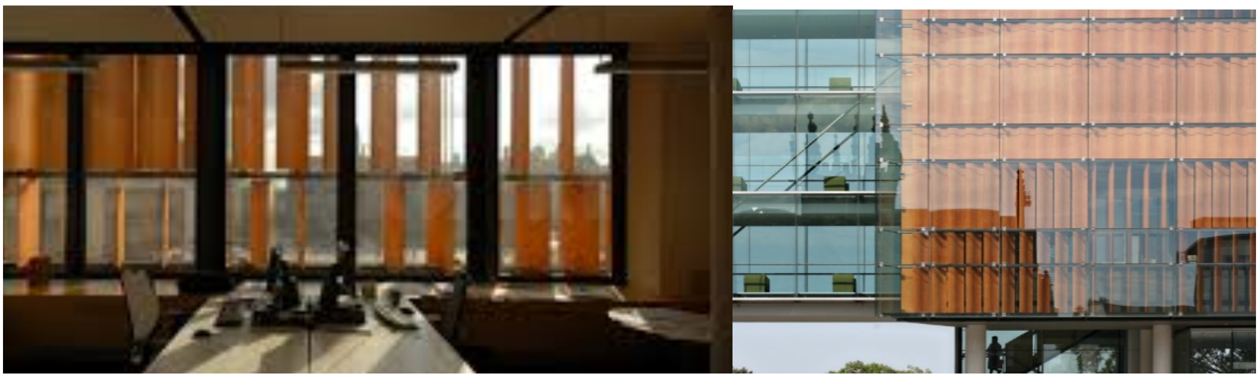

Fig. 4. DSF & Kinetic Façade in Faculty of Law, Sydney University

One such example is the building of the University SDU Campus Kolding (Figure 5). Dynamic facade elements, provide comfortable lighting in the premises during the day. Solar shading system consists of about 1600 triangular perforated steel blinds. They are mounted on the facade in such a way that they can be adapted to the changing daylight. The panels create an interesting appearance of the building and at the same time provide the necessary microclimate Figure 5 [24].

The second example is Masdar Institute in Emirate country (Figure 5). It has Pattern & self-shading facades with smart materials. Windows in the building are protected by a contemporary reinterpretation of Mashrabiya, a type of latticed projecting oriel window, constructed with sustainably developed, glass-reinforced concrete, colored with local sand to integrate with its desert context and to minimize maintenance [25].

University in Denmark Masdar Institute

Fig. 5. Examples for IFS in education building

The evaluation of educational buildings with various façade systems indicates a growing trend towards adopting façades that can react to environmental changes and building functions. Intelligent façade elements are particularly effective in meeting the needs of both designers and users, offering more sustainable architectural solutions. To achieve optimal quality in educational spaces, designs must be adaptable to environmental changes, such as light and temperature, while maintaining a comfortable indoor environment for students. One proposed solution is to use components that can be repositioned or stored in different orientations, increasing natural light, achieving thermal comfort and thus enhancing energy efficiency.

2.4 Challenges and Opportunities

Focusing on intelligent facades- as a major element in intelligent building- and their adopt in educational buildings, the challenges were classified into three categories [26]: Political-Administrative Barriers, Social and Economic Barriers and Technical & Environmental Barriers.

On the other hand, there are many motivations that can support and increase the opportunities for utilization intelligent facades in educational buildings, that are represented in: Motivation according to environmental impacts as reducing energy consumption, improving energy efficiency, carbon emission reduction and improving building performance, in addition to motivations according to economic, information and social impacts.

3. Conclusions

Combating climate change and focusing on renewable energy sources require reducing energy consumption and implementing energy efficiency measures, which are crucial first steps. Energy conservation is facilitated by properly employed practices and technologies in educational buildings. Many studies highlight the technological, economic and environmental benefits of adopting energy efficiency systems. This scoping review has revealed a growing interest in the development of intelligent facades and concluded that intelligent facade is the most powerful factor towards achieving environmental sustainability in buildings, which is to solve the most important issue and the biggest challenge in it, which is energy efficiency. The results of the study yielded the following conclusions:

i. Energy consumption at education institutions is influenced by several factors, including the type of institution, the energy sources used, the design and structure of the facilities, occupant activities within buildings, prevailing weather conditions, and user behaviour.
ii. There is a pressing need to strengthen this commitment on a larger scale within higher education institutions, given their influential role in this area and the growing expectations for them to lead in promoting sustainable practices.
iii. Educational institutions that invest in energy-efficient technologies see significant reductions in utility costs, resulting in long-term financial savings. Moreover,
iv. Despite challenges, the economic, environmental, and educational benefits emphasize the need for ongoing research, policy advocacy, and collaborative efforts between higher education institutions, governments, and industry stakeholders to achieve energy efficiency in the building.
v. Conduct a detailed study on smart facades and their types that are suitable for educational buildings and choose the ideal types for such buildings that aim to achieve energy efficiency.
vi. The participation of architects, sustainability experts, and other stakeholders in the planning and design process is essential for creating effective and sustainable higher education facilities.
vii. Due to the importance of university buildings, it is recommended that future research be directed towards future research is directed towards accessing the most effective intelligent facade solutions for optimizing energy efficiency in university buildings.

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