Environmental Sustainability of Textile Architecture: A Review of the Thermal, Optical and Acoustic Properties of Textile Membranes

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Abstract

Textile architecture is concerned with creating buildings and structures by using "textile" or "fabric" materials that are environmentally, functionally, and aesthetically accepted, due to its unique and sustainable characteristics like lightness, flexibility, translucency, portability and ephemerality. It is also characterized by its creative forms, and the ability to transfer loads through tensile forces, adapting its shape to the direction of force path. Thus, textiles architecture uses the least quantity of materials to cover spaces with even with large spans.

Many studies have addressed the structural behavior and material technology of textile membrane structures. However, only few have considered the sustainable behaviors of such structures. This paper investigates the sustainable aspects of textile architecture and the behavioral and the environmental characteristics of the textile membranes, including the thermal, optical and acoustic properties. It also examines the impact of textile materials on environment, the recycling process, and the adaptation of textile membrane structures with the surrounding urban and cultural context. All of these aspects represent the emergence of new era of eco-friendly, climate-responsive sustainable textile architecture that could help combat the climate crisis.

The research concludes that despite the low thermal mass and low thickness of textile membranes, it is possible to get higher thermal insulation through membranes. Textiles' translucency has the advantage of transmitting heat and light, as well as providing sound insulation using the membranes. As for the environmental impacts of textile membranes, most of the textile materials are recyclable, where ETFE has the maximum levels of recyclability. Besides, textiles have the ability to adapt with the environment and the surrounding context through shape, form and color to create a spectacular sustainable textile architecture.

Keywords: Textile Architecture, Textile Membranes, Environmental Sustainability, Thermal Properties, Optical Properties, Acoustic Properties.

1. Introduction

Fabric structures have been used for a long time. They date back to the first human-built tents, which were used to protect people from bad weather in areas without natural shelters. They have since evolved to meet the demands of increasingly complex applications, coming up in a variety of sizes, shapes, and forms. These kinds of structures have a wide range of useful contemporary applications in architecture that address human requirements and the demands of diverse activities and functions, including stadiums, theaters, sport centers, open spaces, pavilions. They are also used in covering building facades, and separating interior spaces acoustically, visually and physically, etc., as movable or fixed structures, thus creating adaptive- flexible spaces (Aboud & Al-Alwan, 2010; Kronenburg, 2015). In addition to tents, other types of contemporary fabric structures include air-supported structures enabled by air pressure differentials between the interior and exterior environments, or high-pressure air systems where the fabrics are shaped into structural elements (Kronenburg, 2015). Throughout the 20th century, the field of smart materials witnessed significant growth. The advent of the new millennium accelerated that development (Abdullah & Al-Alwan, 2019). Besides smart materials, a new creative movement in architecture has emerged in recent years, marked by the development of intriguing, free-flowing structures that exhibit expressiveness in form and design, as well as originality in structure and construction methods. Many people view these intriguing constructions as monuments that harmoniously integrate into their surroundings (Hameed et al., 2020). This changed the way architects and construction experts thought and cleared the path for the evolution of architecture itself in general, and textile architecture in particular (Abdullah & Al-Alwan, 2019).

The world is currently paying great attention and interest to textile architecture and its structures as a result of the vast developments in the first decades of the twenty-first century. These developments have taken place on several levels including modern contemporary technological developments related to textile architecture to create interactive, responsive, digitally controlled smart textile architecture that meets human needs and saves energy. Another level includes digital programs in terms of producing free-forms structures inspired by nature and robotic fabrication, which offers outstanding aesthetic results. A third level tackles the developments in the manufacturing of contemporary textile structures and the technical innovations in structural and architectural membrane materials that have also been evident in the past decades (Shareef & Al-Alwan, 2020; Al-Azzawi &Al-Alwan, 2022). The combination and potentials of textile structure, techniques and materials contribute to sustainability concepts constituting what is known as "sustainable tectonics", as a way to generate remarkable and empathic architectural forms, and resulting in creating poetic architecture (Mahmood & Al-Alwan, 2020; Mahmood & Al-Alwan, 2023).

Nowadays, the globe is going through many challenges related to the depletion of natural resources, including fossil fuels, being the main source of energy. Sustainable solutions have been constantly searched for since the last few decades until the present day (Garbe, 2008). One of the main worrisome challenges is the increase of energy consumption worldwide, along with the high consumption of water, as a source that is widely used in the traditional construction industry. Energy consumption contributes to an increase of CO_2 emissions, which negatively affect the environment in general, causing climate change and global warming (Abdulateef & Al-Alwan, 2022). The construction of buildings (the construction sector) in industrialized countries contributes to the depletion of supplies of fresh water, natural resources, fossil fuels and manufactured materials in the world (Garbe, 2008). São Joãoa et al. (2016) assure that contemporary designers, architects, urban designers and urban planners have become more committed to the principles of environmental design with the intention of creating a built environment that is more in harmony with its natural surroundings "environmentally-friendly". Building materials are re-evaluated and redesigned to be more sustainable and environmentally-efficient building materials "eco-efficient building materials" that has low embodied energy to reduce energy consumption and to save the natural resources used in construction. Thus, these new materials are efficient as a beneficial alternative to the urban spaces at the same time. Examples of eco-efficient structures are membrane structures (textile architecture) that are increasingly being used fruitfully in many modern architectural projects in the urban environment (Mollaert & De Laet, 2017). However, Garbe (2008), points out that textile structures can also play an important role in sustainable architecture, as they are considered an efficient environmental solution and a mean of attractive and distinct visual appearance, as they tread slightly and gracefully on the ground. Textile architecture uses less materials and fewer energy resources, in manufacturing, production and shipping processes. It also reduces the amount of gas emissions (CO_2) through the process of material manufacturing and construction, and through the life cycle of the material as well, leading to the least environmental impact.

Furthermore, from an environmental point of view, textile structures are characterized by their ability to reduce solar and heat gain, through reflecting part of the sunlight and heat falling onto the surface of the membrane. Even though, there is a potential of using these membranes with two or more layers, which contributes in creating a warm interior space in winter in cold regions, and cool one in summer in hot regions, thereby saving more energy consumed for heating and cooling. It also leads to reduced cooling loads and electricity requirements, hence, reducing energy costs for buildings. Natural light that penetrates the translucent textile membrane, contributes in reducing the requirements for artificial lighting. In general, a large amount of electrical energy consumed for heating and cooling in buildings can be saved (National Research Council, 2002).

Environmental studies focus on many levels, starting with the reduction of energy consumption by using more techniques of utilizing daylight, natural ventilation, thermal insulation, etc. This leads to more interest in studying the internal environment of spaces surrounded by textile membranes, which play a major role in thermal mitigation, as well as their influence on the visual appearance of spaces (Elmokadem et al., 2019). For this reason, the construction sector must take an environmentally-friendly approach, while considering the importance of promoting this sector at the same time. This is possible with sustainable design and sustainable materials, and with the conscious consumption of the world's natural resources, preserving the need to take the environment into consideration when designing and constructing buildings, to make a big difference in the global environment (Alioğlu, 2018; Alioglu, & Sirel, 2018).

In this context, the aim of this research is to shed light on the environmentally sustainable aspects of textile architecture represented by its thermal, optical, and acoustic properties, recycling. Its objective is to identify their adaptation to the surrounding environment, and the urban and cultural context to create a sustainable textile architecture.

2. Review of Literature

Textile architecture has been the subject of numerous studies from various angles. Ekici et al. (2023) have investigated the interconnections between textile and architecture at the levels of material and spatial properties of textiles, as well as the cultural and political implications of textile products and structures, patterns, and metaphors in architectural design. While according to Rawal et al. (2023) and Oñate & Kröplin (2005) focus on the structural, technical and physical characteristics of textile materials represented by textile-reinforced composite materials, which positively affect the properties of these composites, thus enhancing their strength, performance, function, and structural behavior and durability.

Elmokadem et al. (2019) focus on the visual characteristics of tensioned membrane structures and their relationship to the aesthetic, expressive and visual appearance of these structures. Horteborn et al. (2019) focus on the structural behavior of textile architecture represented by textile structures to resist wind forces and identify their impact by using digital and physical simulation to adjust and change the shape and form of the textile structure to reach equilibrium. In 2011, another study has focused on the use of textile membrane materials and plastic materials in the field of various industries in general, and in architecture in particular, especially in textile architecture. These innovative technical developments work to improve the properties of materials and clarify their potentials as building and construction materials, as well as being sustainable and environmentally friendly materials. Textile materials are considered a successful and efficient alternative to traditional materials. It is applicable to various facilities in the form of ceilings, facades, etc (Knippers et al., 2011a).

Mazzola & Liuti (2018) for example, has concentrated on the relationship and close connection between architecture and technological innovation, and how this fusion often leads to improvements in functional performance (in terms of durability, permanence), and environmental performance of temporary fabric structures, with the potential to more deliberately reducing resource consumption throughout the project's lifespan.

In short, research has classified previous literature examining textile architecture into three categories:

- Studies that focus on the characteristic of textile materials and its political and cultural effects (Ekici et al., 2023; Megahed, 2018; Asefi & Kronenburg, 2016; Tani, 2015).
- Studies that focus on the physical, functional and structural behavior, as well as innovative, technical and technological characteristics of textile materials and structures (Rawal et al., 2023; Mazzola & Liuti, 2018; Fiúza, 2016; Chilton & Lau, 2015; Oñate. & Kröplin, 2005).
- Studies that focus on the environmental behavior of textile architecture in terms of optical/ visual characteristics of textile structures (Elmokadem et al., 2019; Hartwig & Zeumer, 2011; Mundo-Hernandez et al., 2004; ElNokaly et al., 2003).

In this context, this paper aims to investigate the environmentally sustainable textile architecture aspects including the thermal, optical and acoustic properties of architectural textile membranes. They include the environmental impact of textile materials, the recycling process, and the adaptation of textile membrane structures with the surrounding urban environment and cultural context.

3. Theoretical Framework

The environmental aspect of sustainable 'textile architecture' must include a high level of awareness of the environmental behavior and the internal environmental characteristics of spaces surrounded by textile membranes (textile enclosures), such as optical and thermal properties, as well as studying the environmental impact of textile materials, their recycling, and adaptation with the surrounding environment, in its urban and cultural context. Figure (1) illustrates the elements of sustainable environmental design in textile architecture.

Building a theoretical framework is based on data collected from recent studies concerned with textile architecture, with a special focus on the relationship between the environmental aspects of textile architecture and sustainability. The acquired data is categorized to produce a framework that covers the above-mentioned aspects of environmentally sustainable textile architecture.

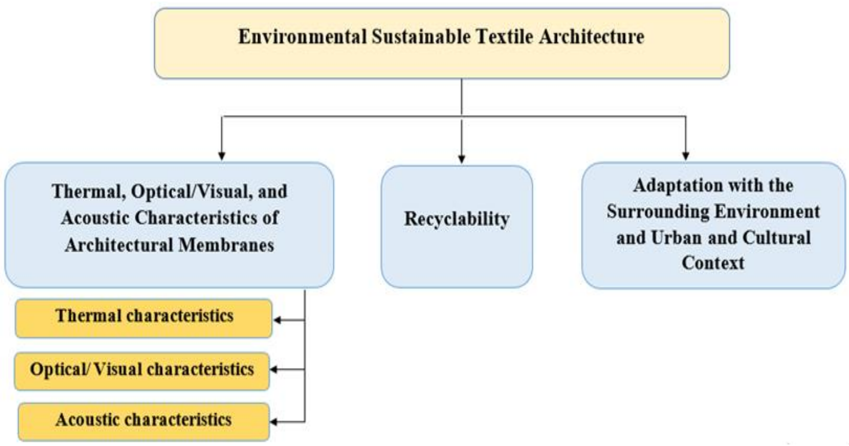

Fig. 1: The Elements of Sustainable Environmental Design in Textile Architecture
Source: Author

3.1. Thermal, Optical/Visual and Acoustic Characteristics of Architectural Membranes:

3.1.1. Thermal characteristics of architectural membranes:

The thickness of the textile cover (architectural membrane) is usually about (1 mm) even that its mass is about (1 kg /m^2) (Elnokaly et al., 2002a; Harvie, 2015). Compared to a brick wall with a thickness of (12 cm), its mass is about (200 kg /m2). The (U-value[1]*), which is a measure of "thermal conductivity", is about (5 W/m2.K) for the textile membrane, compared to the (U- value) for traditional construction, which is about (0.2 W/m^2.K) (Harvie, 2015). That means properties like thickness, mass and thermal conductivity, which are the basis of conventional thermal analysis, are of no importance for architectural textiles.

Under standard winter conditions, the "thermal Resistance" or (R-value[2]*) of the base material for a thin architectural fabric could represent only (1 %) of the total resistance, while for conventional materials, it is likely to be more than (90 %). Practically, this means that the mass of the architectural membranes is (zero), and therefore the thermal resistance of their mass is also "zero" (Harvie, 2015).

Since the textile membranes have a small thickness, a relatively low thermal mass, and very little thermal insulation (unlike the traditional heavy-weight structures), they interact significantly and quickly with the surrounding environmental variables, so they heat up quickly during the day due to exposure to direct sunlight, and cool down quickly at night. When the outside temperature drops, the heat is reflected back to the outside environment (by radiation). In addition, they allow light and solar radiation to pass through them, which causes environmental problems related to the thermal comfort of the occupants (ElNokaly et al., 2002a; ElNokaly et al., 2003).

On the other hand, one of the important features of membrane architecture is the possibility of providing thermal insulation in terms of materials and design, where membrane producers addressed the issue of low thermal insulation values, through the production and construction of thermal insulation membranes with very high (R) values, which has "high thermal resistance" (Garbe, 2008).

The thermal behavior of textile structures can be accurately determined by the combination of two concepts: the (U-value) or (thermal transmission), and the solar heat gain coefficient (SHGC) or (shading coefficient), which is a property that is applied to the solar heat gain through the surfaces of the textile membranes (inner and outer sides). It is originally applied to the solar heat gain through the glass (Elnokaly et al., 2002b).

The thermal properties of textile materials are completely different from the thermal properties of traditional buildings. As in the traditional structure, the term thermal resistance (R-value) of the materials is dominant, thus, the heat conduction across the building envelope is proportional to the difference of air temperature on its surfaces (internal and external surfaces). As for the "surface resistance" of traditional building materials, it is neglected because its effect is very low when calculating the value of the coefficient (R-value). Priority is given to the resistance of the material itself, as it gives accurate and reasonable results. This hypothesis cannot be applied to textile membranes, because the surface area of textile membranes is large in relation to its small thickness, which means that it has a low thermal mass that makes it unable to affect its thermal behavior (it does not have the ability to store heat). Therefore, its thermal behavior entirely depends on "surface heat exchange" (Elnokaly et al., 2002a).

[1] *(U-value) or (Thermal Transmittance), is a measure of thermal conductivity, which is the total heat transfer coefficient of the structural component, measured in Watts /m2. Kelvin (ElNokaly et al., 2002a).

[2] *(R-value) or (Thermal resistance): is the reluctance shown by the integrated structure to transfer heat during a specific unit of time (hour) and within a unit area (m2). When the difference between the temperature of its internal and external surfaces is one degree Celsius, it is measured by (m2. Kelvin/Watt) (Garbe, 2008). Or is a function of the thermal resistance of the building envelope material and the effects of surface resistance. It is a term commonly used to describe and evaluate the insulation performance of a building (ElNokaly et al., 2002a).

The amount of heat transfer through textile structures mostly depends on: internal and external air temperatures (in terms of the difference between the surface temperature of the inner and outer textile membrane and the climatic conditions surrounding the two surfaces of the membrane), wind speed, the value of the overall heat transfer coefficient (U-value), and finally, the thickness of the textile membrane, whether it is a single or multilayered membrane (Elnokaly et al., 2002a).

As for the thermal properties of textile structures, they have pros and cons. Positive thermal properties excel by providing textile materials with high thermal resistance properties and low heat conductivity. Thus, providing high thermal insulation within the textile membrane structures.

3.1.2. Optical /Visual Characteristics of Architectural Membranes:

The thermal- optical properties of a material can recognize its radiant behavior within the thermal spectrum. Unlike most structural materials commonly used in the building industry, textile membranes offer a special feature of "translucency" with varying acceptable levels, which in turn provide varying degrees of light transmittance (Elnokaly et al., 2002a). The permeability (transmittance) of coated woven fabric membranes is about (0-40 %), and might be more up to (90 %) for foils. This feature allows large amounts of solar radiation to transmit the entire surface of the building, while the rest of the solar radiation is either absorbed by the textile membrane or reflected to the outdoor environment (Elnokaly et al., 2002a; Chilton & Lau, 2015). Figure (2) shows how the sunlight diffuses through the membrane and is reflected internally and externally.

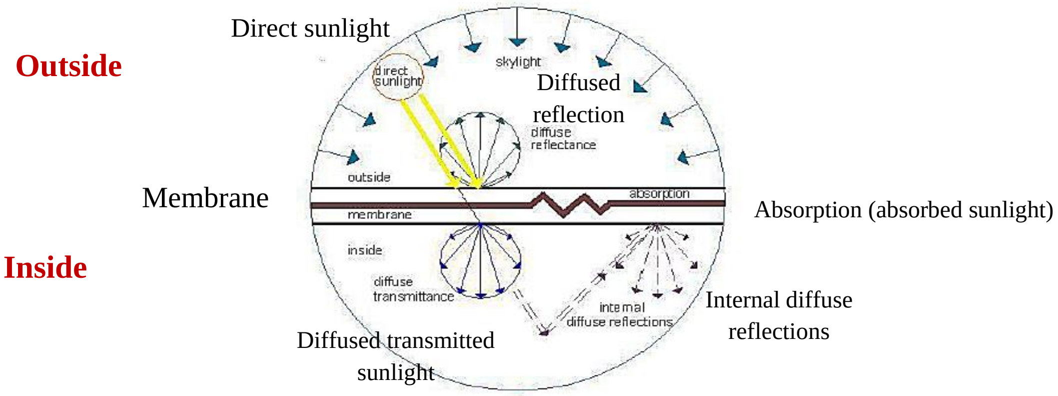

Fig. 2: Sunlight Diffusion Through the Membrane That is Reflected Internally and Externally.
Source: Mundo-Hernandez et al., 2004

The main features of transparent textiles are summarized as follows: (Mundo-Hernandez et al., 2004):

- The transparency feature makes the membrane structure system very useful for various functions, such as transportation stations, sports facilities, music and theatrical activities.
- Provision of a well-lit indoor environment, thus avoiding glare problems.
- Allowing a close visual communication between users and the outside world.
- Allowing the penetration of daylight which can provide a brighter interior environment, while reducing the consumption of electric lighting (artificial lighting).
- Diffused daylight helps provide an indoor environment with constant lighting.
- Allowing internal reflections of light.
- During daytime, the outer surface (exterior side) of the membrane looks opaque, like a soft light skin.
- At night, the structure becomes a major attraction (focal point) in the surroundings as it shows the indoor environment illuminated by using artificial lighting to the outside.

There are also, some factors that affect the amount of light transmittance through textile membranes. They are as follows: (Elnokaly et al., 2002a; Mundo-Hernandez et al., 2004):

- The type and color of the membrane material used.
- Solar angle incidence.
- Wavelength of the radiation.
- Type of weaves and pre-stressed textiles.
- The type of coating material.
- Tension applied to fabric.
- Maintenance on fabric, which includes removing dirt and dust from the fabric's surface.
- The number of fabric layers, the higher layers means less transparency and less light transmittance.
- Thickness of the fabric.
- Furthermore, depending on how the textile membrane is used, either as a membrane structure covering a long-span building, or as an internal or external louvers (Mundo-Hernandez et al., 2004), Figure (3).

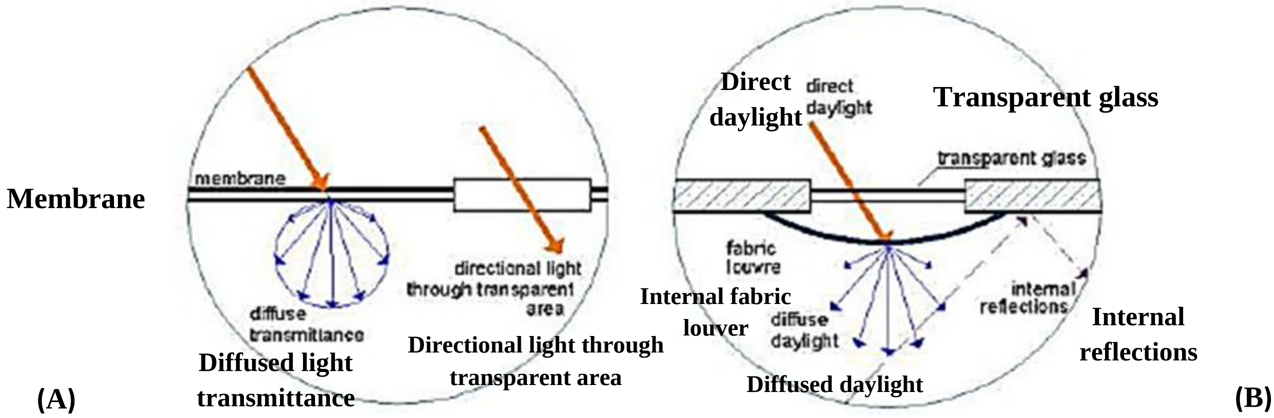

Fig 3: The Behavior of Textile Membranes When Exposed to Daylight (transmitted and diffused light through the textile membrane).
A- Light transmitted and diffused through a transparent area/medium (without a louver).
B- Light transmitted through a transparent area and scattered (diffused) by internal louvers.
Source: Mundo-Hernandez et al., 2004

There are some thermal-optical properties of textile membranes, which can be measured, such as: solar energy transmittance, solar energy absorption, as well as emissivity[3]* (The absorption of long-wave IR radiation). As for the other properties, such as thickness, mass, and thermal conductivity, they have no importance. As each of the thermal-optical properties depends on the "angle of incidence", so that the greater the angle of incident radiation, the greater the reflection, and the greater the absorption of the remaining incident radiation, with less transmittance (Harvie, 2015), Figure (4).

[3] *(Emissivity): is a measure of long-wave infrared radiation that a certain surface emits to its surroundings. The emissivity of a surface is equal to its radioactive absorption at a given temperature and wavelength (Harvie, 2015).

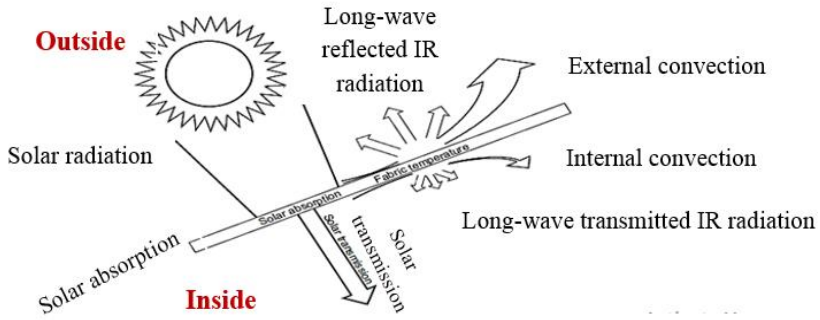

Fig. 4: Heat Transfer Mechanism That Affects the Thermal Behavior of Architectural Membranes.
Source: Harvie, 2015

Textile membranes are characterized by "high reflectivity" and "low absorption". The reflectivity of some membrane materials, such as PTFE (Teflon) coated fiberglass, is mostly about (70%). This feature is very beneficial, especially when used in hot climates regions, because it reduces the accumulated heat inside the building or space surrounded by textile membranes due to the "continuity of insolation" during the day, while it loses and radiates heat at night. This reduces the load on air conditioning systems (Elnokaly et al., 2002a).

One of the prominent examples that demonstrates visual /optical properties such as transmittance, reflection and absorption of textile membranes is the (AELTC) covered courts at Wimbledon, where the covered tennis courts were built in 1989. The complex comprises of five indoor tennis courts; three of them are covered by a membrane structure of polyester fabric coated with PVC, with a thickness of (1 mm), and an area exceeding (2000 m^2) (Mundo-Hernandez et al., 2004), Table (1).

Table 1. Solar Properties (Optical/ Visual Properties) of Textile Membranes, the (AELTC) Covered Courts at Wimbledon, UK, 1999
Source: Author

Solar Property	Transmittance	Absorption	Reflection
	9.8 %	26.42 %	63.78 %

According to the table above, the solar properties of the textile membranes represented by PVC membrane of (AELTC) covered courts at Wimbledon, UK, shows that it has a relatively maximum light transmittance, low absorption and a high reflection.

Table 2. The Most Prominent Solar Properties of Textile Membranes
Source: Author, cited from Birdair, 2021

Solar Property / Membrane Type	Reflectance	Absorption	Transmittance	U-value (Watt/m2. Kelvin)	Solar Heat Gain Coefficient (SHGC)	Translucency
PVC (Polyvinyl Chloride) Membrane	75-78%	13-22%	4-10%	5.6	8-14%	6-8%
PTFE (Polytetrafluoroethylene) coated fiberglass Membrane	72-75%	10-12%	10-21%	7.2	14-28%	7-15%
PTFE (ePTFE) Membrane	59-79%	2-3%	19-38%	5.9	28-44%	40%

ETFE (Ethylene tetrafluoroethylen) Film	5-60% Depending on the number of layers, color and frit printing.	1-2% Depending on the number of layers, color and frit printing.	20-90% Depending on the number of layers, color and frit printing.	Single Layer: 5.7 Double Layer: 2.9 Triple Layer: 1.9	Single Layer: 80% Double Layer: 65% Triple Layer: 50%	90-95%

3.1.3. Acoustic Characteristics of Architectural Membranes

There are many different types of textile membranes: woven, non-woven, knitted and others, whose acoustic properties in relation to architectural design can be investigated from different points of view (Chmelík et al., 2015). One of the most important situations that designers face is the acoustics of textile membrane structures. Acoustics represent an important challenge, especially in textile architecture, due to lightweight physical property, which characterizes the membranes (Chiu et al., 2015). Acoustics of a building is also directly related to sound propagation (sound spread), in terms of transmission, reflection, and absorption of energy. Since the reverberation time is a good indicator of sound reflection, it should be limited to a set of standard values in order to avoid echo and provide good emission and reception of sound inside the building, as the transmission of sound is the result of areal and percussion sounds. Regarding sound absorption, it is a direct result of the acoustic insulation of the membrane system (Fiúza, 2016).

Architectural membranes do not provide good sound insulation, due to their lightweight and low mass (tensile fabric membranes weigh about 1% of weight of glass). Therefore, membranes are often described as "acoustically transparent". If the material is acoustically transparent, it does not isolate or absorb large amounts of sound energy. The advantage of this acoustic transparency is that the reflected sound can enhance and improve the acoustic energy reflected in the indoor space. An example of this effect can be noticed in stadium designs, where noise from the crowd can enhance the sense of excitement (Chiu et al., 2015).

"Sound absorption" is one of the most significant acoustic characteristics of membrane structures. Textiles' acoustic characteristics are also impacted by their "porosity". Porous materials, such as perforated panels, absorb sound waves of medium and high frequencies above 500 Hz (Chmelík et al., 2015; Tani, 2015). Textile membranes are effective in absorbing low frequencies (below 200 Hz). Since non-woven fabric has poor absorption capacity at low frequencies, its thickness should be raised to enhance its capacity for absorption at medium and high frequencies. To boost sound absorption at low and medium frequencies, an air gap (air space) is added behind the textile membrane structure. In general, flexible and light membranes typically absorb a lot of acoustic energy. Knitted textiles have improved acoustic absorption qualities. In terms of their capacity to absorb sound, they behave similarly to acoustic materials and microperforated panels (Chmelík et al., 2015). To maximize sound absorption at low and medium frequencies, knitted textiles can have up to (4) layers with air gaps between them. Conversely, non-porous woven fabrics (those with small pores) have superior sound absorption (Chmelík et al., 2015; Nocera et al., 2014).

Some interior spaces with membrane coverings have an issue with worse sound absorption, which can increase acoustic reverberation time and reduce the quality of the acoustic environment. Membrane structures are mostly used to form roofs. The use of "double-membrane structures" can improve acoustic conditions by improving their acoustic performance. "Double-leaf membranes" can be used as special sound-absorbing elements, as "partitions" (Chmelík et al., 2015). Commonly used membrane absorbents are usually in the form of a "single-layer membrane", suspended parallel to a massive back wall. An air cavity is placed inside a gap in such structures. Since the membrane itself does not have significant absorbance, absorption in the cavity plays an important role, unless the membrane is acoustically permeable (Chmelík et al., 2015).

When it comes to "sound reflection", the reflections of these sounds on surfaces make it simple to direct or amplify the sound. Solid and flat materials typically cause sound to reverberate and magnify, producing pleasing, and vibrant acoustics. On the other hand, soft furnished spaces create a calmer atmosphere. The first treatments are applied in concert halls and theatres, where sound has to be transmitted from one area to another. The latter treatments are recommended for usage in interior designs for both residential and commercials. Textiles with various texture patterns are the ideal solution (Wærsted, 2014).

Regarding the "sound transmission" property, it is typically believed that textile structures have relatively poor sound insulation. It is possible to reduce the property of acoustic transmission through thin membranes within certain frequencies by making them inhomogeneous, by merging small blocks with the membranes, to create what is called “membranes with additional weights (MAW)”. This technology improves and increases the efficiency of acoustic insulation (Chmelík et al., 2015).

Structures created using membranes often have many acoustic problems such as echo, flutter echo, standing waves, sound focusing, etc., which significantly reduce the clarity of the sound talk. Tensioned membrane structures must ensure the highest level of loudness, sound energy, clarity and speech intelligibility in every part of the space (Chmelík et al., 2015). One of the biggest issues with textile membranes is how difficult it is to regulate echoes and noise accumulation in the mid- to high-frequency range for speech intelligibility, emergency sound systems, and public speech. Additionally, noise coming from a place enclosed by a membrane-skin facade could annoy nearby buildings and people. Environmental or external noise (airplanes, cars, railways) can be easily heard within a space that may distract occupants. So, it is also necessary to take into account external sounds (urban noise), and indoor sounds, along with rain noise, which is an important aspect that should not be overlooked (Chiu et al., 2015).

There are many different solutions to improve sound insulation in architectural membranes. In the case of "pneumatic structures", sound insulation can be improved by using "multi-layered membranes", which have air gaps between their layers or by adding porous materials inside the cushions. In "tensioned saddle-shaped structures", sound levels can be reduced by installing additional absorbing materials inside the membrane. Both of the latter solutions use absorption materials with micro perforations, which absorb sound and convert it into heat, reducing sound reverberation time and thus lowering noise levels (Fiúza, 2016). Another important point to mention is the "building's shape". For example, buildings with a "concave shape" will effortlessly reflect internal sound waves so that the sound is collected in one area and not another, causing a high concentration of sound energy (sound focusing phenomenon), and a high sound level in that area, which is a bad thing and should be avoided. While buildings with a "convex shape (hyperbolic shape)" will blend sound more easily than those with a concave shape, as they disperse, reflect, and spread sound energy and distribute it evenly within the space (Chmelík et al., 2015; Fiúza, 2016).

Table 3. The Most Prominent Important Thermal, Optical/ Visual and Acoustic Properties of Architectural Membranes
Source: Author

Characteristics	Textile Materials	Traditional Materials
Thermal Characteristics	- The thermal conductivity (U-value) is at its highest levels, which is about (5 W/m2.K).	- (U-value) is at its lowest levels, which is about (0.2 W/m2. K)
	- Thickness, mass and thermal conductivity, are have no importance for architectural textiles.	- Thickness, mass and thermal conductivity are the basis of conventional thermal analysis.
	- Thermal resistance (R-value) is at its lowest levels, where (R-value) of the base material for a	- (R-value) is at its highest levels, where it is likely to be

	thin architectural fabric could represent only (1 %) of the total resistance.	more than (90 %) of the total resistance.
	- Thermal insulation is at its lowest levels. Membrane manufacturers have addressed this issue by the production of heat-insulated membranes with very high (R-values); with a high thermal resistance.	- Thermal insulation is at its highest levels for concrete, brick and stones, while less in metal and the least in glass.
	- Its thermal behavior entirely depends on "surface heat exchange" due to the low thickness of the textile membranes. That is, it has a low thermal mass (it does not have the ability to store heat).	- In the traditional structure, thermal resistance (R-value) of the materials is dominant, thus, the heat conduction across the building envelope is proportional to the difference of air temperature on its surfaces (internal and external surfaces). As for the "surface resistance" of traditional building materials, it is neglected because its effect is very low when calculating the value of the coefficient (R-value). Priority is given to the resistance of the material itself, as it gives accurate and reasonable results.
Visual Characteristics	- Unlike most structural materials commonly used in the building industry, textile membranes offer a special feature of "translucency" with varying acceptable levels, which in turn provide varying degrees of light transmittance. The light transmittance of coated woven membranes is about (0-40%), and reaches (90 %) for foils.	- Most conventional materials are solid and have no "translucency", except the "glass".
	- High reflectivity, up to 70%. This feature is very useful, especially in areas with hot climates, as it reduces cooling requirements in summer.	- Less reflectivity.
	- Low levels of solar absorption.	- High to medium levels of solar absorption.
	-Textile membranes might be completely transparent, but their optical properties are totally different from those of glass.	- Glass has a high transmittance to solar radiation and very little reflection compared to textile membranes. As the angle of incidence of solar radiation increases, the level of reflection increases, and thus the transmittance is lower.
Acoustic Characteristics	- For textile membranes, sound insulation and sound absorption at its lowest levels (acoustically transparent). Acoustic defects can be fixed to achieve sound insulation as follows:	- Traditional materials have better sound insulation and sound absorption compared to textile membranes.
	•For pneumatic structures:	

	Using multi-layer membranes that contain air gaps between their layers. Adding porous materials inside the pillows.	
	•For tensioned structures: Installation of porous absorption materials with additional fine holes installed inside the membrane.	
	•Interior spaces: Using double-layer membranes as sound-absorbing elements, as dividing partitions in the interior space.	
	• Building shape: Internal concave shape: It easily reflects internal sound waves and focuses the sound in the concave part. Buildings with a convex shape: reflect and mix sound more easily than those with a concave shape.	

3.2. Recycling

"Recycling" process is one of the treatments that textile materials are subjected to after the end of their life span. This process represents one of the main stages in the sustainable construction industry. It involves recycling the polymeric materials that make up textile membranes with the aim of producing “new materials” made from recycled ones. The possibility of recycling membrane materials contributes to reducing their impact on the environment. However, environmental scientists are still concerned about the environmental damage that occurs during the manufacturing process of materials such as (PVC), because it contains chlorine, which is then used for sterilization of drinking water (Hartwig & Zeumer, 2011). With the use of textiles, the goal is to make the product "replaceable" or "recyclable", rather than disposable products that are later buried, incinerated, or dumped in open areas at the end of its life span. Therefore, recycling is preferable for architectural uses. Not all membrane materials can be recycled, so this process is directly dependent on the type of polymeric material used (Alioğlu, 2018). The environmental impact of the most prominent types of textile membranes can be summarized in Table (4), as follows:

Table 4. The Environmental Impact of The Most Prominent Types of Textile Membranes
Source: Author

Membrane Type	Environmental Impact
PVC (polyvinyl chloride) coated polyester	With regard to the environmental impact, both PVC and polyester can be recycled, in addition to the possibility of decomposing PVC into chlorine (chlorine gas) and hydrochloric acid, and these two materials can be reused in industry as well (Knippers et al., 2011).
PTFE coated fiberglass	Both PVC and polyester can be recycled, in addition to the possibility of decomposing PVC into chlorine gas and hydrochloric acid, and these two materials can be reused in industry as well (Knippers et al., 2011).
ETFE Membrane	It can be recycled (100) % (Alioglu & Sirel, 2018). Its use contributes to reducing carbon dioxide emissions (Supartono et al., 2011b).
ePTFE Membrane / Expanded PTFE Sheeting	In terms of environmental impact, it does not contribute to the depletion of the ozone layer, unlike chloro-fluoro carbons (CFCs). It does not contain chlorine, and does not contribute to the formation of carcinogenic chloro-bromo-dioxins. In addition, it does not contain plasticizers or stabilizers (Sefar Architecture, 2017).

	This type of membrane can be recycled, so it can be classified as a sustainable material (Belt, 2006).
HDPE (High-density polyethylene) Membrane	It can be recycled 100% (Lewis, 2009).
PVDF (Polyvinylidene fluoride) Membrane	It can be recycled (Houtman, 2015).
ECTFE (High clarity ECTFE film/ foil)	It can be recycled (Paech, 2016).

3.3. Adaptation to the Surrounding Environment: The Urban and Cultural Context

Adaptation with the surrounding environment, and the urban and cultural context is one of the most crucial features of sustainable textile architecture structures. Asefi & Kronenburg point out that architectural fabric structures, particularly when used in temporary architecture, must be transformable, flexible, as well as adaptable to environmental changes. This is not only restricted to regional environmental changes, but it must also have the potential and ability to be successfully used in a variety of environmental conditions throughout the year, in all seasons, and in various locations. The use of lightweight, flexible materials and the integration of structural and architectural components are the two key elements in the design of both permanent and temporary fabric structures that allow them to interact with their surroundings (Asefi & Kronenburg, 2016). According to Fox & Kemp, the social and urban changes that come along with sustainability challenges in architecture have increased the demand for interactive architectural solutions, resulting in designs that adapt to human demands within the surrounding environment and the urban context. Textile structures are also characterized by the possibility of being used in a way that makes them aesthetically pleasing and harmonious with the cultural environment in which they serve and are located, in addition to serving the effectiveness and function for which they were created or designed (Megahed, 2018). "Form" and "climate" are prioritized in architectural design and construction in order to adapt to the "surrounding environment". While priority is given to the "form", which comprises (space, shape, scale, and materials), in addition to "activity patterns" and "climate patterns", when adapting to the "urban context and the built environment", since the aspect of adapting to the surroundings represents a significant point. In architectural design, this helps and enables the designer to facilitate the process of adapting to the conditions of the contextual environment and adapting it to the surrounding urban conditions. Here, environmental adaptation includes changing the "form" in response to climatic conditions to meet the user's needs (Fouad, 2012).

As an illustration of this is the "Loud Shadows" project, which is a thin and transparent temporary inflatable structure manufactured, produced and implemented by the German company (Plastique Fantastique), in the context of the annual “Oerol” festival of music, arts and dance that is held inside the forest, on the island of (Terschelling), in Netherlands, 2017. The project, which is divided into four sections, was planned by taking into account the distinct location of each tree in each section of the "Forumforest". Each element of this project is integrated with its environment: the first transparent spherical airframe is pierced by a tree, while the second spherical airframe (translucent white) is squeezed between tree branches and is cast in their shadows. Regarding the inflatable air ring (the third space), it connects the two inflatable balls around the pine and oak trees. While the forest that surrounds the “Loud Shadows” project, represents (the fourth space) (Plastique Fantastique, 2021). The audience is free to move, rotate, and take any position within this mixture, whether in the transparent spherical structure, the white ball, the inner circle within the inflatable air ring, or the surrounding forest (Plastique Fantastique, 2021). This structure is a hybrid between architecture and arts. Despite its huge monumental size, the membrane blends gently with the natural surroundings, while creating a transparent, reciprocal conversation between its transparent shell and the activities or events taking place in the surrounding environment (the forest). In other words, the ephemeral, translucent shell has an impact on the surroundings to the extent that its interior environment and space allow for visual communication and a clear view of the outside (Mazzola & Liuti, 2018). This project represents adaptability with the surrounding environment and the cultural context by blending and integrating with the Mother Nature, while the transparency of textile structure allows to keeping in touch visually with the surrounding environment at the same time.

Another example is the foldable membrane structure of the "Quba Mosque" in Medina, Saudi Arabia, designed by (Bodo Rasch), 1987. This shelter protects the occupants during the day from the intense sunlight of the desert before retracting and closing in the evening, to allow for ventilation and cooling. When open during the daytime, direct sunlight is kept out from entering the interior space. While at night, heat is allowed and permitted to be reflected and radiated outside the courtyard (Asefi & Kronenburg, 2016). The fact that this membrane, despite being modern, it has historical precedent in the form of traditional cable-tensioned structures, makes it architecturally compatible with its surrounding context. The membrane's environmental interaction is controlled by a system that allows any necessary modification in opening and closing times based on changes in ambient temperature. Functional flexibility and adaptability are achieved and obtained, because there is no internal support due to the hanging mechanism of the folding membrane (Asefi & Kronenburg, 2016). This kind of adaptability represents adaptation with the surrounding environment and the cultural context by the change of shape and form of the textile structure "as a retractable and foldable shelter" to protect the prayers form the direct sunlight during the hot summer days when opening, while allowing for air ventilation in closing mode during the night.

Another illustration is the retractile membrane roof covering the inner courtyard of the heritage military building, known as the "Carré des Arts", in Mons, Belgium, in 2014, at the "Festival au Carré". The space can accommodate up to 1,200 people. This courtyard, which is also the largest open courtyard in the city center, is covered by five large membrane vaults that respond and complement with the design and rhythm of the building's arches (complement the structure's architectural rhythm and form). The membranes can be completely removed, preserving the heritage building intact without affecting and changing its traditional design. The unique structure was created to facilitate quick and simple ground handling and to incorporate all structural reinforcements into the concrete's thickness that already exists (Archdaily, 2014). Here, the textile structure completely integrates with the cultural context, where it has five arch-shaped vaults inspired by the design of the building and its traditional style. This supports the term 'Affective Perception' caused by the 'cultural attributes' of the built environment that arouse emotional responses to certain stimuli (Al-Alwan et al., 2022; Qeisi &Al-Alwan, 2021). It also helps in protecting the inhabitants form harsh weather conditions during winter and summer seasons within fast and ease retracting and folding mechanism.

4. Conclusions

This paper concludes the following

- Textile architecture is currently being utilized to create a variety of aesthetically acceptable and functional forms and structures. It has been in use from ancient times until the present.
- They have both negative and positive characteristics. Its disadvantages is that it has high (U-values), which means that, its thermal conductivity value is very high as a result of its low thickness and low mass, and therefore its thermal insulation values are very low, which makes it greatly interact with the environmental variables surrounding it, in order to reflect the ambient temperature of the environment during the day or night.

  The low thickness of the textile structures makes the process of heat transfer in textile membranes mainly through the surface of the membrane, in contrast to traditional building materials, where surface effects are neglected. As for its advantages, it is possible to provide membranes with high thermal insulation, with a high coefficient (R-value). The thermal behavior of textile structures is determined by combining two concepts: the value of the (U-coefficient) and the (shading coefficient), which are basically applied to the solar heat gain through the glass. In other words, providing thermal comfort for occupants using textile materials considers a mean of sustainability from an environmental point of view.

- The light transmittance property through the fabric skin must achieve the maximum transmittance of natural daylight inside the building. The transparency of the membranes controls the penetration of light into the building, as it gives a sense brightness of its internal spaces (internal environment), and creates a comfortable interior lighting environment, free of glare, and brings joy to the occupants. At the same time, it reduces the need for electric lighting consumption (artificial lighting). That is to say, it contributes to saving and reducing the amount and costs of energy used for mechanically controlled lighting and cooling purposes. The visual /optical properties of textile membranes change dramatically, as the angle of incidence of solar radiation increases, the reflectance increases, and the transmittance decreases. The high reflectivity and low absorption characteristic of textile membranes contribute to reducing the heat that enters the building during the day, and increasing its reflection outside with low temperatures at night. This feature is very beneficial, especially in hot climates regions, as it reduces the cooling requirements in summer. Thus, reducing amounts of consumed energy using textiles, increases environmental sustainability of textile architecture.
- Textile membranes do not provide good acoustic insulation (do not insulate or absorb significant amounts of sound energy) due to their low weight and mass. Therefore, membranes are poor acoustic insulators. Sometimes acoustic transparency is a positive attribute, as reflected sound can enhance the reflected acoustic energy in an indoor space, such as in the design of sports stadiums where crowd noise can enhance the sense of excitement. As for the response of membranes to the acoustic properties (the most prominent of which are the sound absorption property, the acoustic reflection property, and the acoustic permeability), they are variable and unstable, and depend on the thickness and weight characteristics of the material, the sound frequency, the type of material (if it is solid, flexible, porous, or has a soft or rough texture), and the number of layers of the textile or membrane material.
  As for the acoustic defects represented by echo and noise, which negatively affect the clarity of speech, there are several solutions to overcome them to achieve sound insulation and improving the acoustic characteristics and clarity of speech. For "pneumatic structures", sound insulation can be improved by using multi-layered membranes that have air gaps between their layers, or by adding porous materials inside the cushions. For "tensioned structures", sound levels can be reduced by installing additional absorbing materials embedded within the membrane. Both of the latter solutions use absorption materials with micro perforations, which absorb sound and convert it into heat, thus, reducing sound reverberation time and lowering noise levels. While in "interior spaces", double-leaf membranes can also be used as special sound absorption elements (as partitions) in these spaces. In addition to the above mentioned solutions, the "building's shape" affects the process of achieving sound insulation, where buildings with an internal "concave shape" reflect internal sound waves easily but cause sound concentration in that area at the expense of the rest of the areas of the internal space, while buildings with a "convex shape/ hyperbolic shape" mix and reflect sound easily and distribute it more evenly throughout all areas of the interior space than those with a concave shape. All of these solutions lead to increasing the efficiency of architectural membranes and thus increasing their use. As a result, improving sound insulation in a specific space increases human's comfort, wellbeing, health and prosperity, thus providing environmentally sustainable textile architecture within its spaces, structures and enclosures.

- Recycling membrane materials contributes to reducing their environmental impact, making them environmentally sustainable. Instead of producing large quantities of products that can be used once and then disposing of them by burying, burning them or dumping them in open areas at the end of their life-span, they are recycled or replaced to produce new materials. In addition to reducing the costs and energy consumption in manufacturing and producing them, and reducing (CO_2) emitted from them during manufacturing and production processes after the end of their life cycle.
- Architectural fabric structures can adapt to their surrounding environment and their urban and cultural context through "form" and "shape", represented by the creation of environmentally responsive and transformable fabric structures (able to open and close in a mechanical manner under computer control), as well as the choice of color, details, the diversity of using textile materials, and the size and scale of the fabric structure used that serves various needs and functional activities are specific to humans, to meet the users' needs and provide them with comfort and protection from different climatic conditions, making them harmonious, adaptable and compatible with the surrounding urban and cultural context. Thus, textile membrane structures are one of the foreground structures that calls for environmental sustainability in textile architecture.

  This adaptation includes using it in different climatic conditions and in different seasons of the year, locations and positions, making it environmentally, functionally and economically efficient. What helps and contribute to achieve this efficiency and adaptation is, its light weight, flexibility, transparency of the textile material and the integration between the architectural and structural form as well, which makes it not negatively affect the basic design and the surrounding context (in in case of it is added to a particular project), but rather integrates with it, blends in, enriches and enhance it from the environmental, functional, visual and structural aspects. In addition to the possibility of using textile structures in a way that makes them consistent and harmonious with the cultural environment in which they serve and exist, as well as serving the effectiveness and function for which they were created and developed.
- When it comes to stabilizing entire structures and the usage of materials like PVC/polyester, PTFE/glass, PTFE/silicone, ePTFE (Tenara®), HDPE, PVDF, and ETFE, these approaches are both appropriate and suited for hot, humid, and hot, arid environments. The latter is the best sustainable textile membrane since it can withstand extreme heat and UV radiation, is lightweight, 90%–95% translucent, 100% recyclable, somewhat fire resistant, and costs less than glass panels.

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