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Preface

This book compiles the papers presented at the 4th International Conference on Energy & Environment: bringing together Engineering and Economics (ICEE2019) that took place in Guimarães, Portugal in May 16-17, 2019

The conference was organized by the School of Engineering, University of Minho and the School of Economics and Management, University of Porto.

ICEE2019 brought together leading academic scientists, researchers and scholars from the energy and environment science community to interchange knowledge, to discuss and to disseminate new ideas towards a low-carbon, sustainable future.

Indeed, energy and environment transition issues require much more than pure technology knowledge. Instead, they involve processes of technological transfer where economics, social sciences, and even politics play decisive roles. Recognizing this quest for interdisciplinarity, papers covered the following issues: Energy Economics; Renewable Energies; Sustainable Mobility Solutions; Sustainability in Energy and Buildings; Environmental and Social Impact Assessment; Energy Modelling; Sustainable Development; Energy Storage; Environmental Management and Technological Change; Energy and Environmental Policy; Energy Markets and Efficiency; Climate Change; Biomass/Biofuels; Economic Growth and Sustainability; Energy Systems Analysis and Waste Management.

The Editors would like to thank all the authors and reviewers for their valuable contribution and for making ICEE2019 such a big success.

Paula Ferreira
Chair of the 4th ICEE

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FOG HARVESTING MESHES PHYSICAL, ECONOMIC AND ENVIRONMENTAL CHARACTERIZATION

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KEYWORDS

Fog harvesting, Energy, Environmental Impact

ABSTRACT

As fresh water becomes scarce nowadays, fog harvesting appeared as a new opportunity to be considered as an economical and a reliable fresh water source. Thus Fog collectors represent a functional solution to provide fresh water to be used in agriculture and in some cases, also as drinking water. Fog harvesting techniques had been used first by farmers as some types of adjoining cavities and containers were added around plants to take advantage of the humid weather, after that, these techniques were turned into structures. With fog harvesting techniques emerging, new materials and new structures are being developed, providing a range of options in regards to the meshes and to the harvesting methods. In this paper, Fog harvesting meshes are reviewed and analysed to process its ability on providing environmental conditioning of exterior spaces. The purpose of such tests is to acquire a new understanding and provide other options for fog harvesting materials while taking into consideration the economic and environmental aspects of each material used.

INTRODUCTION

Fog harvesting techniques are based on the physical principle that when humid air encounters a cold solid surface it results in gathering water molecules on that surface (Mull, 1997). Approximately one billion people lives with no access to clean water around the world, with the water being an important source of life in the planet, it was noticed that some plants have the ability to collect dew in foggy climate to compensate for the lack of liquid water. Taking that into consideration, the last years witnessed the development of different techniques in the purpose of harvesting water from the humid air. On Cape Verde, Oman, and Canary Island the farmers traditionally put containers under different species of trees to collect water dripping from the leaves on fogging periods. While in Palestine, the idea of a fog-collecting structure became more concrete as the inhabitants used to build structures with adjoining cavities around their vines so the surrounding fog and mist could participate in the irrigation of their plants. The idea of developing a certain structure that provides a better water collection started with Schemenauer and Cereceda as the Standard Fog Collector (SFC) was suggested (Schemenauer and Cereceda 1994), later to be involved in recent projects such as the Warka towers and recent fog harvesting projects all around the world, (WARKA WATER 2017) (Olivier 2002) (Schemenauer R. S. 2005). A fog collector is simply a frame that supports a section of mesh in a vertical plane. As for the mesh, it is normally exposed to the atmosphere where the foggy air could be pushed through the mesh by the wind, with the droplets being disposed to the mesh, they combine to form larger droplets that run down passing into the storage tank in the bottom.

Raschel mesh is the material that is mostly used in fog harvesting applications worldwide. The mesh is made of a food-safe polyethylene and has a fibre width that makes it efficient in collecting water. On another hand, in some areas, it is not possible to use the Raschel mesh in the fog harvesting structure due to the lack of the material. In this paper, we explore the possibility of using different types of meshes and their environmental impact, as the construction industry had not only supplied some materials with positive environmental impact but ones that could be accompanied with pollution due to their production process.

METHODOLOGY

The process of using the meshes for the environmental structure must take into consideration their functionality and also must be accompanied by an evaluation of the impact of those meshes on the environment and their production effect on the atmosphere. The study includes an onsite and laboratory analysis of 10 suggested meshes and an analyzis of the environmental impacts of the meshes depending on their physical properties and the material used in their production.

MESHES TESTS

Laboratory and on-site tests were performed. The laboratory tests were performed in a controlled environment in the Textile department laboratory and the Polymer department in the University of Minho on some suggested meshes. The tests took in regards to test the meshes composition and permeabilities for Water Vapour and Air and also provided information about their physical characteristic that could affect their durability and maintenance such as the weight, and thickness. The results of the tests are as the following Table 1.

Table 1 Laboratory tests results on the suggested meshes

Meshes	Composition	WVP ratio	Air Permeability l/m^2/s	Weight g/m^2	Thickness mm	Open areas ratio
PA (a)	Polyamide	92.23%	N/A	477	1.68	59.91%
PE1* (b)	Polyethylene	97.5%	8805	305	1.56	43.89%
PVCPE1 (c)	72% PVC – 28% Polyester	93.92%	6784	235	0.78	40.55%
PVCPE2 (d)	71% PVC – 29% Polyester	91.26%	3194	317	0.77	22.92%
PVCPE3 (e)	65% PVC – 35% Polyester	85.57%	3475	309	0.90	20.96%
PVCPE4 (f)	50% PVC – 50% Polyester	84.95%	1175	314	0.64	7.54%
PE2* (g)	Polyethylene	83.39%	2889	64	1.31	23.47%
PVCPE5 (h)	67% PVC – 33% Polyester	82.93%	1707	353	0.67	11.85%
PVCPE6 (i)	57% PVC – 43% Polyester	79.72%	1210	331	1.00	7.63%
PVCPE7 (j)	58% PVC – 42% Polyester	75.96%	1813	477	1.00	14.09%

*Meshes tested on site and in the laboratory

(a) Nylon shading mesh; (b) Plastic Green mesh; (c) Print MS25 (Endutex); (d) Print MS40 (Endutex); (e) Print RC3 (Endutex); (f) SunWorker (Dickson solar protection); (g) Black Shading mesh; (h)Print MS55 (Endutex); (i) Print MS74 (Endutex); (j) Print MP90 (Endutex).

The meshes with higher Air permeability were found to have higher open areas ratio, while most of the meshes with high WVP ratio were also found to have higher open areas ratio. The meshes selected for the on-site tests were those that present high air and water vapour permeability and at the same time have high open areas ratio, see Fig 1.

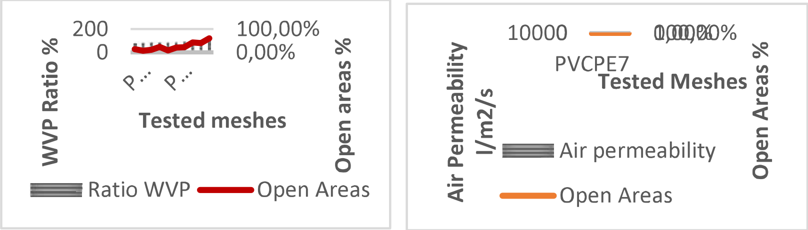


Figure 1 Ratio between the meshes Open areas and their Water Vapour and Air Permeability

The on-site tests were done by mounting some of the meshes on an experimental outdoor structure, in the laboratory of Paisagem, Guimaraes. The structure is, mainly, a frame of two horizontal aluminium pillars and of ropes that hold a mesh in between, a collecting tube and a storage is installed under the mesh, see Fig 2.

Figure 3: Fog harvesting structure, Laboratory to Paisagem, Guimaraes.

ENVIRONMENTAL CONDITIONING BENEFITS OF FOG HARVESTING MESHES

The meshes used in fog harvesting can have varied environmental effects depending on their material and their physical appearance. The composition, thickness and weight of the meshes have important effects on their durability, maintenance and their environmental properties, which are explored in this section.

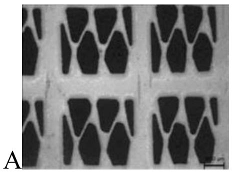
Thermal Comfort

Most of the meshes used in fog harvesting have a certain amount of open areas that could affect the mesh ability to allow wind to pass through the mesh thus enhancing or worsening the mesh ability to collect water. The open areas in the meshes don’t only affect its ability to collect water and filter the wind but also affect their ability of providing shading and protection from heat. It was found that with more solar radiation passing through the mesh higher is the temperature. To assure a good protective effect the mesh shading factor must be at least 50% (Buyle and Virgo 2015). The Raschel mesh is preferred to have a 35% shading coefficient to perform efficiently as a fog harvesting mesh. Other meshes are produced with different open areas percentage and shading factors, that in some cases enhance their ability to provide shading and that might affect their water harvesting abilities, where, it is critical for the mesh to allow wind to pass through it to be able to capture water droplets deposited in the air, while larger percentage of open areas could increase its ability to capture fog, however it may decrease its ability to provide shading, as can be seen on Table2.

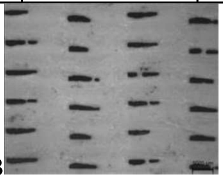
Table 2: Meshes with different Open Areas

Name	Open Areas	Thickness mm	Composition
PVCPE1 (A)	41%	0.78	72% PVC – 28% Polyester
PVCPE6 (B)	7.54%	0.64	57% PVC – 43% Polyester
PE2 (C)	23.5%	1.31	Polyethylene

A



B



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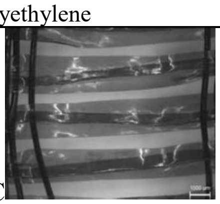

Air Pollution Abatement

Fog harvesting mesh with their ability to collect fog could help in some cases, as the collection of fog, could limit the number of toxins in the air, where the meshes with higher ability of collecting water could provide improved air quality either by collecting toxins pollutants in the humid air or by rainfall which eventually also wash of the pollutants on the mesh surface down to the collector. However, this could have an opposite effect on the water collected, as it won't meet the WHO standards, making the collected water not safe for human and other living beings consumption. It was found that the urban areas fog could be affected by the presence of industries' emissions, as higher levels of particles and heavy metals are found in the fog of those areas (D.Ritchie, Richards and A.Arp 2006). The ability to absorb toxins disposed on the air proved to be higher in urban areas compared to rural areas, as the fog in urban areas exhibit higher levels of total organic carbon, nitrate and sodium and as a result have a lower PH level (Raja, et al. 2008).

Noise Pollution Abatement

Scientific literature is lacking studies on the physical and acoustical characteristics of polyester fibre materials, some barriers could add polyester to its composition as the ability of the polyester to absorb noise pollution could be affected by its thickness, surface area and fibre size , thus the higher the open areas of the mesh the lower its ability to perform as a noise barrier, for example in the study of (Lin, et al. 2015) it is noted on the first stages of the study that the mesh with higher open areas ratio have a lower sound absorption coefficient. On the other hand, PVC films could be added to the fabric as it could increase the fabric sound absorption at low and mid frequencies at the expense of higher frequencies (Seddeq 2009). It must be taken into consideration that fog harvesting meshes if implemented alone, are not able to provide effective noise abatement due to the lack of thickness and the openings in the meshes' fabric which affect their noise absorption. Thus, the only protection from nets alone to the noise is psychological as they offer visual protection to the source of noise, that could not be easily seen, thus reducing noise sensitivity.

ENVIRONMENTAL IMPACT

The environmental impact of the meshes could be linked to their harmful effect on the environment, taking in consideration the pollution emited during production and after wasting. In the study case, most of the meshes under analysis are composed of polyester with PVC coating. Production of PVC emit chlorine gas, ethylene, dioxin, vinyl chloride, dichloretane, mercury and other damaging substances. Thus leading to serious health problems, especially for the workers directly exposed to the production process if not enough cautions are taken. PVC is considered to be the largest source of chlorine in waste products. When burnt it can form concentrated hydrochloric acid and dioxin, among other gases such as Carbon Monoxide CO, Carbon Dioxide CO_2, methane CH_4, Barium Ba and Cadmium Cd (Berge 2000). On the other hand, Polyester can produce Styrene and dichloromethane during its production, while if burned it emits CO, CO_2, benzene, styrene, formaldehyde, which could be considered harmful in high concentrations.

Other meshes similar to the Raschel mesh are made from Polyethylene. Polyethylene is not easy to decompose, however, it could be burned without emiting dangerous gases (Berge 2000). Furthermore, some meshes are also composed of Nylon, one of the most commonly used Polyamides (PA), the production of nylon emits carbon dioxide, nitrous oxide, sulphur dioxide and methane among other gases. Nylon could be produced in many forms such as nylon 6 and nylon 6.6, where nylon 6 is produced from caprolactam and nylon 6.6 is produced from hexamethyl lene diamine and adipic acid. Nylon 6.6 is hard to recycle, and burned it emits harmful gases such as dioxins, nitrous oxide and hydrogen cyanide (Boustead 2005), (Boustead, 2005) and (Muthu 2014).

Embodied Energy and Green House Gas Emissions

Plastic products are mostly made from feedstocks derived from crude oil and natural gas processing. While half of the fossil fuel goes into the composition of the plastic itself the other half is combusted to provide the energy during manufacture. The amount of embodied energy and green gas emission, however, differs depending on the type of plastic products as demonstrated in Table 3 (Berge 2000).

On another hand, one of the most gases that increases the greenhouse effect is carbon dioxide, which is released from industrial manufacturing of the fossil fuel, and could pose a harmful effect on the environment if it passed a certain level, according to the United Nations' climate panel IPCC, there is a need to reduce human-caused emissions of carbon dioxide (CO_2) by about 45 percent from 2010 levels by 2030, reaching 'net zero' around 2050 (IPCC, 2018). Thus, the GWP (global warming potential) associated with the carbon dioxide emission, AP (acid Potential) associated with sulphur dioxide formed through burning fossil fuels and other industrial processes, are taken into consideration in the assessment of the material air pollution impact, (Berge 2000) and (Jones 2008).

Table 3 Embodied Energy and Pollution Potential

Material	Embodied Energy MJ/Kg	Embodied Carbon CO_2/Kg	GWP g/kg	AP g/kg
Polyester	103.83 (a)	2.7 (c)	2720(e)	21(f,g)
Polyvinyl chloride (PVC)	77.2 (a)	2.41 (a)	1400(b)	13(b)
Polyethylene	83.1(a)	1.94(a)	751(b)	9(b)
Polyamide	160.07(a)	5.5-6.5(a)	6700(d)	12(d)

Sources: (Jones 2008)[a], (Berge 2000)[b], (EIC 2010)[c], (Boustead, 2005)[d],(Adrien Bton 2012)[e], (Nousiainen 1999)[f] and (Patel 2010)[g].

Taking that in regards, the embodied energy and carbon of the suggested meshes was calculated depending on their weight and compostion, see Table 4.

Table 4 Embodied Energy and Pollution Potential of the tested meshes

Meshes	Composition	Embodied Enrgy per m^2	Embodied Carbon per m^2	Weight Kg/m^2	GWP g/Kg	AP g/kg
PA	Polyamide	76.35	2.6 -3.1	0.477	3295.9	5.72
PE1*	Polyethylene	25.35	0.59	0. 305	229	2.7
PVCPE1	72% PVC – 28% Polyester	19.89	0.59	0.235	415.72	3.6
PVCPE2	71% PVC – 29% Polyester	26.9	0.79	0.317	564.9	4.8
PVCPE3	65% PVC – 35% Polyester	26.7	0.77	0.309	575.36	4.9
PVCPE4	50% PVC – 50% Polyester	28.4	0.8	0.314	646.8	5.3
PE2*	Polyethylene	5.3	0.12	0.064	48.06	0.58
PVCPE5	67% PVC – 33% Polyester	30.35	0.88	0.353	647.9	5.5
PVCPE6	57% PVC – 43% Polyester	29.34	0.84	0.331	651.3	5.4
PVCPE7	58% PVC – 42% Polyester	42.16	1.21	0.477	932.2	7.8

ECONOMICAL ASPECTS

Fog harvesting structure needs to be applicable by being easy to construct and maintain, and it must be economical. As the structure, piping and maintenance costs remain constants, the changing factor was the type of the mesh used.

The different values of the meshes were obtained from the factories that produced the meshes and in some cases from the store were some meshes were bought, the cost of the meshes, illustrated in Fig 3.

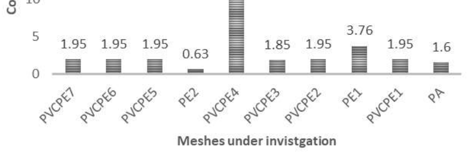

Figure 3 Meshes under investigation and their costs from the factory

As mentioned earlier most of the meshes are composed of Polyester with PVC, however, the difference of the economic value of each mesh could be due to the percentage of each material, the thickness of the fabric and the rate of open areas in the material.

RESULTS AND DISCUSSION

In regards to the laboratory results, the meshes ability to provide higher water vapour permeability and air permeability is connected to its opening areas ratio, and the on-site results showed that two of three tested meshes are able to capture water from fog, the PA and PE1 meshes, thus, the physical characteristic of those meshes are considered as a reference to evaluate the ongoing laboratory tests' results. Where it was demonstrated that the ability of these two meshes to collect water is related to their open areas ratio and water vapour and air permeability. However, although the meshes collected water but they were unable to drain it down to the collecter, so it was suggested that a coating material could help lowering the adhesion of the meshes to water, however, when applying a coating material such as Baygard clean, oil and water repellent fluorocarbon, with the standard heat of 170°C for fixing, it melted the nylon and polyethylene meshes, thus, promoting the need for a coating with no thermal fixing, such as in the case study of (Park, et al. 2013) where dip coating and spray coating on woven meshes were successfully used. Taking that into consideration, the functionality of the mesh is not the only aspect that affects the choosing process, but the environmental effects and the physical and economical properties of the mesh are also aspects to be considered when designing a functional harvesting system, see Table 5.

Table 5: Result of the meshes environmental analysis

Meshes	PVCPE 1,2,3,4,5,6,7		PA	PE1,2
Composition	Polyester	PVC	Polyamide	Polyethylene
Noise Abatement (Lin, et al. 2015), (Seddeq 2009)	Alone, psychological effect of reducing noise sensitivity.	Enhance the ability to reduce noise at low and medium frequencies	Alone, psychological effect of reducing noise sensitivity.	Alone, psychological effect of reducing noise sensitivity.
Air pollution Abatement (D.Ritchie, Richards and A.Arp 2006),	If functional as a fog harvesting mesh it has the ability to collect toxins attached to fog from the air			Some products have high ability to collect water from fog, thus, as a result collect toxins attached to the fog
Thermal comfort	Provides shading however that depends on the open area ratio or shading coefficient and type of the material			
Economical properties	Between 1.85 to 20 €/m^2		1.60 €/m^2	0.63 to 3.76 €/m^2
Embodied Energy MJ/kg (Jones 2008)	103.83	77.2	160.07	83.1
Embodied Carbon Co_2/kg (EIC 2010), (Jones 2008)	2.7	2.41	5.5 to 6.5	1.94
GWP g/kg (Berge 2000),(Boustead, 2005),(Adrien Bton 2012)	2720	1400	6700	751
AP g/kg (Berge 2000), (Nousiainen 1999), (Patel 2010)	21	13	12	9
Weight g/m^2	220 to 530 g/m^2		477 g/m^2	64 to 305 g/m^2
Thickness mm	0.60 to 1 mm		1.68 mm	1.31-1.56 mm

CONCLUSIONS AND FURTHER RESEARCH

While Polyethylene meshes are preferred due to their low levels of embodied carbon and embodied energy compared to most of the other meshes, however, PVCPE1,2 and 3 had similar embodied energy levels to the PE 1 mesh which is mainly composed of polyethylene, thus providing an alternative without the anticipated environmental damage linked to the production of the material, it must be noted, that the PVCPE1, 2 and 3 meshes, however, offer a high GWP and AP potential compared to the PE1 and PE2. On the other hand, although PA mesh was proved to be functional in collecting water it must be taken into consideration the high levels of embodied energy and embodied carbon associated with the mesh production and the high levels of GWP and AP compared to the rest of the meshes. PVCPE meshes have the advantage of providing more options for shading in comparison with the ability of the PE meshes, as some of them were designed for shading purposes. On another hand, Polyester, PVC and Nylon production processes and burning may emit some harmful gases to the environment if not treated properly while meshes composed of Polyethylene are not known to emit a high concentration of harmful gasses if burned.

In the process of deciding which mesh to apply on a structure, the functionality and the environmental profile of the mesh is important as the Polyethylene meshes have a lower harmful environmental impact and proved to be functional in some cases, i.e. PE1. However, it is possible to use other meshes that may have a higher economic and harmful environmental impact if not treated properly, but could capture water and provide some positive environmental benefits taking in consideration their physical characteristics.

Finally, when striving to achieve a functional system that provides environmental benefits, it is advised that further analysis is done both on the site and in the laboratory.

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