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METHODS OF HARVESTING WATER FROM AIR FOR SUSTAINABLE BUILDINGS IN HOT AND TROPICAL CLIMATES

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Abstract

A rapid rise in demand for fresh and potable water every day has impacted global water resources that become an international matter of significant concern in keeping with the global population's fast growth. Although tropical countries receive abundant rainfall levels throughout the year, the lack of access and supply of clean water in many rural areas in this region considers an environmental challenge of this century. Atmospheric air represents a reservoir of clean water with an estimated quantity of 12,900 km^3, while the amount of renewable fresh water on the planet is approximately 12,500 km^3. Therefore, there is a need for new sustainable methods to provide a supplementary water supply for buildings. This research aims to examine passive methods and mechanisms of extracting water from ambient air that can be used in tropical buildings compared to rainwater harvesting systems. The methodology is based on a comprehensive review to explore the potentials methods, challenges and opportunities for collecting atmospheric water on-site in the tropics. Analytical evaluation of approaches, mechanisms, systems' productivity and performance was conducted. The research results revealed two technical ways that would be effective to extract water from humid air, namely: regenerative solar desiccant/collector and dew water condensation systems. This study would help to shape the application of Atmospheric Water Generation (AWG) that is expected to be more cost-effective, sustainable and adaptable to tropical building applications.

Keywords: *water issues; atmospheric water harvesting; rainwater harvesting; sustainable buildings; desiccant; dew collection; fog collection; tropics*

INTRODUCTION

World Health Organization (WHO) stated there is only 2.5% freshwater, while the rest of the water is salty (WHO, 2021). In terms of atmosphere, it contains 12,900km^3 of freshwater (Meran, Siehlow, & von Hirschhausen, 2021). Also, a percentage of 2.5% of freshwater makes 30% of groundwater, while 70% appears in the form of ice and snow, which represents less than 1% of freshwater available for human consumption (Alsharhan & Rizk, 2020; Eslami, Tajeddini, & Etaati, 2018). Although many countries enjoy plenty of water resources, the distribution of these resources is unequal, leading to water shortages in many urban regions.

Due to the rapid growth of the world's population, global water resources have become a critical international concern (SILVA, 2019). The rise of the worldwide population has increased clean water resources consumption, especially for people living in arid or semi-arid areas (Zhang, Huang, Chen, & Lai, 2017). Nevertheless, the increase in water consumption over the previous century was twice the global population growth (United Nations, 2021b; Vargas-Parra, Villalba, & Gabarrell, 2013). Access to clean water has become a crucial global concern for sustainable urban developments. Cities are increasingly growing, and their infrastructures are developing to meet residents' different needs. In order to adapt to current demands, several studies have drawn attention to new solutions for creating a greener and smarter urban environment. Furthermore, the promotion of sustainable urban development calls for reducing reliance on desalinated water sources by decreasing of energy-intensive approaches to water treatment (Farreny et al., 2011).

Freshwater is vital for life and human well-being; however, people in many urban areas lack simple access to a secure and constant supply. Due to harmful human activities and emissions, natural freshwater resources, such as lakes and rivers, are decreasing. Besides, due to different factors, the amount of rainfall has been significantly reduced in many regions (e.g., global warming) (Mancosu, Snyder, Kyriakakis, & Spano, 2015). Inefficient water distribution, treatment and disposal systems that require vast quantities of capital and energy, resulting in unnecessary extra costs and environmental degradation, are another factor compounding the issue (Santos & Taveira-Pinto, 2013). In response to this situation, extensive efforts have been made, particularly in the last decade or so, to find and exploit alternative freshwater supplies. One of the promising solutions is water extraction from atmospheric air to solve freshwater scarcity in the tropical built environment. Several approaches have been introduced in the available literature. However, careful examination of the available and relevant literature points out the need for a study that introduces the approaches and analyses their technical features.

Based on this backdrop, this review article aimed to fill the gap in the literature and investigate a sustainable solution for the provision of drinking water in tropical buildings specifically linked to UN Sustainable Development Goals: G3. Good health and well-being and G6. Clean water and sanitation (United Nations, 2021a). To reach its aim, this study will examine passive methods and mechanisms of collecting water from ambient air, which would open a new possibility to be considered in tropical buildings. Accordingly, the sections below will illustrate the potentials and challenges of generating fresh water on-site using passive Atmospheric Water Generation (AWG) systems.

METHODOLOGY

A review of relevant published studies focusing mainly on those of the last decade from 2010 to 2020 was employed to assess the mechanisms, productivity, and acceptability capability of atmospheric water generation AWG to support the demand for fresh water at tropical buildings for water sustainability. Web of science, science direct, Scopus and published official reports constituted the main sources of material for the analysis in this study.

A concept was developed from different sources through content analysis of the literature, and the research flow was divided into two stages: tropical water issues and passive methods of atmospheric water harvesting (Figure 1). The first stage analysed the current water issues in tropical regions and buildings. Accordingly, the second stage investigated the passive methods for sustainable water supply from the air, which then categorised based on its occurrence into drops collection and drops coalition. Drops collection included rainwater harvesting systems (RWH), whereas drops coalition, which refers to AWG, involved fog collection, dew condensation and vapour sorption/ desorption using desiccant materials. The analytical evaluation was conducted on the passive systems based on their mechanisms, systems' performance and productivity aspects. Subsequently, the study highlighted the challenges and opportunities of implementing AWG systems in tropical buildings.

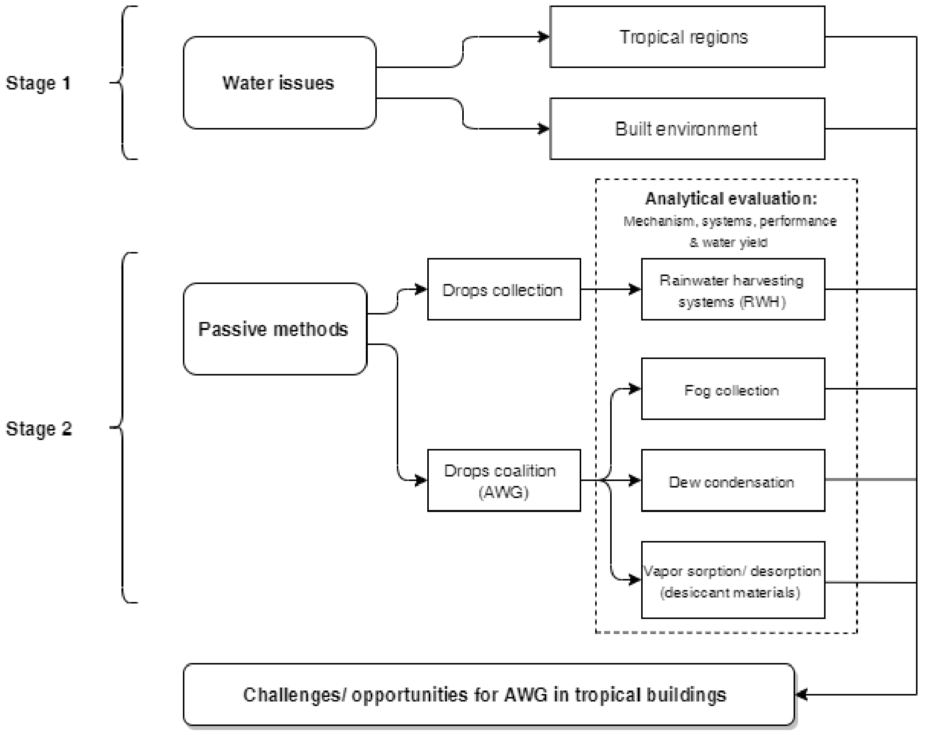

Figure 1: Review framework for the study.

WATER ISSUES IN THE TROPICAL BUILT ENVIRONMENT

Increased global temperatures led to a rise in cyclones, hurricanes and floods in many areas of the world (Veenema et al., 2017). In terms of economic development and urbanisation, tropical regions such as Southeast Asia are considered one of the world's most dynamic regions. At the same time, the area is also vulnerable to many hydro-meteorological hazards that are likely to worsen due to climate change. Lorenzo and Kinzig (2020) emphasised that more severe disasters, particularly floods, could immediately decrease water quality after the event and for more extended periods of time, and lead to damage of infrastructure in many tropical countries. Furthermore, climate change-related water disasters (CCRWDs) have a detrimental effect on communities and people's health (Veenema et al., 2017). Moreover, Marcotullio (2007) argued at a lower level of income, the problems in water are numerous, such as increased access to drinking water and sanitation and increased flood planning.

Moreover, over the last few decades, Malaysia has never had a dire water crisis. However, rainfalls in Malaysia are unevenly distributed, leaving some areas dry and the other regions flooded. Particularly in cities such as Kuala Lumpur, Selangor and Putrajaya, despite the tropical climate and rich water resources, water is scarce sometimes (Lee, Mokhtar, Hanafiah, Halim, & Badusah, 2016). El Nino's phenomenon, which caused a severe drought in 1997/98, exacerbated this situation, with significant consequences for the country, particularly for the public water supply sector and residents. Afshar and Suhaimi (2018) found that Water resources in Kuching might not be viable for much longer, as the existing water supplies sources are almost at their height for catchments. Although the effect of climate change on water security in the tropical regions has been widely discussed, the alternatives for water production on-site to overcome water security and issues in the built environment have not been explored in as much detail (Biggs et al., 2014; Biswas & Seetharam, 2008; Weiss, 2009).

Many studies have been conducted on atmospheric water generation in the built environment. For example, Sivaram, Mande, Premalatha, and Arunagiri (2020) proposed a building integrated passive solar power technology (BIPSET) for water and power generation. The system is composed of a solar still, PV and combined with a chimney. However, the brackish water was needed to be used inside the solar still. Bradshaw (2016) proposed an air-water generator (AWG) attached to the building roof. The study employed pre-fabricated heat sinks utilising thermoelectric units to produce water from the air.

Energy use and carbon emissions are often the primary targets in green construction efforts. Even though clean, potable water is sometimes ignored, water is still a critical resource to daily life. Thus, devices of providing water to buildings have a tremendous effect on municipal water supply (Craig, 2009).

Proponents of green buildings argue that the built environment is the main factor in energy consumption and carbon emissions. So, the design and modification of buildings and their operations significantly reduce these issues. This concept is also applicable to water consumption. Even though it is challenging to achieve net-zero water buildings, reducing water consumption in every building has a major impact on alleviating the pressure on freshwater sources (Joustra & Yeh, 2015). Therefore, there is a need to improve novel systems capable of generating water on-site with little energy consumption or even reducing water quantity to be piped from distant locations.

RAINWATER HARVESTING SYSTEMS

Rainwater harvesting has a well-established historical past as a water conservation theory and supply (Haut, Mays, Han, Passchier, & Angelakis, 2015). In almost every part of the world, all communities have widely used this method. RWH has emerged as one of the interventions in response to climate changes that strengthen human society's resistance to water scarcity (DeNicola, Aburizaiza, Siddique, Khwaja, & Carpenter, 2015). RWH consists of the concentration, capture, storage, and treatment of rainwater from vertical and horizontal surfaces in urban environments, including rooftops, courtyards, terraces, and other impervious on-site building surfaces. There is a wide range of civic uses of the rainwater collected (for example toilet flushing, washing, garden irrigation, clean-up on the terrace, other intermittent outdoor applications, such as vehicle washing) (Campisano et al., 2017).

Numerous factors affect the sustainability of RWH in the built environment. These include social acceptability, quality of water and the ability to fulfil household requirements due to spatial and temporal rainfall variation (Neibaur, 2015). Water quality is an essential factor in the viability of RWH since it has a direct effect on human health (Baguma, Loiskandl, Darnhofer, Jung, & Hauser, 2010). Many studies show rainwater is usually cleaner, whereas pollution can occur once rainwater interacts with the atmosphere, roof, or storage tank (Helmreich & Horn, 2009; Schets, Italiaander, Van Den Berg, & de Roda Husman, 2010). Moreover, few studies have usually concluded that most of the rainwater's physio-chemical characteristics follow WHO guidelines (Chang, McBroom, & Beasley, 2004; Neibaur, 2015; Quaghebeur et al., 2019). Several other RWH studies indicated that stored water is contaminated by bacteria which exceeds WHO guidelines due to poor system design and poor maintenance (Domènech, Heijnen, & Saurí, 2012; Hafizi Md Lani, Yusop, & Syafiuddin, 2018; Islam, Akber, Rahman, Islam, & Kabir, 2019; Ward, Memon, & Butler, 2010). The functional feasibility and reliability of RWH mean that these systems are capable of satisfying household water demands. The temporal distribution of rainfall, consumer demand, catchment size and storage capacity affect RWH efficiency (Notaro, Liuzzo, & Freni, 2016). The predicted precipitation trends showed that feasible RWH systems are expected to be influenced by climate change.

Although Malaysia has large quantities of water resources, some areas now have water shortages (Ern Lee, Mokhtar, Mohd Hanafiah, Abdul Halim, & Badusah, 2016). The rising water demand has led to attempts to search for alternative water sources. As part of the solutions to alleviate the water shortage problem, the government suggested harvesting rainwater. The Malaysian government started encouraging the use of RWH in 1999 (Hafizi Md Lani et al., 2018). RWH has begun to achieve practical implementation with the recently increased water scarcity and rationing events. Besides, Lee et al. (2016) explored rainwater harvesting possibilities under the fluctuated climate in Malaysia. Five interconnected dilemmas were identified, namely: environmental, political, economic, social and technological aspects. In order to consolidate RWH as an alternate water supply, these issues must be addressed in planning, financing, construction, operation and maintenance. Accordingly, RWH systems could be useful in the tropical regions that enjoyed high rainfall levels; however, it needs a proper design and strategies to be applied to the tropical buildings.

PASSIVE SYSTEMS FOR ATMOSPHERIC WATER GENERATION

Extracting water from humid air is not a new technique. In this area of ancient Byzantium and particularly Theodosia, massive, mysterious structures condense the dew inside them and provide the inhabitants of the cities with sufficient freshwater supply, sited at (Carvajal et al., 2018) from (Zibold, 1905).

There are essentially three main approaches to collect water from the air: namely dew condensation, fog collection and direct vapour sorption/desorption (desiccants materials) as follow:

1. Dew condensing by exposure of air to surface temperatures is lower than the air dew point's temperature.
2. Fog collection.
3. Absorption of water from atmospheric air utilising desiccant materials with subsequent desiccant regeneration.

The first method cools down atmospheric air below the dew point temperature, but it is a very complicated and costly method. The second method increases water production higher than in other ways. Still, this method might only be implemented in specific regions, especially those with 100% relative humidity and an adequate wind speed level. In the third method, a desiccant is used to absorb humidity from the atmospheric air during nighttime, which then uses a heat source, such as solar energy, to generate moisture that is condensed after that. This method generates an acceptable amount of water, and it is easier and cheaper than the other methods. More details about the aforementioned atmospheric water generation approaches will be discussed in the following sections.

Dew condensation

Since the radiative cooling mechanisms, physics and thermodynamics of condensation surfaces are more precisely understood, dew collections have grown in the last 20 years (Tomaszkiewicz, Abou Najm, Beysens, Alameddine, & El-Fadel, 2015). Though relatively limited yields, dew positions themselves are a viable water substitute, as they occur in many places worldwide naturally and often.

The formation of dew is a transition step from vapour to fluid or condensation. The formation process can be represented by four physical processes that repeat many times during a dew event: heterogeneous nucleation, droplet growth, renucleation and removal of droplets (Figure 2) (Tomaszkiewicz et al., 2015). Dew condensation occurs primarily when the environmental temperature is lowest, and relative humidity is usually the highest (Late at night and around sunrise the most favourable conditions for dew gathering).

The upper limit of the dew yield is 0.8 kg/day/m^2 based on the radiation cooling capacity available for condensation; however, in arid and semi-arid climates, the maximum observed dew water outputs generally fall within 0.3 – 0.6 kg/day/m^2 (Khalil et al., 2016; Tu, Wang, Zhang, & Wang, 2018). The process is usually restricted by radiative heat exchange rates, climate conditions and surface characteristics. In particular, weather conditions decide the ratio between latent and sensible heat between ambient air and the surface.

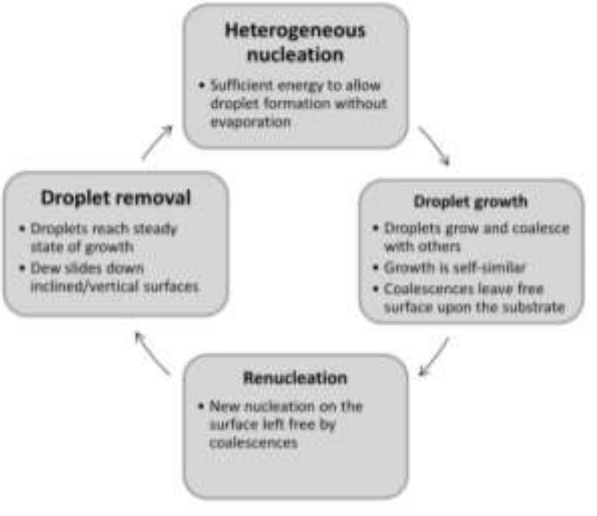

Figure. 2: Dew formation process (Tomaszkiewicz et al., 2015).

Due to the dependence of radiative systems on the physical processes of dew formation, their design must be optimised to allow surface cooling without any external input of energy. A variety of factors are essential for improving yield. Firstly, maximising the condensing surface's infrared wavelength emitting properties is necessary to enable night surface cooling. Secondly, the visible light absorption must be decreased to prevent the condenser from heating up during the day (i.e., white materials). Third, the wind's heating effect must be minimised by reducing its velocity, typically accomplished by a tilt angle on the condenser or a particular shape. Fourth, to recover much of the water, a hydrophilic surface is required to collect it in a reservoir and prevent early morning water evaporation. Finally, a light condenser is necessary to minimise heat inertia, make it easier to adjust the surface temperature and have adequate insulation to prevent heat transfer from the ground (Khalil et al., 2016; Tu et al., 2018).

Passive cooling device study involves research on materials with low emissivity surfaces. Sharan (2011) investigated three condensed surface types that were analysed: galvanised iron (GI), commercial aluminium sheets and PETB-films (polyethylene blended with 5% TiO_2 and 2% $BaSO_4$), as shown in Figure 3. The condensing surfaces were evaluated as a 1 m x 1 m radiative condenser mounted in northwest India's semi-arid coastal area. The quantity of water obtained on most nights (60 %) ranged more or less consistently between 0.05 and 0.25 mm from the daily data collected over 2-year periods in 2004 and 2005. The maximum collection was in the PETB sheet (19.4 mm), followed by GI (15.6 mm) and aluminium (9 mm) from all three surfaces measured.

Figure 3: Different types of condenser surfaces investigated (Sharan, 2011).

The largest dew and rainwater collecting system worldwide was constructed in 2006 at Panandhro in the semi-arid area of Kutch (NW India) (Sharan, Clus, Singh, Muselli, & Beysens, 2011). This big dew condenser has a surface area of 850 m^2 net with ten ridge-and-trough modules that output a total of 6545 l for 2007, equal to 7.7 mm/day with a total registered maximum collection rate of 251.4 l/night (0.3 mm). This condenser can collect rain in addition to the dew, and sometimes it collects fog.

Fog collection

Fog harvesters are not a new technology; they have been in use for many years by many cultures worldwide. A rectangular mesh perpendicular to the wind, which collects fog droplets, is the standard way to capture fog water. If the water droplets carried by the wind are exposed to a foggy environment, they are forced against the mesh and trapped. The droplets continue to grow after successive impacts so that they are too large to fall through gravity, and a gutter moves water into a reservoir, as shown in Figure 4 (Park, Chhatre, Srinivasan, Cohen, & McKinley, 2013). Today fog collection is considered one of the most passive and sustainable way of producing ambient water as they do not need any power to work and use only the changes in temperature and energy during the day to condense water into the mesh.

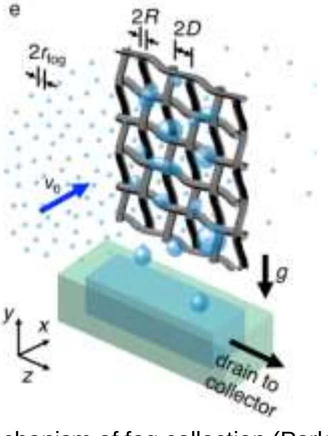

Figure 4: Basic mechanism of fog collection (Park et al., 2013).

The successful initiatives influenced the development and implementation of similar fog collection projects in many areas of the world today (Batisha, 2015). Most sophisticated fog systems have a capacity of 2–11.8 kg/day/m^2 in water generation, as summarised by Tu et al. (2018) as shown in Table 1.

Table 1: summary of the literature review on fog water collectors (Tu et al., 2018).

Reference	Material	Location	Operation year	Fog days/ year	Elevation m	SWP kg/day/ m^2	Method
(MacQuarrie et al., 2001)	Raschel 65% shadow net	Nepal	2001- 2010	122	3750	3.7	Exp.
(Fessehaye et al., 2014)	/	Peru	1995- 1999	210	800	11.8	Exp.
(Olivier & De Rautenbach, 2002)	Polypropylene yarn	South Africa	1999- 2001	184	1600	4.6	Exp.
(Marzol, Sánchez, & Yanes, 2011)	/	Canary Islands	2000- 2010	354	700	10	Exp.
(Larrain et al., 2002)	Raschel mesh type	Chile (Alto Patache)	1997- 2000	365	700	7.8	Exp.
(Fessehaye et al., 2014)	/	Guatemala (tojquia)	2006- 2010	210	3300	6	Exp.
(Fessehaye et al., 2014)	/	Chile (padre Hurtado)	2010	365	550	2	Exp.

One of the key infrastructure expenses that made the device uneconomic and hydraulically challenging was the pipe's cost from collectors to consumers. Therefore, Abdul-Wahab, Al-Hinai, Al-Najar, and Al-Kalbani (2007) examined the potential of residential-type fog collectors built in the houses' vicinity (Figure 5). Schemenauer, Cereceda, and Osses (2003) revealed the following conditions should be met for a feasible and effective fog extraction project:

1. Fog has to occur regularly during the year and is likely to continue for a relatively long period.
2. The collection of fog water is mainly attributed to high-level locations with relatively high liquid water content.
3. The wind must accompany the aggregation of fog to enhance the performance.

Figure 5: Fog collection project in Oman (Abdul-Wahab et al., 2007).

Today, the major challenge in the collection of fog is the low efficiency specified as the ratio from water reaching gutters to the normal water flux from the collector mesh (Montecinos, Carvajal, Cereceda, & Concha, 2018). Dual limitations are imposed on the wire meshes currently used to collect fog: coarse meshes do not efficiently catch microscopic fog droplets, whereas fine meshes suffer blocking. Shi, Anderson, Tulkoff, Kennedy, and Boreyko (2018) proposed a way of avoiding such problems; they replaced the conventional cross-like mesh using small-scale, vertically arranged wires. Furthermore, Tian et al. (2017) showed high efficiencies in the directional transport of water by spider-web mesh assembled by low-cost cavity-micro-fibre.

FogQuest is a non-profit with fog harvesters deployed worldwide, which started conducting its projects in 1987 (FogQuest, 2020). Since the mesh is installed as a wall, the high wind easily damages the mesh, as it is the weakest part of the structure. The evolution of the FogQuest is the Warka Water Tower designed by an architect (Hobson, 2016). It provides the user with a common space and shade. The tower is conical, 30 ft high and 13 ft in diameter. It costs approximately 1500 dollars and produces 80 l/day. Design opportunities remain in structural costs and size. However, these devices are highly reliant upon the filaments' size and material that form the net for the collection of fog and should therefore not be discarded as an excellent method of water supply mitigation.

Figure 6: A community surrounds a warka water tower (Hobson, 2016).

Desiccant materials

Desiccant materials are widely used in the harvesting of water from the ambient air. Mohamed, William, and Fatouh (2017) depicts the concept of a solar-driven air-water generation system (Figure 7).

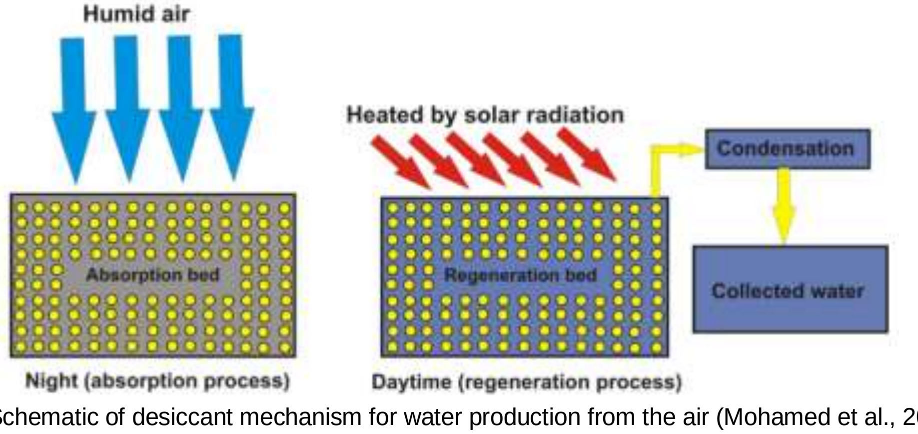

Figure 7: Schematic of desiccant mechanism for water production from the air (Mohamed et al., 2017)

Many researchers have presented their work on water extraction using solid, liquid and composite desiccant materials from ambient air (Table 2). For instance, H. Gad, A. Hamed, and I. El-Sharkawy (2001) introduced an integrated desiccant/solar collector system (1.42 m x 1.42 m) to produce water from atmospheric air. This system's result showed that it could provide about 1.5 l/m^2/day of pure water. At a glance of the absorption bed's design parameters, the sand weight to desiccant ratio affects the absorption rate and hence the rate of water generation. This issue is experimentally explored by (A. M. Hamed, 2003). Also, Kabeel (2007) proposed a pyramid system consisting of a multi-shelf solar system. In the experimental stage, the researchers used two pyramids with different beds. The first pyramid bed was built of saw wood, and the second one was made of cloth. The researchers saturated the beds with 30% $CaCl_2$ solution. The findings showed that the cloth bed has better results. The cloth absorption reached 9 kg with 2.5 L/day m2 of water production (Figure 8a).

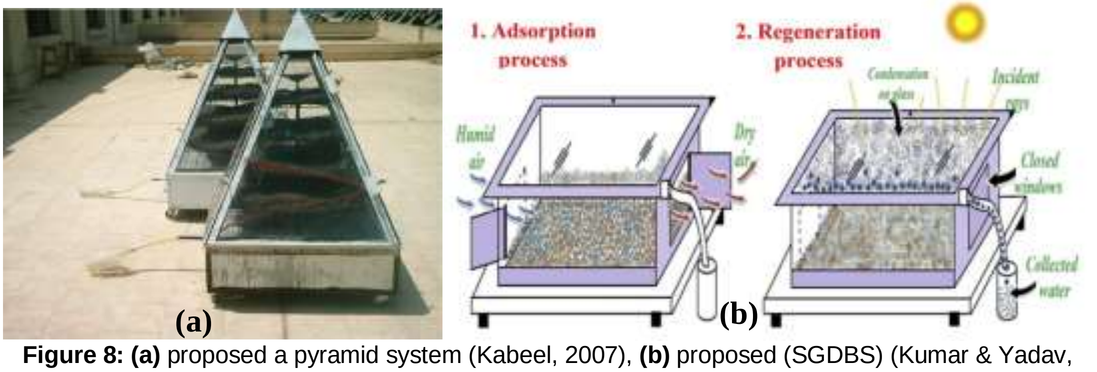

Figure 8: (a) proposed a pyramid system (Kabeel, 2007), **(b)** proposed (SGDBS) (Kumar & Yadav, 2015)

Ji, Wang, and Li (2007) used MCM-41, a highly efficient water-absorbent, as a hosting material with $CaCl_2$ as a desiccant to produce water from atmospheric air. This study's findings showed that the new composite material was a better absorber than silica gel, and it has a lower desorption temperature. Also, Ahmed M Hamed, Aly, and Zeidan (2011) introduced a desiccant/collector solar regenerator with an area of 0.5m^2 for atmospheric water production in Saudi Arabia. The study used $CaCl_2$ (30% concentration) as a desiccant material and sand as a host bed. The findings showed that freshwater generated could be reached one l/m^2/day. Besides, (Kumar & Yadav, 2015) presented a solar glass desiccant box type system (SGDBS) to produce water from atmospheric air (Figure 8b). This system used the new composite material, including saw wood and $CaCl_2$. The host material was the saw wood, while $CaCl_2$ was used as a hygroscopic salt. The experiments were used during day and night with different salt concentration for absorption and water production, and the best results were obtained for 60% concentration, and water production was 180 ml/kg. Also, Kumar and Yadav (2016) used Vermiculite/Saw wood floral foam (10 x 30 $cm^{3)}$ composite as a host material with different concentrations: 9, 16, 23, 28, 33 and 37% of $CaCl_2$ for extracting water from atmospheric air. The maximum amount of produced water was 0.35 ml/cm^3/day with 37% $CaCl_2$ concentration, leading to 76.44% for system efficiency. Kumar and Yadav (2017) repeated all the previous steps by replacing Vermiculite/Saw wood composite as a host material. The maximum amount of water produced was 195 ml/kg/day using this composite.

William, Mohamed, and Fatouh (2015) designed a fibreglass trapezoidal prism, and they used solar energy for producing water from atmospheric air. This study increased the bed surface by making the collector with multi-shelves, and they used two types of host materials, namely cloth and sand, that were saturated with $CaCl_2$. The percentage of 30% $CaCl_2$ concentration produced 2.32 and 1.23 kg/m^2/day evaporated water for cloth and sand with a system efficiency of 2.93 and 17.76%, respectively. Also, Srivastava and Yadav (2018) collected water from air using a novel design of 1.54m^2 Scheffler reflector experimentally. They investigated three absorber salts: $CaCl_2$ LiCl and LiBr with a 37% concentration and sand as a host material. The maximum production of $CaCl_2$, LiCl and LiBr composites was 115 ml/day, 90 ml/day and 73 ml/day in 270 min, 330 min and 270 min, respectively, while the annual cost of production was \$0.53, \$0.71 and \$0.86. Besides, Wang et al. (2019) presented an interfacial solar heating system based on the salt-resistant GO-based aerogel. The study used a liquid-sorbent atmospheric water generator at a high concentration ($CaCl_2$ 50 wt% solution). The results showed a clean water amount of (2.89 kg/m2/ day) with about 70% RH through solar input only, and the desorption efficiency was up to 66.9%. Generally, harvesting water from atmospheric air using desiccant materials still under research. Different parameters of desiccant properties and proper system design mainly affecting water productivity and system efficiency. Therefore, desiccants regenerative approach is considered as a promising solution for water supply in the tropical built environment.

Table 2: Atmospheric water harvesting systems using desiccant materials.

Reference	*Location*	*Procedure*	*Desiccant*	*Water production*
(H. E. Gad, A. M. Hamed, & I. I. El-Sharkawy, 2001)	Egypt	Experimental & mathematical	$CaCl_2$/ corrugated cloth	1.5 *l* /m^2/ day
(Kabeel, 2007)	Egypt	Experimental	$CaCl_2$/ saw wood	2.5 *l* /m^2/ day
(Ji et al., 2007)	China	Experimental	$CaCl_2$/ MCM-41	1.2 *kg* /m^2/ day
(Ahmed M Hamed et al., 2011)	Saudi Arabia	Experimental	$CaCl_2$/ sand	1.0 *l* /m^2/ day
(Kumar & Yadav, 2015)	India	Experimental	$CaCl_2$/saw wood	180 ml/kg/day
(Kumar & Yadav, 2016)	India	Experimental	$CaCl_2$/floral foam	35 ml/cm^3/day
(Kumar & Yadav, 2017)	India	Experimental	$CaCl_2$/Vermiculite/Saw wood	195 ml/kg/day
(William et al., 2015)	Egypt	Experimental	$CaCl_2$/ cloth	Cloth = 2320gm/m^2 Sand = 1235gm/m^2
Srivastava and Yadav (2018)	India	Experimental	LiCl, $CaCl_2$ and LiBr/ sand	LiCl = 90 ml/1.54m^2 /day $CaCl_2$ = 115 ml/1.54m^2 /day LiBr = 73 ml/1.54m^2 /day

CHALLENGES IN THE IMPLEMENTATION OF AWG INTO TROPICAL BUILT ENVIRONMENT

The lack of water resources has a detrimental effect on urban growth and residents' basic lives and has become one of the critical factors hindering social development (Hashim, Hudzori, Yusop, & Ho, 2013). Also, observational research into the efficiency of alternative water supply technologies is urgently needed to be carried out in the built environment in line with sustainability goals (Imteaz, Ahsan, & Shanableh, 2013).

Efforts to establish sustainable water supplies, in general, must be driven by a clear and integrated national strategy (Mourad, 2020). Through national water and climate change policy, RWH implementation must be integrated, institutionalised and updated. The development of RWH systems can be authentic and coordinated by enacting laws and promoting detailed directives. The costs of constructing, maintaining and using RWH are considerably higher than those for domestic water. A comparison of the cost of RWH with domestic water is needed for promoting the RWH system as an alternative to the water supply.

RWH might not be the most suitable option for alternate water supplies in the short term, but it will be possible to reduce water consumption. Consequently, creative technological methods to upgrade RWH into the new and existing buildings must also be implemented to make RWH an integral part of the water supply system. The tropical building envelope should be utilised to enhance sustainability. However, further quantitative investigations are needed in the tropics (Ariff, Ahmad, & Hussin, 2019).

The amount of water in the air ranges from one ml to more than 30 ml per cubic metre in hot, humid regions (Lehky, 2017). Passive dew condensation method could naturally be implemented into tropical buildings for water collection from ambient air. Water yield from this method is limited and affected mainly by environmental conditions. However, radiative dew condensation systems could be integrated into RWH systems to provide an acceptable water amount. Besides, water vapour absorption into a hygroscopic substance is another effective way of collecting water in the built environment. Absorbers have a broad ability to bind water and can be transported easily. Without other air pollutants and odour, it selectively absorbs water vapour. Generally, this method could collect more water than dew condensation, especially in the tropical climate, which enjoys a high relative humidity (usually more than 90% during the night). In addition, integrating renewable energy such as solar panel (PV) or wind into those systems would increase the system efficiency and hence water yield. Also, fog collectors' projects presented themselves as an effective solution to overcome water shortage, especially in developing countries. Such a method could be adjusted to provide sufficient water for the built environment community. However, fog collection systems could be established only in specific tropical locations with regular fog occurrences and adequate wind speed.

A comprehensive awareness of the environmental changes and the resulting adjustment and mitigation of water resources is essential for sustainability development. Thus, an alternative, convenient and low-cost source of clean water for the tropical environment is increasingly required. Moisture harvesting systems do not replace traditional water systems that are accessible and sufficient, but where these alternatives are limited or costly, moisture harvesting systems may provide a sustainable source of tiny amounts of drinking water, especially during disaster events. Furthermore, in tropical or coastal regions which are warm and humid, atmospheric moisture harvesting should be more cost-effective. However, it cannot compete with the basic rainwater harvesting system (Sharan et al., 2011). Much testing and experience in the pilot projects are required before this technology can be sufficiently matured.

The topical built environment requires an effective way of collecting clean atmospheric water. This approach should be simple and reliable. It can work for a village or even households in small decentralised units without the need for costly piping systems. No fossil energy should be required. It should be easily sponsored and installed on-site from readily available materials even by uneducated people.

CONCLUSION

This study examined passive approaches and methods to produce water from the air in the tropical built environment. RWH and AWG were discussed to understand their potential, challenges and limitations to produce water on-site in the tropics. Even though RWH has emerged as a solution towards the water shortage problem, harvested water is polluted by microbiological contaminants and pathogenic organisms. Besides, RWH involves interconnected challenges, including environmental, political, economic, social and technological aspects. It is clear that there is an urgent need to introduce sustainable alternatives for water supply, such as AWG. For instance, fog collection might be applicable in high regions with 100% RH or near to oceans with a sufficient wind speed. The sorption/ desorption approach (desiccant materials) is highly recommended to produce water from the air in tropical buildings. Radiative dew condensation has a limited amount of produced water. Therefore, radiative dew condensation systems can be incorporated into the tropical building structure such as roofs and car parks in the future.

Furthermore, integrating renewable energy into either dew condensation or desiccant systems would increase water production with no effects on the tropical environment.

Moreover, with more research, AWG can be more efficient and cost-effective in tropical buildings. Despite various challenges, this study highlighted the possibility of harvesting water sustainably from the atmosphere to supply clean drinking water to buildings in the tropical climate areas.

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