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Nanotechnology As a Tool for Sustainability Towards A "Sustainable/Economic" Assessment Tool for Nanomaterials

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ABSTRACT

Technological development has a positive impact on all aspects. Sustainability is considered as a one of the most important contemporary trends, which can prevent life demands for the future. We can consider nanotechnology as a one of the modern science branches, which has achieved many developments in properties of materials with a positive impact, which have contributed to the development of many fields. So, the problem of the research can be determined in studying the integration between applied nanosciences and sustainability to introduce a system has a positive impact on sustainability through modern nanotechnologies, achieving higher levels of sustainability and advanced solutions for systems. The research aims to create an evaluation sustainable matrix for the nanomaterials that can be changed to a "sustainable/economic" scale for comparison and selection between alternatives of nanomaterials of the same applied field compared to the material in its traditional form. The study uses an organized methodology including firstly the study of the nanomaterials, and its important properties, secondly identifying the main properties for nanomaterials, which have a positive impact in achieving sustainability and thirdly creating the sustainable nanomaterials evaluation criteria to develop the proposed "sustainable/economic" tool to evaluate nanomaterial alternatives. The research provides a preliminary evaluation matrix depending on the material sustainability level and its economics and its division into four zones. The research provides also the classification of the nanothermal protection materials as a practical example to achieve the optimum sustainable building design.

KEY WORDS

Nanotechnology – Sustainable nanomaterials – sustainable materials evaluation – sustainable economic material selection.

النانو تكنولوجي كأداة لتحقيق الإستدامة
نحو أداة تقييمية"إستدامة / إقتصادية" للمواد النانوية

الملخص

التطور التكنولوجي المستمر في القرن الحديث كان له أكبر الأثر والمردود الإيجابي على كافة نواحي الحياة الأمر الذي يتضح معه كل يوم أهمية تطوير تلك العلوم الحديثة وتطويعها لخدمة البشرية، ويعتبر القطاع الهندسي من أهم القطاعات الخادمة للبشرية في مفهومها الحديث. وتعتبر الإستدامة من أهم التوجهات الحديثة التي تعتبر من أحد الوسائل التي تحفظ الحقوق الحياتية للأجيال القادمة والتي تعتبر مسؤولية الجيل الحالي تجاه البشرية. حيث يعتبر النانوتكنولوجي من أحد أفرع العلوم الحديثة والتي لاقت العديد من التطورات والمميزات والتي تطورت معها العديد من الأنظمة وخواص المواد بما كان له الأثر الإيجابي في استخلاص واكتشاف العديد من الخواص الفيزيائية والكيميائية الحديثة، والتي ساهمت في تطور المجالات التطبيقية الطبية – الصناعية –الهندسية - ....إلخ. وبناء على ذلك تكمن المشكلة البحثية في الحاجة إلى دراسة الدمج والتكامل ما بين العلوم التطبيقية النانوية ومفاهيم واستراتيجيات الإستدامة لتشكيل منظومة من خلالها يمكن تحقيق الأثر الإيجابي لتفعيل استدامة المواد من خلال التقنيات النانوية الحديثة محققا مستويات أعلى من نظم الإستدامة والحلول المتطورة للأنظمة والمواد التقليدية لصياغتها في صورتها الحديثة المحققة للإستدامة. يهدف البحث إلى استحداث مصفوفة تقييمية لقياس استدامة المواد النانوية يمكن تفعيلها لوضع مقياس "استدامة/إقتصادي" للمفاضلة والإختيار بين بدائل المواد

النانوية ذات نفس المجال التطبيقي مقارنة بالمادة في صورتها التقليدية وبيان مدى التطور النانوي الحادث للمادة. حيث تقدم الدراسة البحثية التصميم الأولي لمصفوفة تقييم للمواد النانوية إعتمادا على حساب مقدار إستدامة المادة وإقتصادياتها وتصنيفها إلى أربع مجموعات كركيزة للإختيار بين بدائل المواد النانوية. كما تناول البحث تصنيف مواد الحماية الحرارية النانوية كمثال عملي لتحقيق التصميم الأمثل للمباني المستدامة.

الكلمات الدالة:
النانوتكنولوجي، المواد النانوية المستدامة، التقييم المستدام للمواد، التقييم النانوي المستدام الإقتصادي.

INTRODUCTION

Trends calling for achieving environmental sustainability in all life areas have emerged since the 1970s. In 1987 the UN World Committee for Environment and Development held a global conference on development through which an official report entitled "Our Common Future" was issued. In this report (Alagarasi, 2011), sustainable development was defined as that which meets the requirements of the present without affecting the future needs of future generations.

The concepts of the sustainable development in the architecture and urbanism movement have been developed through the concepts, principles and strategies of sustainable architecture. For this objective, there developed several systems including LEED - BREEAM among others, which are based on evaluation criteria to achieve the required environmental sustainability. Recently, nanotechnology has been used in architectural buildings on a large scale that revolutionized architectural scientific progress. One of its most important applications was what was planned for many advanced solutions to environmental issues, which was used to develop systems and concepts of sustainable architecture.

1. NANOTECHNOLOGY: CONCEPT AND IMPORTANCE

1.1 Nanotechnology Definition

The word “nano” refers to everything that is so small and subtle that it cannot be seen with the naked eye (Soueid, 2011). The origin of that word refers to the Greek expression 'Nanos', which means dwarf. The 'nano' was used as a standard unit as 1 nanometer = 10^{-9} meters. Figure (1) represents a very subtle microscale. For example, the virus scale is 100 nanometers, the writing point is 1,000,000 nanometers, and the head hair diameter ranges from 50,000: 75,000 nanometers (Alagarasi, 2011).

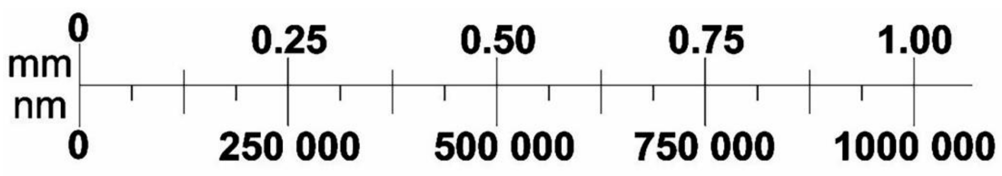

Figure (1). Millimeters to nanometers conversion scale, Source: The author.

1.2 Nanotechnology Field

Previous studies have concluded that the physical and chemical properties of the substance at the nanoscale differ from those of the same substance in its normal size. This resulted in the extraction and exploration of many new physical and chemical properties in what is known as nanotechnology (El-Habashy, 2011). Figure (2) refers to studying and discovering those emerging properties of substances in their nanostructures with dimensions ranging from 1:100 nanometers. It includes all the substances that were produced with granular measurements equal to 1:100 nanometers.

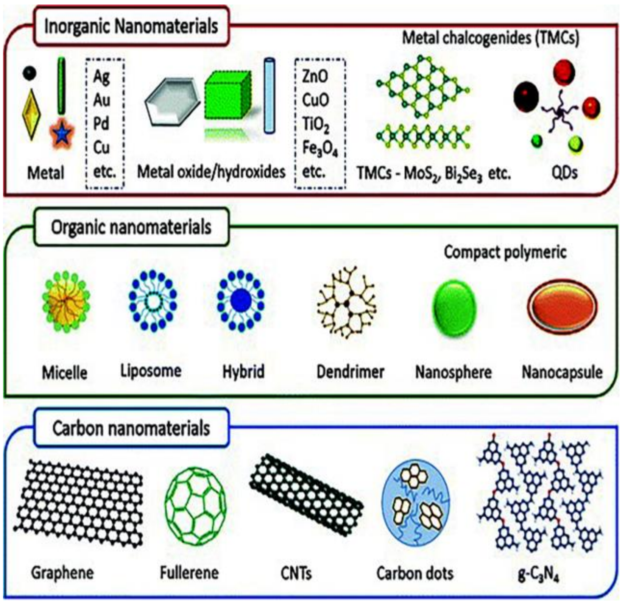

Figure (2). Nanomaterials samples, Source: Kumar & Ray, 2018.

1.3 Nanomaterials

As previously mentioned, they have advanced emerging properties not available in the substances in their traditional shape. That helped them being used in several fields including industries, medicine, treatment, engineering sciences, energy, ……… etc (Buzea, et al. 2007). in a more distinctive and advanced way, which in turn contributed to turn science fiction into tangible reality.

The nanomaterials have been classified according to several classifications that follow different criteria, namely, the dimensions, the formation stages, the manufacturing process. Table (1) shows the classification of those materials.

Table (1). Nanomaterial's classifications

Samples		**Classification**
Dimensions	The three dimensions are less than 100 nanometer.	Granules - Quantity Points - Hollow Balls.
	The two dimensions are less than 100 nanometer.	Pipes - wires - fibers – sheets.
	The one dimension is less than 100 nanometer.	Coating - chips - multiple layers.
Formation stages	Solid one-stage materials.	Amorphous and amorphous molecules – layers.
	Solid multiple-stage materials.	Matrix components - coated particles.
	Multiple-stage systems.	Colloidal materials – Aerogel.
Production process	The gas reaction stage.	Condensation - precipitation of chemical fumes.
	Water reaction stage.	The gel method – sol-gel.
	Mechanical process.	Mechanical milling - plastic deformation.

Source: Liang & Hodson, 2009.

2. NANOTECHNOLOGY APPLICATION FIELDS IN BUILDINGS

Nanotechnology was used in architectural buildings in the twenty-first century, bringing a technological revolution in all sectors and systems. First, it relies upon nanomaterials with their distinct and advanced technological characteristics (Sebestyen & Pollington, 2003). In the following part of this research, I'll handle the application fields of nanotechnology in architecture, indicating the most important nanomaterials that contributed to each application field concluding with its composition and sustainable advantages. Hence, nanotechnology has been used in the following fields (Ercolani, 2012):

- Energy systems and source field:
  - Traditional energy sources development.
  - Renewable energy systems.
  - Energy storage Methods.
- Thermal insulation materials.
- Glazing systems.
- Building envelope protection.
- Finishing materials.
- Construction materials and systems development:
  - Concrete Construction.
  - Steel construction.
  - The wooden construction.
  - Contemporary construction materials.
- Artificial lighting systems.
- Water conservation field.
- Internal spaces healthy environment.
- Nano Bioengineering field.

2.1 Energy Systems and Source Field

2.1.1 Traditional energy source development

1. Porous nanoparticle silica fluids:
Increasing oil production field by separating pollutants from refining substances and controlling its viscosity.
2. Solid nanocoating:
Increasing the resistance of the mechanical parts of the drilling screws of the oil equipment and the depth of drilling.

2.1.2 Renewable energy systems development

1. Thin layer silicon solar cells (De Luca & Nardini, 2002):
Making a very thin 1-nanometer-thick silicon incorporating hollow nanoparticle molecules from the following: fullerenes - silver - cadmium chloride - titanium dioxide TiO_2. This silicon has two advantages, first one that It increases the efficiency of absorbing different wavelengths of light by 80 watts/hour per 1 m2 of cells (Casini. 2016). And the second that It reduces carbon dioxide emissions as a result of using renewable energy by 1.62 tons annually (Casini. 2016).

2.Thin-layer Solar Cells:
Silicon has been replaced by other materials including copper - indium - gallium - sulfur - selenium as shown in Figure (3) and is characterized by the following:

- 20%higher efficiency than normal cells (100 W/ hr per 1 m2) (Sev & Ezel, 2014).
- 20% of the cost of silicon cells.
- The possibility of merging it with the layers of facades and windows due to its thickness.
- Savings on manufacturing materials and low temperature used in production.

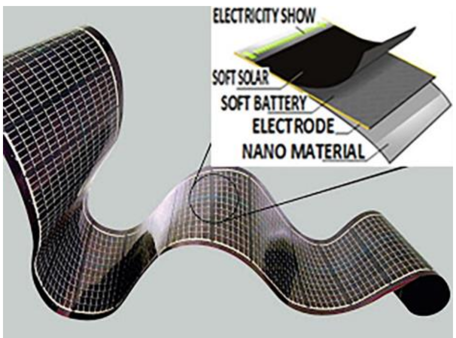

Figure (3). Thin layer solar cells, Source: Fatade, 2014.

3. Titanium Dioxide Nanoparticles in Dye Solar Cells (Arnall, 2003):

It is used in making solar cells made from pigment cells as shown in Figure (4). It has a Low manufacturing cost compared to silicon cell and transparency with the ability to design cell colors that can be integrated with building elements. However, its efficiency is 10% less compared to the conventional cells (Fouad, 2012) with the possibility of leakage through the electrolyte liquid.

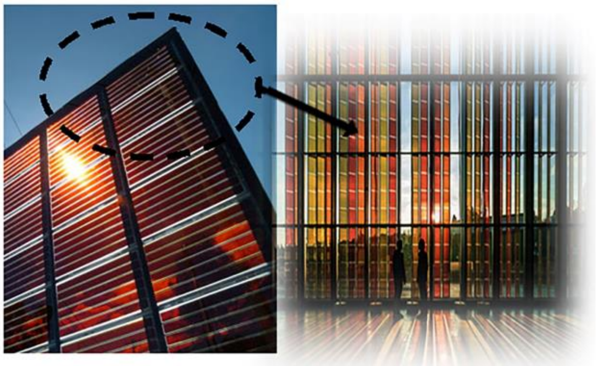
Figure (4). Colored solar cells, Source: The author.

4. Quantum Dots for Solar Cells (Sev & Ezel, 2014):

Micronanomaterials that make higher energy semiconductors lead to more than one photon release and it has more cell efficiency up to 60% than the conventional types. Figure (5) shows the conceptual cells form and mechanism.

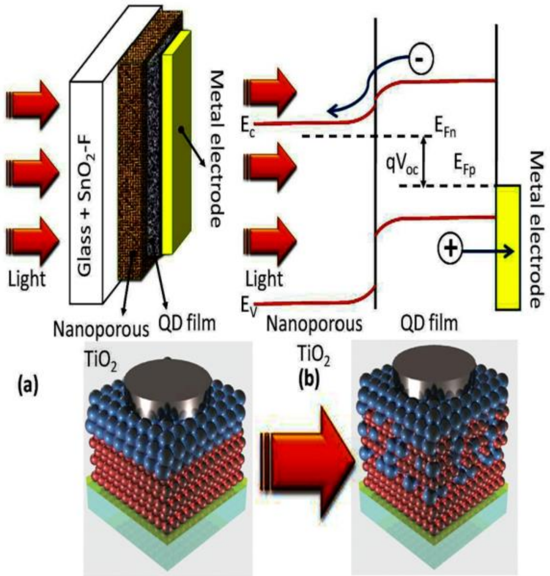

Figure (5). (a) Diagram of Depleted-hetero function Colloidal Quantum Dots Solar Cells, (b) energy band diagram, Source: Kosyachenko, 2015.

5. Nanostructured Antireflection Layers:

Silicon dioxide coating with nanopores that reduces light reflection loss from 2: 8% and increases the heating area of solar collectors to 10%.

6. Carbon nanotubes from composite materials (Elvin, 2009):

Can be used in Manufacturing lightweight wind turbine fan panels. It is characterized by reducing turbine noise intensity and extending the lifespan and lightning strike protection. Figure (6) shows its main structure model.

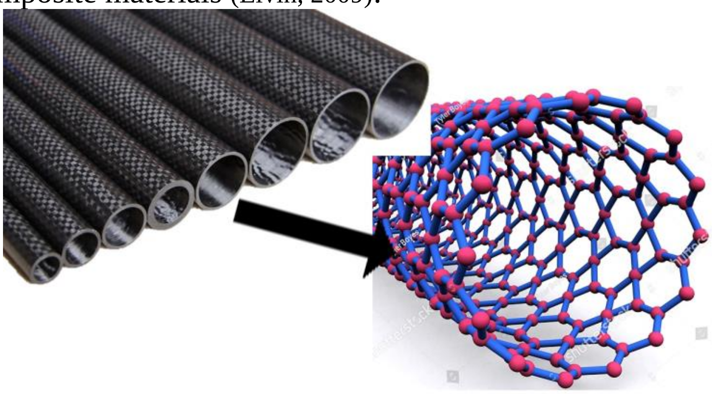
Figure (6). Nanocarbon tubes, Source: The author.

2.1.3 Energy storage Methods

1. Flexible batteries:

The paper mixed with carbon nanotubes along with a lithium layer between aluminum foil, we can use them with flexible solar cells and merging them with the architectural elements of the building.

2.2 Construction Materials and Systems Development

2.2.1 Concrete construction

Nanotechnology has particularly contributed to the development of the concrete materials, which has the greatest impact on reducing the negative of the traditional concrete, represented as follows (Mann, 2006):

- Carbon materials and waste emissions during the manufacturing phase reach 1.3 tons of carbon dioxide per 1 ton of concrete (Atwa, et al. 2015).
- This amount is equivalent to 8% of the total carbon dioxide emissions.
- The recycling rate is only 5% of concrete waste (Mohamed. 2015).

1. Green nanoconcrete (celetmete):

The manufacturing possibility in furnaces with a temperature of 200 Celsius degrees with less gear amounts instead of 1450 Celsius degrees (Mohamed, 2015). This is characterized by the following:

- Carbon dioxide emissions reduction by 50% (Mohamed. 2015).
- Denser, more durable and requiring less time for drying,
- The ability to absorb carbon dioxide from the air.

2. Porous nano concrete (Mohamed, 2015):

It is produced by using very little or no quantities as shown in Figure (7). This allows air movement through concrete pores and water to drain through it when needed.

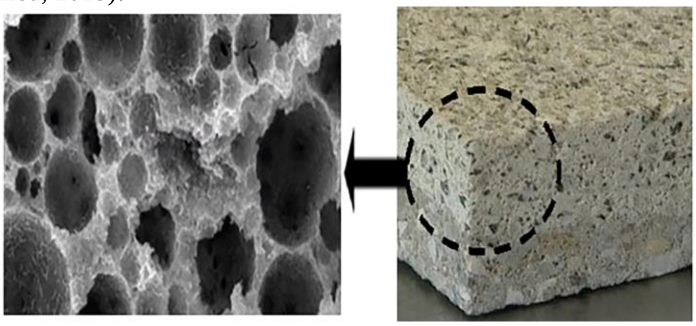

Figure (7). Nano pours concrete, Source: Mohamed, 2015

3. Transparent nano concrete (Mann, 2006):

Thin concrete with the addition of 5% of optical glass fibers is characterized by the following:

- The optical fibers connecting one side of the concrete to the other allow the light to be transmitted through it. Figure (8) contributes an example for its use.
- Using solar radiation as a source for natural lighting for interior space.
- Contributing to reducing energy consumption.

Figure (8). Nanotransparent concrete, Source: Skyfi, (2021)

4. High performance nanoconcrete:
It consists of adding polymer artificial resins that improve the concrete efficiency in terms of tensile strength.

5. Advanced nano concrete (Higgins, 1994):
It consists of adding nanoparticle silica oxide and nanotitanium oxide. Figure (9) shows Nanoconcrete compressive strength for (3%) nano (SiO2) addition. It is characterized by the following:

- Being used in constructing roads based on its ability to purify carbon monoxide from car exhaust.
- Increasing concrete strength and durability by 10 times.
- Its white color is effective, with multiple positive environmental effects.
- The ability to filter water by dams and water canal projects.

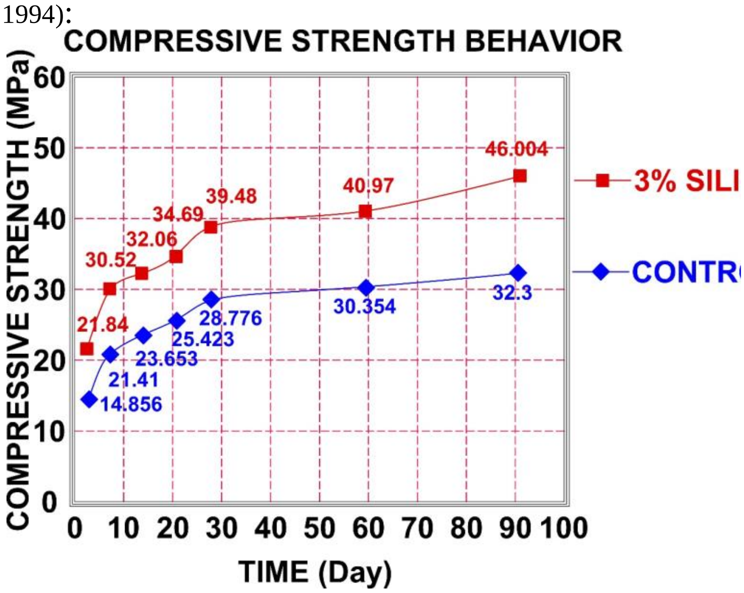

Figure (9). Nanoconcrete compressive strength for (3%) nano (SiO2) addition, Source: Rasin et al, 2017.

6. Self-Healing Concrete:
A healing factor and a chemical catalyst are incorporated into the epoxy matrix, which has the ability to self-treat cracks. This is characterized by self-medication in case of rupture, to regain 75% of its strength (Quercia, et al, 2010). This increases its lifespan from 3 to 2 times.

7. Absorptive concrete:
It consists of nanocement atoms and nanofibers, which gives it a lower percentage of carbon dioxide pollution at the manufacturing stage. It does not absorb fluids and water with a production and maintenance low cost.

2.2.2 Steel construction

It is manufactured by adding nanomaterials of copper, magnesium and calcium particles in an attempt to achieve the following:

- Improving the bonding of iron particles.
- Increasing its resistance to corrosion and heat.
- Reducing the effects of hydrogen fragility.
- Increasing the bending strength of iron.

The following are examples of the most famous types of nanoiron and its most important features:

1. MMFX/MMFX2 nano steel (Mann, 2006):
It has a crack resistant more than 5 times as shown in Figure (10) so it is used by about 20: 50% less than iron Grade60. It is characterized by reducing labor costs to 60%.

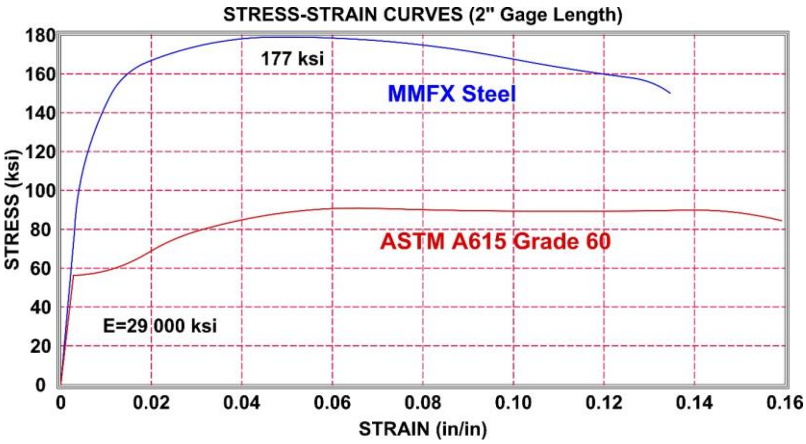

Figure (10). Stress-Strain Behavior of MMFX Steel, Source: Malhas, 2016.

2. Nanosteel CF and Guardian/SANDVIK:
It can be used as a good surface finishing and formability due to its hardness, light weight, rust resistance and longevity.

2.2.3 Wooden construction

This is done by adding nanomaterials to improve the wood performance and endow it with sustainability:

- **Nanoaluminum oxide:** Increases the hardness and resistance to erosion and scratch.
- **Iron oxide and titanium dioxide:** Protect the wood from ultraviolet rays, resist fungi, and extend life time.
- **Nano Silica:** Increase the hardness of wood and prevent water leakage.

The following table No. (2) shows the examples of the most common types of nanowood.

Table (2). Nanowood types

Nanowood type	features
Wood with cellulose nanocrystals	The increase in the tensile and permeability coefficient.
Wood with cellulose nanofibers	Tensile strength up to 7.5 GPa and hardness degree of 145 GPa, equivalent to the strength of carbon nanotubes used in the armament.
Wood with plastic components (PVC / PP / PE)	Weatherproof ability and environmentally safe.

Source: The author

2.2.4 Contemporary construction materials

Nanotechnology contributed to the creation of new structural materials such as carbon nanotubes, which consist of a flat carbon plate with a single atom thickness wrapped in a cylindrical shape with a diameter ranging from 1 nanometer to a few nanometers. Figure (11) shows its types which can be either Single-Walled CNT or Multi-Walled CNT. They are characterized by the following:

- Thirty to 100 times more hardness than steel that reach 0.16 of its density.
- Thermal conductivity is higher than copper conductivity.
- Versatility, as skybridge cables with lifespan 3 times higher, wind turbines.
- The development of concrete properties when used in armament, including the increase of its compressive strength to 70% more, less density 50%, reducing thermal conductivity from 12 to 20%, which make concrete more sustainable.

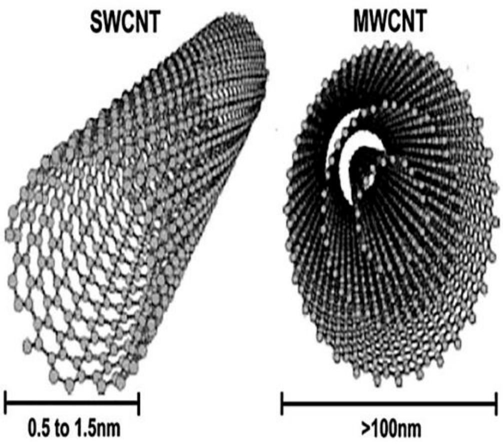

Figure (11). Nano carbon tubes, Source: Fatade, 2014.

These materials have also been developed to become **carbon nanotubes**, which are stronger than steel and transparent layers with a high conductivity of heat and electricity. They effectively contribute to energy saving by using them as electrode in the organic diode OLEDs.

2.3 Thermal Insulation Materials

Nanotechnology has contributed to providing 30% more efficient insulation materials than conventional ones. Some of the most important examples are the following:

1. Aerogel (Kibert, 2007):

It consists of silica and nanocarbon in the form of a generation whose liquid component has been replaced by gas to develop a solid called frozen smoke. It contains 5% solids and 95% air as shown in Figure (12). It is characterized by the following:

- Thermal insulation efficiency given that the thermal conductivity coefficient reaches 0.018 W/M. K. only.
- Its airspace helps increase its efficiency in sound insulation.
- Transmittance to light in a glare-free image.
- It is effective in thermal insulation between glass panels.
- Waterproof, which makes it against moisture and mold.
- Suitable for acoustic insulation between interior spaces of buildings.


Figure (12). Aerogel, Source: Lanning, 2019

2. Vacuum Insulation Panels "VIPs":

It consists of foam and nanoglass fibers of porous material that is discharged from the air and is covered with an outer insulating layer of plastic or aluminium. Figure (13) contributes its form. These panels' final thickness reaches between 2: 40 millimeters. They enjoy the following characteristics (Hornyak et al, 2008):

- Low thermal conductivity of up to 0.035 W/m. Kelvin, which equals only 10% of the conductivity coefficient of the conventional insulation materials.
- The lifespan is between 30:50 years with recyclability.

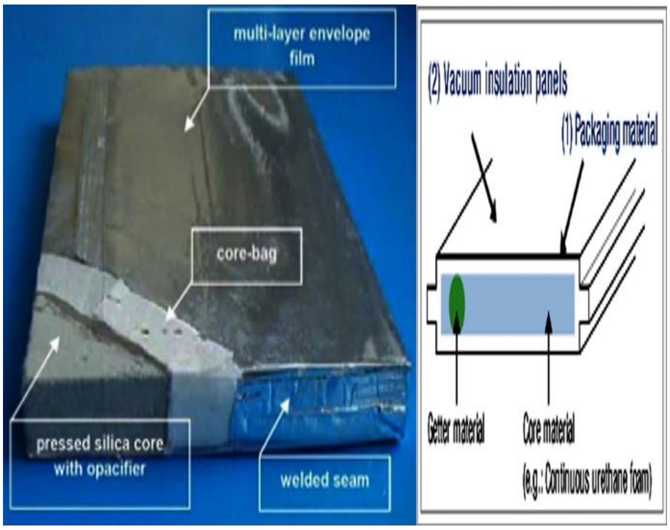

Figure (13). Vacuum insulation panels, Source: Hornyak et al, 2008.

- Perfectly suited for existing buildings' modernization and upgrading to increase their efficiency in thermal insulation.
- Providing more interior spaces when used instead of the traditional materials due to their thickness.

However, one of its drawbacks is that the end of the panels is tightly closed and hence these panels into different surfaces; they must be made with the previously required sizes.

3. Thin film insulation:

Thin nanofilms work to reduce the permeability of the solar load, such as glass-insulating nanopaint or nanocoated fibers, stainless steel film as shown in Figure (14). Among their main advantages are the following:

- The ability to absorb infrared and ultraviolet rays and prevent 99% of them.
- Allowing light to pass through by up to 61%.
- Reducing the internal vacuum temperature between 2: 3 Celsius Degree.
- The advanced types of silicon dioxide and titanium dioxide are anti-reflective with a rate of only 1.05%.

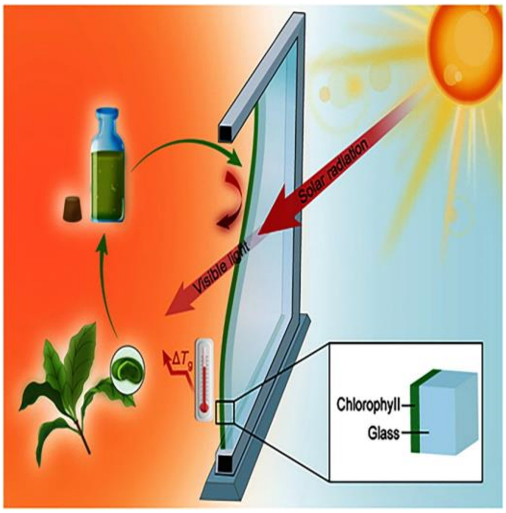

Figure (14). Thin film insulation, Source: The author.

2.4 Artificial Lighting Systems

1. Light Emitting Diode (LED):

Light is produced in it by two asymmetrical semiconductors when the voltage reaches the intersection between the materials. It is characterized by the following (Morrison, 2005):

- The lifespan of 35: 50 thousand hours compared to other types up to 8 thousand hours.

- It consumes only 20% electricity rate than other types.
- Reducing carbon emissions by 300 tons annually.
- Higher efficiency with less heat radiation, as it saves about 3.5 × 10 5 thermal units annually.
- Reliance on it will reduce the energy required for lighting in half by 2025 AD.

2. Organic Light Emitting Diode (OLED):

It consists of a layer of thin nanofilms from organic compounds that emit light in response to the electrical current. Its layers can be determined from Figure (15). It has the following features:

- High flexibility that can be aesthetically used with the building elements.
- It is extremely thin that can be formed on any surface of the building.

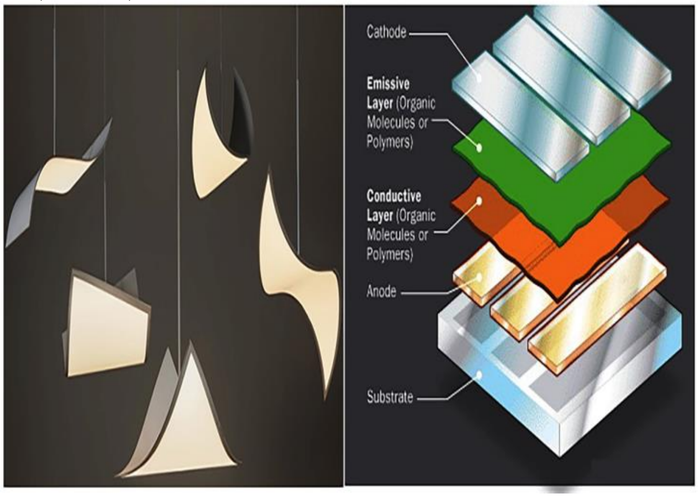

Figure (15). OLED's structure, Source: Navaneetha, et al, 2016.

- Long lifespan and low economic cost in production.
- The possibility of merging it with the components of the building, especially the windows, in order to simulate the landscape lighting.

2.5 Glazing Systems

Nanomaterials have contributed to the change of many glass-properties in a positive effective way. This is useful in reducing negative environmental impacts on buildings resulting from the use of the traditional types of glass. Table No. (3) shows the most important nanomaterials and their positive impact on the glass properties.

Table (3). The effect of nanomaterials on the properties of glass

Nano-material	The positive effect
Tio2	Pollution resistance - water flushing - optical self-cleaning.
Sio2	A coating layer between the glass layers to protect from the impact of solar radiation.
Zno + Tio2 + N2	Water flushing - Generating a solar anti-radiation glass surface.
VO2 – Based	The change glass color and temperature.
VIO2–Based / Nio-Based	The change glass color by electric waves.

Source: The author

The most important general features of nanoglass common in its multiple types can be mentioned in the following points (Spinelli, et al, 2013):

- Anti-fog and self-cleaning feature.
- The ability to control the intensity of the window lighting.
- Preventing solar radiation thermal leaks.

- Contributing to the reduction of the energy consumed.
- Inverting ultraviolet rays.
- Acting as a heating source in some types that have the ability to store heat and re-broadcast it to the internal vacuum if it falls under the thermal comfort area.

The most important nanotechnology of some types of advanced glass and the most important additional characteristics of each type can be shown in table No. (4).

Table (4). The advanced nanoglass properties

Nanoglass type	Properties
Thin Film glass coatings	It uses sensitive layers of titanium dioxide TiO2, Zno, and Ceroxide that help reduce thermal gain, protect against ultraviolet rays, absorb UV-B-rich rays and reduce UV-A.
Thermochromic glass	It can absorb heat equivalent to a 15-centimeter-thick concrete wall, through salt hydrates as packing substances inside the glass, which has a positive effect in storing the latent heat of the solar radiation, to achieve thermal protection for the inner space.
Electro chromic glass	Coating with tungsten oxide turns dark without electrical current.
Fire rated glass	Through the use of silica nanoparticles with dimensions less than 7 nanometers between glass panels, it expands in the form of foam that prevents fire from spreading for more than 120 min. in addition to its efficiency in isolating noise.
Heat absorption glass	The nanocoating of indium oxide, tin oxide, lithium solution, and the electrode network that control the transparency of the paint, as the nanoparticles absorb the heat of the solar radiation converting it into an electrical current that contributes to reducing the electrical energy consumed in the building.
Multifunctions glass	Through surface nanotextile paints, the properties of glass can be stimulated to achieve several positive properties such as self-cleaning and fog resistance, anti-reflective, energy consumption reduction, the achievement of safe and healthy indoor environmental conditions, and the reduction of negative impact on the external environment.

Source: The author

2.6 Water Conservation

Nanotechnology acts as a major tool in water conservation field, for example table No. (5) shows the major applied examples for that.

Table (5). The advanced nanoglass properties

Nanofilter type	Properties
Nano filters	It is characterized by its ability to remove impurities up to a size of 25 nanometers by 99.99% through carbon tube filters and the 3-layer nanooxidized aluminum filters (nanocarbon - nanosilver - nanocopper and zinc) with small nanopore membranes (Roco, et al, 2011).
Nanomaterials catalysts	Through the use of titanium dioxide and nanoiron to remove salts and minerals.

Nanofilter type	Properties
Gold nanoparticles	Gold nanoparticles covered with a thin layer of palladium are used. Through them, the groundwater can be purified from toxic compounds, namely, TCE
Nanosensors	In it, water pollutants are detected without the need to perform sample analysis, providing the energy needed to perform these analyses

Source: The author

2.7 Building Envelope Protection

Nanotechnology acts as a major tool in providing thin layers that are deposited on the external envelope materials and its importance in improving its sustainable properties, for example:

2.7.1 Self-cleaning layer

1. Artificial lotus surfaces:

By using nanotechnology to generate a rough surface with small protrusions, pointed ends, and a mixture of wax on these ends to depend on the formation of water as small grains descending to take all the dust along with it. Figure (16) shows an example for the artificial lotus surface. It still has some negative which can be listed as follows:

- Not suitable for floors, as it cannot stand friction forces.
- It needs to be renewed every 5 years.
- In case there are a few drops of water; they cannot descend and hence cause dry spots on the surface.

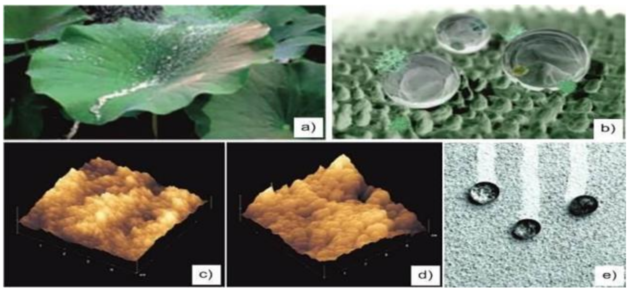

Figure (16). Artificial lotus surface, Source: The author.

2. Optical stimulation:

It is the outer layers of titanium oxide nanoparticles, where photocatalysis breaks the dust by exposure to ultraviolet radiation and shovels it by rain. It can be applied to glass or ceramic and it has an anti-bacteria and reflection surface.

3. Easy surface cleaning:

They are smooth surfaces with low surface energy to reduce the surface adhesion between them and water droplets. It is commonly used in the outer layers of ceramics of the sanitary installations.

2.7.2 Anti-fog external layer

It can be achieved by using one of two techniques. The first technique includes the use of titanium oxide (TiO_2) outer layer with high surface energy on the nanoscale. The second technique is using glass with nanopores that cannot be seen with the naked eye in its outer layer. The moisture is directed to it to prevent the formation of water droplets on the glass outer surface. These techniques can be used to provide the thermal energy used in the traditional methods for removing fog from surfaces.

2.7.3 Scratch-resistant external layer

Through an inorganic filling of 40 to 60 nanometers of ZrO2, SiO2, and ALOOH, this layer is scratch resistant while maintaining the transparency of the outer layer (Leydecker, 2008).

2.7.4 Anti-bacteria external layer

Through the use of nanoparticles from antibacterial and antimicrobial solids

2.7.5 Anti-microbe's layer

It is suitable for stainless steel and glass surfaces by using nanolayers with the characteristics of exploiting light refraction in the same way as fingerprints.

2.7.6 Self-cleaning paints

It has two techniques. The first is through nanopaint that contains a biocide of silver particles and titanium dioxide. The second is through a mixture of microscopic hollow spherical ceramic granular compounds on the nanoscale. It has the following features:

- Analysing bacteria, microbes, and dust.
- Reversing and dispersing the solar radiation, which helps in providing the energy needed to provide the thermal comfort to the internal space.

2.8 Healthy Environments for Internal Spaces

The quality of the internal air is considered one of the most important factors for the functional success of the building and among the most important sustainability elements upon which the provision of a healthy environment suitable for the users of the internal spaces depends. Nanotechnology has contributed to providing nanofilters that have had an effective positive environmental impact on providing the required healthy environment, namely:

1. Nano-Titanium filters:

It uses 5-nanometer titanium dioxide particles to provide ventilation filters that eliminate odors and dust from the internal space (Roco, et al, 2011).

2. Nano e-HEPA filters (electric High Particulate Arrest):

Here, dust coated with 8-nanometer silver particles is used to eliminate unpleasant odors and fumes from volatile organic compounds (VOCs) from paint and overcome viruses (National Institute, 2009).

3. NCCO Filters (Nano-Confined Catalytic Oxidation):

They are nanopores that separate pollutants greater than 0.3 micrometer and analyse them into harmless oxides of excellent and safe air purification, removal of viruses and bacteria and the removal of harmful VOCs (National Institute, 2009).

2.9 Finishing Materials

2.9.1 Nanocoatings

Nanotechnology contributes to the development of coating layers, as shown in table No. (6), there are several examples for the nanocoating materials with special advanced properties.

Table (6). The advanced nanocoating properties

Nanocoating type	Properties
Nano-Z Paint	A transparent coating of nanoparticle-artificial zinc oxide is effective in protecting wood from moisture and resisting decomposition, mold and insect attack.
Fire rated paints	Coating with carbon nanotubes with cement and polypropylene fibers are less expensive than traditional fire insulation materials.
Nanoelastic materials	A series of atoms of carbon atom as a basis with silicon, oxygen and sulphur atoms of a thickness up to 1 nanometer, characterized by their endurance up to a temperature of 700 Celsius degrees and their strength increases with the increased temperature (Leydecker, 2008).
Nano ANZ Paint	Insulator against the following: humidity - salts - water - the heat of solar radiation. Also reflects the solar radiation by more than 85% and disperses more than 80% of infrared radiation.
Nano-Ski Fire Protect Paint	Can be used to make a fire-retardant layer in wood and works as a means of extinguishing fire. It is free from toxic substances.
Nano Sky Coat Paint	Protects surfaces from oxidation - rust – corrosion, Prevents dust deposits and anti-pollutants and it is suitable for use on glass, wood and metal surfaces.

Source: The author

2.9.2 Nanoplaster Surfamix C
It has strong adhesion, elasticity and porosity blocked, and shrinkage cracks reduction.

2.9.3 Plastics and polymers
There are nanocomposites of microscopic glass globules through the pyrolysis process spray. It is characterized by avoiding the negative effects of PVC compounds, which have a harmful effect on the airways and the consumption of chlorine gas that reaches 16 million tons annually.

2.9.4 Fibrillin components and nanopolyester
It is a strong stainless steel electrical insulator with a good surface finishing.

2.9.5 Nano-gypsum boards
It is characterized by avoiding the negative effects of the traditional gypsum panels represented by the consumption of the manufacturing capacity at a temperature of 260 Celsius degrees and the consumption of a non-renewable resource at a rate of 100 million tons of calcium sulfate. It is also resistant to mold and reduces the harmful negative effects.

2.9.6 Nanomarble
It is characterized by the quality of the touch, color, scratch resistance and sunlight.

2.10 Nano Bioengineering Field
It is considered to be a branche of biomimicry science, where nanotechnology contributed to the manufacture and production of building materials that simulate the characteristics of living organisms. One of the most important examples of these materials is Nano Vent Skin which shown in Figure (17). It is nanosensors that result

from the combination of electronics and biochemical functions. It is characterized by making a strong connection between the inside and outside to take advantage of air, water, light as follows:

1. **AIR:** It interacts with the wind and directs it inward after it passes the air purification filters.
2. **WATER:** It collects rain water in special channels for reuse after purification.
3. **LIGHT:** The sensors direct the natural lighting of the internal space toward the places of movement and activity, limit the heat transfer, and support them with solar cells to provide electrical energy for the artificial lighting at night.

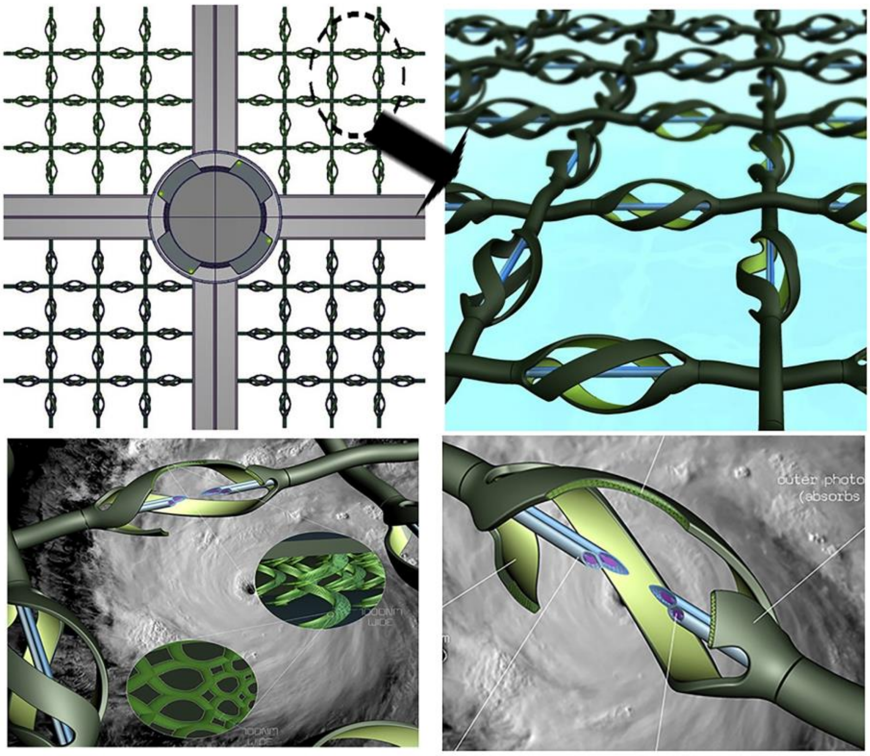

Figure (17). Nanovent skin, Source: The author.

3. SUSTAINABLE PROPERTIES FOR NANOMATERIALS

The materials and systems are considered one of the basic pillars for achieving sustainability in the building sector. Through studying the nanocharacteristics and advantages of the previous materials, the most important sustainable advantages can be drawn out as shown in Table No. (7). They try to achieve buildings' sustainable design, where these advantages were extracted for each applied field of the previously identified nanotechnology fields.

Table (7). The positive sustainable properties for the nanomaterials

Nanotechnology applied field	Sustainable properties	Nanomaterials & systems reference base
Energy field	• The traditional energy consumption reduction. • Developing and increasing the traditional energy sources production and its efficiency. • Reducing carbon dioxide emissions and reducing pollution. • Increasing the efficiency of the renewable energy sources • Innovative by integrating renewable energy systems with building elements. • Achieving acceptable economic standards during the production and operation stages.	1. Energy systems and source field. 2. Thermal insulation materials. 3. Building envelope protection. 4. Artificial lighting systems.
Structure field	• Some systems allow natural lighting and ventilation to be passed through it. • Environmentally safe manufacturing and reduce emissions of industrial pollutants. • The more economic and higher efficiency in implementation time. • Improve the efficiency of the structural element in terms of strength, maintenance and life cycle. • Some systems contribute to reducing pollutions. • Improving properties for the natural structural elements such as wood. • Innovating by creating technologically advanced building materials.	1. Construction materials and systems development. 2. Nano Bioengineering field.
Insulation field	• Increasing the thermal insulation efficiency and thermal comfort of the internal space. • Reducing energy consumption. • Increase the life cycle of insulation materials. • The efficiency of sound insulation. • More economic due to its thin layers required for the internal space. • Contribute to a healthy internal environment by preventing the infrared and ultraviolet radiation.	1. Thermal insulation materials. 2. Glazing systems.
Lighting field	• More economic with life cycle efficiency.	1. Artificial lighting systems.

	• Reducing of energy consumption. • Innovative in integrating with the building design elements.	2. Energy systems and source field.
Glazing field	• Quality of the thermal comfort of the indoor environment and achieving a suitable lighting level. • Indoor healthy environment by preventing the harmful solar radiation. • Reducing energy consumption. • Provide protection to users of the internal space.	1. Glazing systems. 2. Internal spaces healthy environment.
Water field	• Effective in the water recycling systems. • Provide a healthy environment through efficient water purification.	1. Water conservation field.
Envelope protection field	• Provide clean and healthy surfaces. • Provide surfaces with an economic life cycle.	1. Glazing systems. 2. Finishing materials.
Healthy environment field	• Provide a healthy internal space free of bacteria, odors and all harmful items. • Increasing the efficiency of the internal space function for users.	1. Building envelope protection. 2. Internal spaces healthy environment.
Finishing field	• Increasing the functional efficiency of the internal finishing materials. • Economic efficiency of life cycle and maintenance. • Applicable to many local finishing materials.	1. Glazing systems. 2. Finishing materials.
Bio-engineering field	• Contribute to the technological development and innovation of the building systems. • Protect natural resources. • The positive impact of the internal space environment. • Contribute to the reduction of energy consumption. • Lead to innovation and usage of different scientific branches.	1. Energy systems and source field. 2. Nano Bioengineering field.

Source: The author

4. THE EVALUATION MATRIX FOR THE SUSTAINABILITY EFFICIENCY OF THE NANOTECHNOLOGY MATERIALS

The next section deals with the evaluation matrix proposal for nanomaterials, which shows the sustainability of the nanosubstance. First, reliance was placed on identifying areas that serve as major strategies aiming at achieving a sustainable environmental balance and defining the criteria for each of these areas as shown in Table No. (8). These areas include the following:

- Manufacturing and construction fields.
- Waste management.

- Internal space comfort levels.
- The internal environment.
- Safety for the users.
- Energy consumption efficiency.
- Material economics.

Table (8). The proposed standards for nanomaterials sustainability evaluation

Field	Standards	CODE
Manufacturing	- Natural Resources Prevention ------------------------	**NR**
	- Recycled Content -------------------------------------	**RC**
	- Waste Reduction ---------------------------------------	**WR**
	- Environmental Impact Reduction -------------------	**EIR**
	- Ecological Materials -----------------------------------	**EM**
	- Pollution Prevention -----------------------------------	**PP**
	- Embodied Energy Reduction ------------------------	**EER**
	- Non-Toxic Materials -----------------------------------	**NT**
Waste management	- Rapidly Renewable Materials ------------------------	**RRM**
	- Reusability ---	**RU**
	- Recyclability ---	**R**
	- Biodegradability ---------------------------------------	**B**
Comfort levels	- Thermal Comfort --------------------------------------	**TC**
	- Lighting Comfort --------------------------------------	**LC**
	- Acoustics Comfort -------------------------------------	**AC**
	- Vision Comfort ---	**VC**
Energy consumption efficiency	- Energy Development ---------------------------------	**ED**
	- Energy Consumption Reduction ---------------------	**ECR**
	- Renewable Energy ------------------------------------	**RE**
Internal environment	- Natural Ventilation ------------------------------------	**NV**
	- Lighting-Level --	**LL**
	- Indoor Air Quality -------------------------------------	**IAQ**
	- Design Creativity ---------------------------------------	**DC**
	- Environmental Integration ---------------------------	**EI**
	- Low-Emitting Materials ----------------------------	**LEM**
Economics	- Longer Life ---	**L**
	- Maintenance Economics -----------------------------	**ME**
	- Construction Technology ----------------------------	**CT**
	- Operation Economics ---------------------------------	**OE**
Safety	- Fire Protection ---	**FP**
	- Hygienic ---	**H**
	- Use/Function Integration ----------------------------	**UFI**

Source: The author

Through the previous criteria, it is possible through Figure No. (18) to complete the evaluation matrix proposal to measure the sustainability of the nano materials relying on 32 criteria based on the previous areas. The relative weights of the criterions are assumed as having equal weights and based on that the field relative weight can be calculated as shown in the Figure (18). Noting that the field relative weight can be recalculated once more in case of assuming a different weight for each criterion instead of its equal weights.

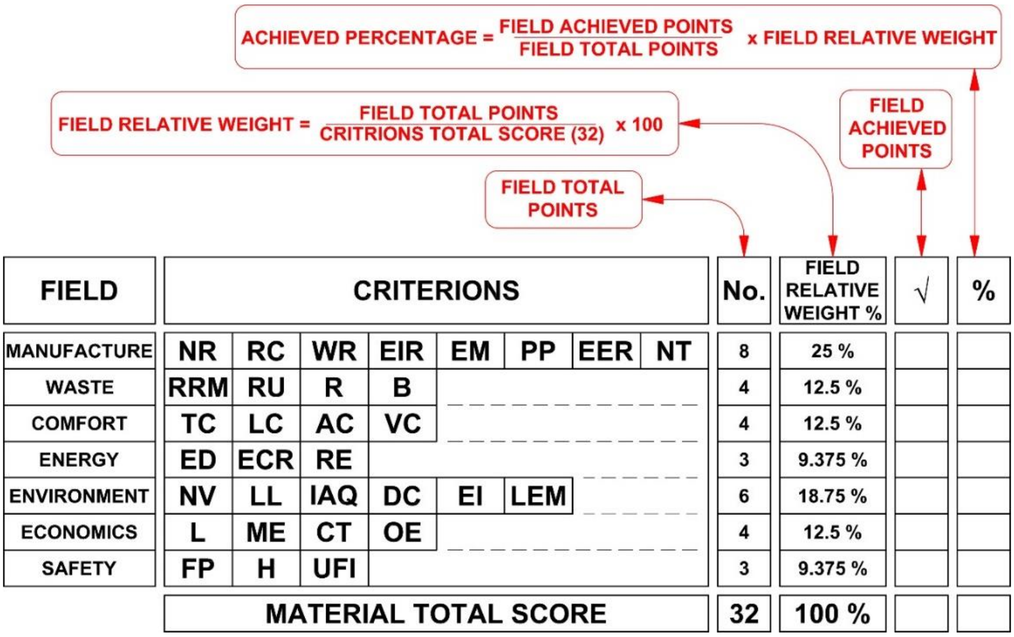

Figure (18). The proposed sustainability evaluation matrix for the nanotechnology materials, Source: The author

5. SUSTAINABLE/ECONOMIC ASSESSMENT TOOL FOR NANOMATERIALS

The evaluation model was designed to compare and select single-function nanomaterials alternatives for each application field of these materials based on two basic criteria:

1. The sustainability ratio of the nano material according to the proposed evaluation matrix.
2. The economic cost of implementing that nano material.

The "economic/sustainable" evaluation model was built through 4 successive steps, which are explained as follows:

Firstly, determining the sustainability value of each nano material for each application field through the evaluation matrix for the sustainability of the nano materials out of a total of (32) points, and the percentage obtained by the material.

Secondly, determining the level of the materials' sustainability according to the number of points obtained. Those levels have been proposed and divided into levels similar to the identified sustainability levels through the LEED sustainability system, Figure (19), as one of the most widespread sustainability assessment tools as shown in Table No. (9).

Thirdly, determining the material economic cost in its traditional form, and the economic cost of the available alternatives of the material in its nanoform, which were evaluated through the previous evaluation matrix.

Fourthly, the graphical representation of the nanomaterials' alternatives with the same application field identified in the previous steps, depending on the sustainability level and the expected economic cost of each alternative, as shown in Figure (20).

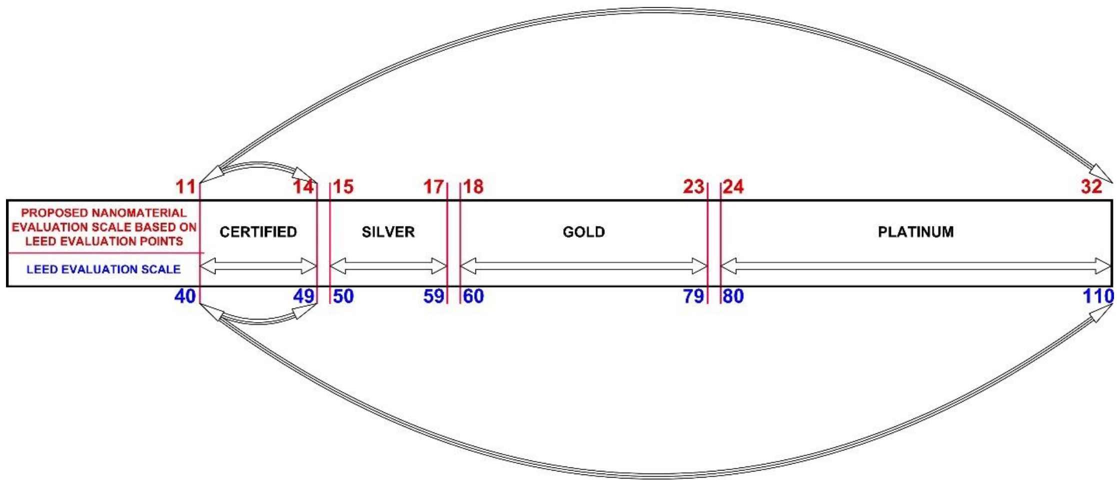

Figure (19). The proposed sustainability levels based on LEED levels, Source: The author

Table (9). The sustainability nanomaterial levels based on LEED levels

	Certified	Silver	Gold	Platinum
LEED V4 for BD+C 110 points	40-49	50-59	60-79	80-110
Nanomaterial evaluation matrix	11-14	15-17	18-23	24-32

Source: The author

The alternatives to nanomaterials can be evaluated for each application field compared to the material in its traditional form. Thus, the evaluation model consists of four main parts according to its sustainable and economic evaluation. These parts are evident in Figure (21), which consists of the following:

Priority (A) ------ Nanomaterial is more sustainable than the other nanomaterials at the same applied field.
Priority (B) ------ Nanomaterial is less sustainable than the other nanomaterials at the same applied field.
Zone (1) ---------- Nanomaterial cost is less than the material at its traditional type.
Zone (2) ---------- Nanomaterial cost is greater than the material at its traditional type.

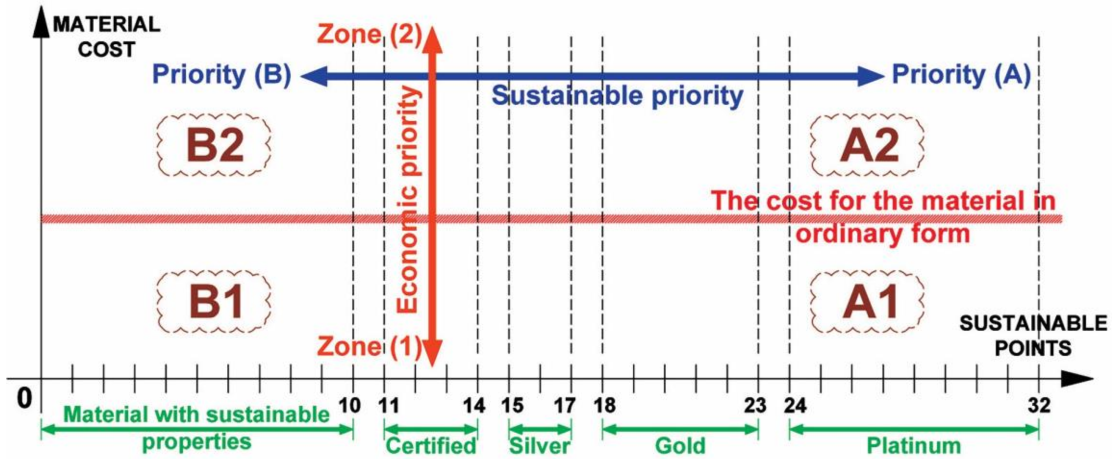

Figure20. Sustainable/economic assessment tool for the nanomaterials compared to the traditional type, Source: The author

PRIORITY			ZONE
B	A		
B2	A2	2	
B1	A1	1	

A1: More Sustainable / More Economic
A2: More Sustainable / Less Economic
B1: Less Sustainable / More Economic
B2: Less Sustainable / Less Economic

Figure (21). Sustainable/economic nanomaterials classification, Source: The author

6. THE APPLICATION OF THE EVALUATION MODEL FOR THERMAL INSULATION NANOMATERIALS

The next part of this research covers the application of the proposed evaluation model on the nano materials in the thermal insulation field of buildings compared to the traditional thermal insulation material (Extruded Polystyrene). These materials include:

1- Aerogel.
2- Vacuum Insulation Panels.
3- Thin Film Insulation.

Figures (22-a), (22-b) and (22-c) show an assessment of the sustainability level of these nanomaterials, with which it is clear that:

1- Aerogel: …………………………….16 points (50%) – Silver.
2- Vacuum Insulation Panels: …………11 points (34.375%) – Certified.
3- Thin Film Insulation: ……………….13 points (40.625%) – Certified.

By calculating the economic cost per meter square for each of these materials, bearing in mind that the thickness of each material achieves the same efficiency of the thermal insulation and comparing it to the economic cost of the material in its traditional form with the average economic cost of the different alternatives for each material being considered on the basis of the average market price, the values are as following:

1- Extruded Polystyrene: ……………………25 $ / m2.
2- Aerogel: ………………………………125 $ / m2.
3- Vacuum Insulation Panels: ………………118 $ / m2.
4- Thin Film Insulation: ……………………73 $ / m2.

Figure (23) shows the "economical/sustainable" evaluation model for the nanothermal insulation materials compared to the conventional thermal insulation (Extruded Polystyrene).

FIELD	CRITERIONS								No.	FIELD RELATIVE WEIGHT %	√	%
MANUFACTURE	NR	RC	WR	EIR	EM	PP	EER	NT	8	25 %	5	15.625
WASTE	RRM	RU	R	B					4	12.5 %	1	3.125
COMFORT	TC	LC	AC	VC					4	12.5 %	4	12.50
ENERGY	ED	ECR	RE						3	9.375 %	1	3.125
ENVIRONMENT	NV	LL	IAQ	DC	EI	LEM			6	18.75 %	3	9.375
ECONOMICS	L	ME	CT	OE					4	12.5 %	2	6.25
SAFETY	FP	H	UFI						3	9.375 %	--	--
	AEROGEL								32	100 %	16	50.0

Figure (22 - a). Aerogel evaluation matrix, Source: The author

FIELD	CRITERIONS								No.	FIELD RELATIVE WEIGHT %	√	%
MANUFACTURE	**NR**	**RC**	WR	EIR	EM	PP	EER	**NT**	8	25 %	3	9.375
WASTE	RRM	**RU**	**R**	B					4	12.5 %	2	6.25
COMFORT	**TC**	LC	**AC**	VC					4	12.5 %	2	6.25
ENERGY	ED	**ECR**	RE						3	9.375 %	1	3.125
ENVIRONMENT	NV	LL	IAQ	DC	EI	LEM			6	18.75 %	--	--
ECONOMICS	**L**	**ME**	CT	OE					4	12.5 %	2	6.25
SAFETY	FP	H	**UFI**						3	9.375 %	1	3.125
	VACUUM INSULATION PANELS								32	100 %	11	34.375

Figure (22 - b). Vacuum insulation panels evaluation matrix, Source: The author

FIELD	CRITERIONS								No.	FIELD RELATIVE WEIGHT %	√	%
MANUFACTURE	**NR**	RC	WR	**EIR**	EM	PP	**EER**	**NT**	8	25 %	4	12.50
WASTE	RRM	RU	R	B					4	12.5 %	--	--
COMFORT	**TC**	**LC**	AC	**VC**					4	12.5 %	3	9.375
ENERGY	ED	**ECR**	RE						3	9.375 %	1	3.125
ENVIRONMENT	NV	LL	**IAQ**	**DC**	**EI**	LEM			6	18.75 %	3	9.375
ECONOMICS	L	**ME**	CT	OE					4	12.5 %	1	3.125
SAFETY	FP	H	**UFI**						3	9.375 %	1	3.125
	THIN FILM INSULATION								32	100 %	13	40.625

Figure (22 - c). Thin film insulation evaluation matrix, Source: The author

Nanomaterials can be evaluated for thermal insulation according to Table No. (10) after evaluated and compared with the conventional thermal insulation materials (Extruded Polystyrene).

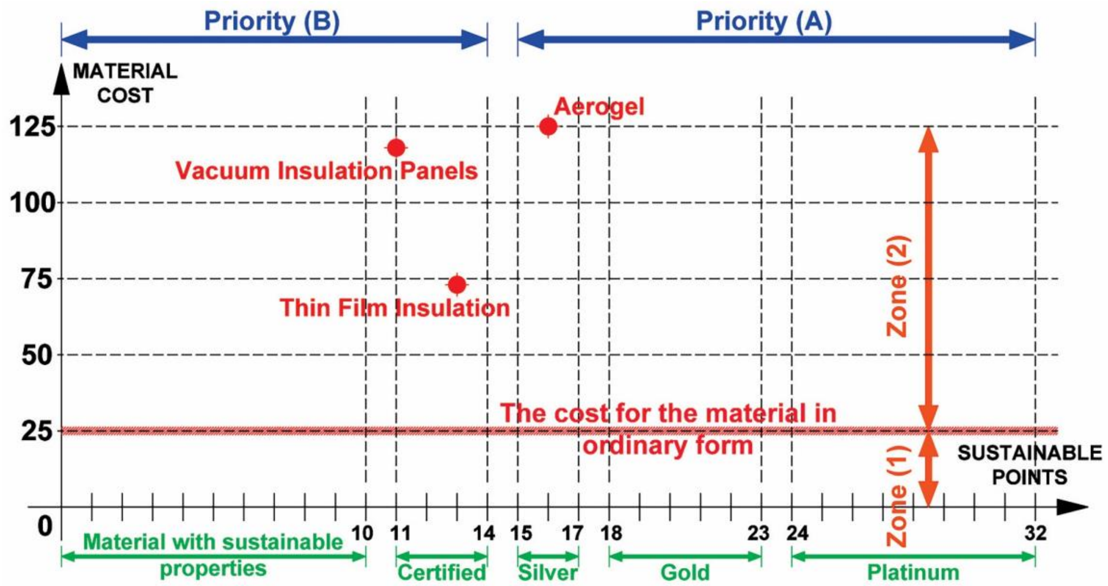

Figure (23). Sustainable/economic model for nanomaterials thermal insulation, Source: The author

Table (10). The Sustainable/economic evaluation for nanomaterials thermal insulation

Nanomaterial	Sustainability	Points	Sustainability priority	Economic zone	Priority selection
Aerogel	Silver	16	A	2	1
Vacuum Insulation Panels	Certified	11	B	2	3
Thin Film Insulation	Certified	13	B	2	2

Source: The author

7. CONCLUSION AND RESULTS

- Nanotechnology has a direct positive impact on material properties, which can lead to achieving sustainability for these materials and the sustainability of buildings.
- Nanotechnology contribute in all items of buildings, which is necessary to develop this technology and exploring new materials with advanced functions and specifications.
- Most of the nanomaterial's cost is still more than the cost in its traditional form.
- Nanomaterials can be evaluated through two main components: sustainability and economic.
- Nanomaterial's evaluation classifications can be divided into four zones as follows:
  - **A1**………… More Sustainable/More Economic.
  - **A2**………… More Sustainable/Less Economic.
  - **B1**…………. Less Sustainable/More Economic.
  - **B2**…………. Less Sustainable/Less Economic.
- The preference for selection nanomaterials according to its sustainability can be with the following order: ....**A1 » A2 » B1 » B2**

8. RECOMMENDATIONS:

- The study provides a proposed evaluation model which can be considered as a framework for the whole building materials testing based on steps similar to the steps done at the practical study to evaluate thermal insulation materials.
- The development of the field of biomimics in architecture, especially through the field of Nanobiological engineering.
- The necessity of issuing lists of updated nanomaterials through research and architectural centers to activate their use in the engineering aspects.
- Activating industrial systems that contribute to reducing the cost of nanomaterials production to be less than the traditional material.
- Issuing a specialized certificate for the sustainability of nanomaterials as same as the sustainability certificates for buildings such as LEED and the other tools.

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