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The Impact of Climatic Variations on Thermodynamic Performance of Atmospheric Water Harvesting in Iraq

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ABSTRACT

This paper examines the effect of climate fluctuations on the thermodynamic efficiency of AWH systems in Iraq as a country that suffers from water rationing due to its unfavourable climate condition. The climatic conditions of Iraq are high temperature, a low amount of rain, and humidity variability, which creates prospects and constraints for applying AWH technologies. The study first gives the reader a general background of AWH systems which involves the removal of moisture directly from the air by methods such as condensation, fogging and the use of sorbents. These systems are especially helpful in places like Iraq where climate change and the over extraction of water from rivers and aquifers make the conventional sources of water inadequate. In the review, the major emphasis is given to the thermodynamic aspect of the AWH systems, with the climatic environment of Iraq considered. A comprehensive evaluation of the various adsorbent materials that are crucial for the optimization of AWH system is also provided. The paper assesses how change in temperature and humidity affects the moisture collection ability of these materials. Also, the study presents the system design factors that require the understanding of the climate in Iraq to enhance water production and energy consumption. The environmental and socioeconomic consequences of implementing AWH technologies in Iraq are assessed with reference to the possibility of dealing with water shortage challenges in the rural and urban settings. Vulnerabilities of expanding AWH systems are also discussed in the paper, such as material costs, energy, and physical structures. Lastly, it outlines the research agenda for enhancing the AWH technology and its application to the national water resource planning in Iraq to address the water scarcity problem sustainably.

1. Introduction

Water conflict and stress has rapidly become a serious issue at the global level as billions are being affected. Globally about 2.1 billion people do not have access to clean water for drinking, and 4.5 billion do not access sustainable sources of water for washing and sanitation. It is against this background that it becomes evident that there is a major need to come up with new strategies in tackling this increasing problem. For instance, in Iraq climatic factors contribute to water scarcity because of long dry season and intermittent rainfall, traditional supply solutions are no longer adequate. Dependence on surface and ground water is not sustainable and is also vulnerable to climate change shocks and other upstream interventions that regulate river flows.

Over and above, as people continue streaming in the region more demands they have for fresh water sources. FAO has informed that water demand is rising at a faster pace than the population, which will engage competition for this precious commodity. This state of affairs calls for evaluation of other options to standard procurement strategies of

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water such as desalination or pumping of groundwater which has its own problems in relation to cost, energy usage, and effects on the environment.

Atmospheric Water Harvesting (AWH) can be presented as a relatively new technology involving the recovery of water from the air, as an efficient and contemporary means of water sourcing for areas, which may experience certain issues with conventional water acquisition. AWH employs different mechanisms including condensation, fog harvesting and others like the use of sorbents that can be optimized depending on the climatic conditions of the places the technology is applied. Since water vapor is present in many regions of the world and, particularly, in Iraq, AWH can contribute to alleviating some of the grave problems related to the ever-growing water deficit.

Some of the current works have established significant enhancements in AWH technologies with a focus on their applicability across various climate conditions. As nations work towards more sustainable development goals that include provision of clean water, AWH presents a decentralized method of producing water that can stand alone from the current utilities and power systems.

Moreover, Iraq has another climatic condition requiring particular attention, such as a high temperature and humidity difference that should be considered while developing AWH systems tailored for Iraq only. It is possible that such specific approaches would give more accurate results not only in terms of the amount of harvested water, but also in its quality.

As research focuses on improving AWH practices with respect to their ecological impact and socioeconomic effects, it is possible to develop optimism for the integration of these systems into Iraq's overall strategies for managing its acute water scarcity problems. The main effects of successful AWH technology implementation include enhanced living standards and enhanced ability to deal with future climate related problems, [1], [8], [30], [9], [3] and [24].

2. Fundamentals of Atmospheric Water Harvesting

2.1. Definition and Principles

Atmospheric Water Harvesting (AWH) is a process of direct collection of water present in the atmosphere as vapor or in minor droplets form. This new technology is already becoming apparent as a sustainable solution to water shortage, especially where conventional water sources are scarce or unsteady. AWH stands on the principle of condensation and adsorption where by it simply relies on the air humidity in producing drinking water.

The increasing interest in AWH is mainly because more people in the world today are experiencing water scarcity than before, particularly in the arid and semi-arid areas. What is curious that the Earth's water contained in the atmosphere is thought to amount to approximately 12,900 km3, which significantly exceeds the total river water volume. This resource is readily available and makes it possible to produce fresh water in many centers without use of water in liquid state.

Typically, AWH technologies can be categorized into three main types: methods such as condensation techniques or fog harvesting systems, or through sorbent based methods. Condensation methods as applied to air are normally centered on the cooling process of air below its dew point temperature which enables the conversion of vapor to water and/or liquid form. This can be done using refrigeration systems or passive systems intended to improve thermal exchange effectiveness.

Fog harvesting involves use of nets or surfaces that can catch individual fog droplets or surfaces that can induce droplet coalescence for later collection. Even though it has been previously employed in different places, it is currently receiving increased attention because of the developments in the material science and engineering.

Sorbent-assisted AWH takes advantage of materials that can absorb moisture from the air at certain conditions and discharge it at other conditions e.g. when heated. Such materials may contain the latest hydrophilic molecules for enhancing the intake of water as well as the minimum energy needed to discharge it. Recent work has identified new materials like metal-organic frameworks (MOFs) as potential candidates for these uses because of their unique physical properties including high surface area tunability.

Environmental conditions which represent major factors that define the performance of AWH systems include humidity and differential temperature of the local environment within different seasons of the year. Knowledge of these factors is important when it comes to designing the system since it informs the scaling, sizing of the system and how is will interface with the already existing systems.

Another strength of AWH is its applicability to situations where it is impossible, or undesirable to develop centralized water delivery systems, for instance in rural areas. As a distributed form, it has the robustness against disruption typically associated with centralized systems and encourages sustainable behaviour by lessening dependence on conventional freshwater sources.

Consequently, AWH encompasses various methods of covering diverse aims of moisture capture based on condensation techniques or environmental-specific sorbents. Exploring the possibility of this technology could be used in solving the existing scarcity of fresh water all over the world, as a viable substantive for many communities around the globe, [1], [8], [14], [9], [2] and [21].

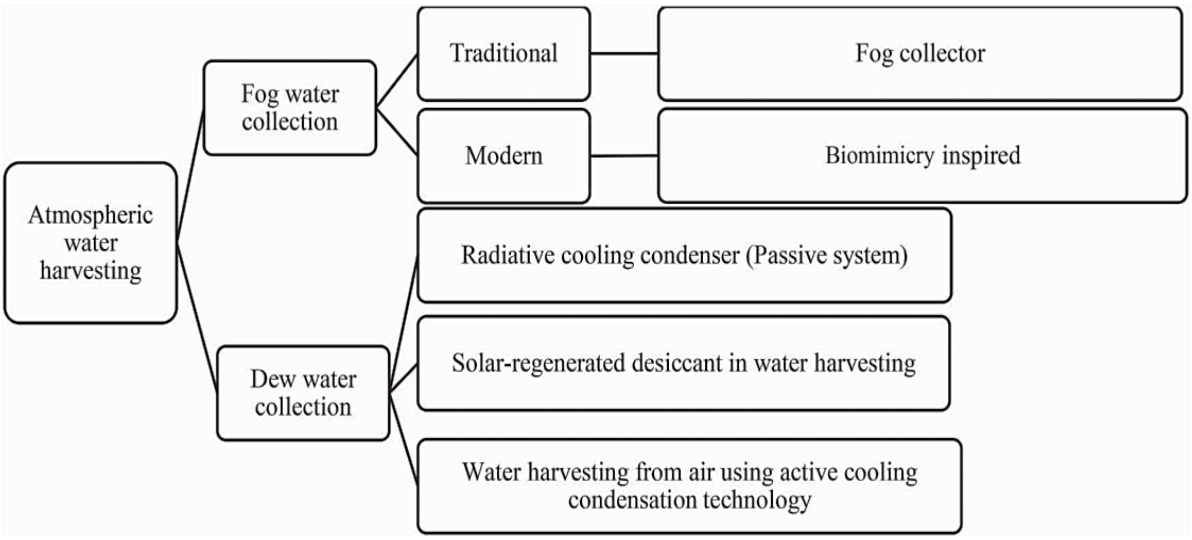

Figure 1. Categories of atmospheric water harvesting techniques, [9]

2.2. Types of AWH Systems

There are two subcategories of AWH systems depending on the working mechanisms which include the active and passive systems. Autonomous systems employ the processes of fog harvesting or dew collection to collect moisture with the least amount of power. These systems normally have extensive exposed surfaces, such as mesh nets, through which it can condense as water vapor cools.

While passive AWH systems must be active all the time, active AWH systems need energy to increase the efficiency of water extraction. This category includes, atmospheric water generators (AWGs) which operates with air cooling where the temperature of air is cooled to below its dew point to create water vapor condensation. Techniques falling within this category include vapor compression cycles (VCC) and thermoelectric cooling.

Active systems use characteristics of the active systems due to their efficiency, yet they also contain characteristics of passive systems since they have their weaknesses. For instance, a partly integrated structure might integrate VCC technology with desiccant materials for raising the humidity before the condensation of water to obtain higher water production rates and lower overall power use across different climate zones.

New developments in material science have greatly improved the AWH systems efficiency, as major improvements have been achieved in their performance. New generation adsorbent materials, specifically metal-organic frameworks MOFs show enhanced performance in terms of traditional adsorbents like silica gels with optimized water harvesting efficiency based on humidity and temperature parameters.

Sorbent based processes are also important in AWH technologies where vapor is captured using desiccant materials during low humidity and released back into the air by either thermal or pressure changes by means of low grade energy sources such as solar energy.

Fog harvesting can be used in the fogs areas requiring natural climatic conditions without employments of mechanical means and high energy inputs. In the same way, dew harvesting also operates by using outside air, cooling it at night so as to be able to induce condensation from the humid air. The selection of AWH technology is determined by the regional environmental conditions such as fluctuations in temperature and humidity, which are characteristic of the climate in Iraq. Current research is dedicated to improving this categorization in order to increase effectiveness in addressing the global water deficit, [1], [5] and [15].

3. Climatic Characteristics of Iraq

3.1. Temperature Fluctuations

Iraq's climate has the effect of having an increase in average temperatures seven times the global rate and of this rate, this results in an increase in the rate of evaporation thus affecting the availability of water in agriculture, industry and homes. The hot season lasts from June to September, and the temperature tops 50 degrees Celsius; moreover, the increased evaporation of water from sources such as the Tigris and Euphrates rivers. These rivers' projections suggest that their flows may decline by 30% to 70% by the end of the century because of warming and shrinking precipitation.

Cool dry season is from December to February having cold climate, frost and even snow in the northern regions of the country. Some of the winter rains help to replenish water resources while others are a problem in water conservation and in planning crops. Climate models give a projection of the distribution of rainfall, while some areas will be experiencing floods the other will be facing a drought season. This inconsistency interferes with conventional farming and poses challenges to food stability since farmers cannot predict the seasons for planting crops adequately.

Moreover, problems in water management are compounded by Iraq's neighbors: these countries build dams across shared rivers to control the water flow, thus, reducing water availability for irrigation at critical times. These climatic as well as geopolitical factors are not only a threat to agricultural yield but also to socio-economic cohesiveness.

Which are now highly exposed to undesirable natural weather circumstances and conditions these have made the population highly sensitive due to the prevailing harsh weather to which they are constantly exposed hence forcing them to seek other better resources and other opportunities outside farming. It is important to get to know how temperature variations influence local water vapour cycles for the development of suitable and efficient atmospheric water harvesting technologies adapted to the climate of Iraq [22], [18], [27] and [16].

3.2. Humidity Levels

Iraq weather plays a great role in density of humidity, which is crucial in atmospheric water harvesting systems. It prevails in a region characterized by an arid to semi-arid climate where temperatures are usually high, and humidity is variable. Provinces in the south receive higher humidity near the Tigris and Euphrates rivers while provinces in the north display varied trends in humidity hence influences AWH effectiveness.

Relative humidity is very important for absorption of water in the air because it defines amount of moisture present in air. It varies according to season and geographical areas, but in Iraq it can be in between 30% and 70%. In the coastal and northern regions, the conditions remain relatively humid during winter as opposed to dry winter but a humid summer.

This is made more complicated by variations in temperatures where it can be as hot as 40 degrees Celsius in summer and as cold as below freezing point in winter, especially at high altitude. This temperature difference poses a challenge on the performance of AWH by affecting dew point temperatures, that is, the temperature at which water vapor turns to liquid. They have proved that effectiveness in AWH depends on condensation, which has a strong relationship with humidity and temperature. During the humid period of November to March, larger water harvests are possible because of humidity ; during May-September the possibility of water harvesting is low because of low humidity.

It is the rates of evaporation that also determine humidity and likely to rise with climate change and projected to be 11% to 25% in some areas for the next few decades. When evaporation goes beyond moisture replenishment from rain or irrigation, water shortage problems are escalated.

Higher temperatures and decreased precipitation frequency due to drought increase the extent of crop damage and the regional humidity needed to operate AWH systems. However, great dryness is more evident in most places despite the moisture in the atmosphere.

With urban population targeted to hit 70-80 million in the year 2050, there is a strong need for efficient AWH technologies. Successful implementation needs to take into account climatic conditions of the region and regional differences especially between hot southern provinces and relatively cooler northern provinces. Adaptive management of AWH solutions is necessary to address these variations in order to improve water security in the different regions of Iraq, [18], [22], [3], [26] and [16].

3.3. Precipitation Patterns

Iraq has observed rapidly changing rainfall regime in the recent past due to climate change and regional environment policies. The country receives an estimated average rainfall of 154mm per annum though there is this variability in different countries. Meanwhile, the northeastern part of the country which is mountainous experiences a rainfall of about 1,200mm per year whereas the arid southwestern region may be lucky to receive less than 100mm. The rains are from October to April most of which is important for water supply and demand.

Since early nineteen nineties Iraq has experienced a significant decrease in precipitation rates. Some of the findings show that in the last forty years the flow of water from the Euphrates and Tigris rivers has reduced by 30/40 percent. This has lead to worsening of the drought conditions, affective crop yield as well as availability of water in the area. As it suggested in 2021 Iraq had its second drought season in four decades owing to record low rainfall and a record of high temperature increase and evaporation.

In future, due to the fluctuating pattern of rainfall, the hydrological problems in Iraq changes according to the regions of the country. For instance, some areas are flooded often as in Maysan Province, while others are still experiencing severe drought. Such floods happen usually after a long dry season, and due to the fluctuation between the two, infrastructure is always at risk and many people are left homeless.

Further, the precipitation scenario is not very smooth for Iraq due to certain geopolitical factors. Security of the water supply depends on regional water management policies that affect the flow of rivers that supply most of Iraq’s fresh water. Larger portions of the water Iraq used to receive from the upstream countries are being either dammed or diverted to other uses during the key wet season.

Analyzing climate changes, researchers found that the level of precipitation will continue to decline unless global warming rates are changed. It has been predicted that alterations of snow cover in adjacent mountainous regions may diminish the contribution of melt water to the Iraqi river during the projected periods of irrigation demand.

The effects described for AWH mean that shifting precipitation regimes have major consequences; these require approaches grounded in local climate. In order to develop or sustain improved AWH systems in Iraq, it is imperative to better understand these changing dynamics of precipitation.

Lastly, the multiple effects of precipitation in different areas will have to be solved for the preservation of natural hydrological cycles and development of the sustainable water management that Iraq needs, [29], [34], [19] and [27].

Figure 2. A street in the Iraqi capital, Baghdad, [29]

4. Thermodynamic Analysis of AWH Systems

4.1. Energy Balance in AWH Systems

One of the most important research areas associated with AWH systems is managing energy balance within the system which can significantly influence practical applicability of the technology in countries where water scarcity is a major issue such as Iraq. AWH employs different methods of removing moisture from the air and some of them are; adsorption and condensation. Every technique comes with specific thermodynamics that determine the amount of energy to be used in a process.

For example, adsorption-based systems usually use a desiccant material to collect humidity during time of high humidity to release the water through heating in the form of liquid water. This cycle process of energy requires moderation in power input to achieve increased water discharge with minimized energy expense. These kinds of systems are more or less efficient depending on the environment where they are operating, for example the temperature and humidity levels that surround them. It was reported that in the low relative humidity conditions below 10%, the energy required for AWH can be much higher than that for conventional desalination processes.

The theoretical foundation of AWH is dependent on thermodynamics, laws of heat, and energy and concepts such as the second law of thermodynamics that defines the amount of work necessary to draw water from air under certain conditions. Optimized high efficiency of AWH desalination system can produce hundreds of liters per kilogram of the desiccant material per day depending with the RH and ambient temperature but these efficiencies may slightly change when the environmental conditions change.

Besides constraints associated with inherent thermodynamic properties, the concept of the system has a great influence on the optimization. Implementation of latest material and the designs like the two stage cycles that can reuse the heat energy during the cycle can go a long way in reducing energy requirements during the two phases of adsorption and desorption. It is understood that enhancing certain aspects such as airflow rates through adsorbent beds or using phase-change materials might enhance production of fresh water by a large margin while at the same time not proportionately enhancing energy use.

However, they have local influences including daily temperature changes and seasonal changes that should be considered when evaluating the annual performance capability of AWH technologies in Iraq. For instance, higher temperatures enhance the evaporation rates but may also imply the need to use enhanced cooling methods for system efficiency during such periods.

Energy utilization per unit of mass (kWh/kg) is an important parameter when comparing the various options of AWH technologies to the regional climatic factors. These metrics are valuable to compare different methods in terms of operational costs and their impacts with sustainability. Some of the newer AWH technologies demonstrate potential for decentralized water production, which is especially important in regions where access to centralized water supply is limited; however, such technologies require significant capital costs and maintenance because of the complexity of their designs.

These dynamics, when fully understood relative to Iraq's climate, can enable the rational adoption of AWH technologies by the decision-makers, where costs of initial implementation that could substantially drive operational costs are weighed against pressing needs in water scarcity that must be urgently addressed, [1], [12], [11], [6], [13] and [23].

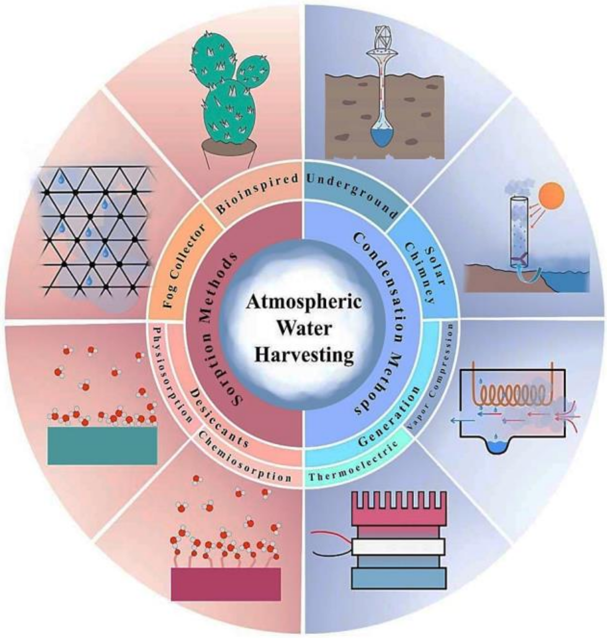

Figure 3. Atmospheric water harvesting methods, [8]

4.2. Efficiency Metrics for Local Conditions

Since AWH systems depend on the ability to extract water from the air, the efficiency of such systems determines their real-world use in Iraq, which features large daily temperature and humidity ranges. If we are to assess efficiency of these systems, we should look through different parameters which can be regarded as important for specific local climate. One of them is the water production rate that shows how many gallons of water one can collect in a given period. This rate is highly dependent on relative humidity (RH); usually the higher RH is the better the performance. For example, under conditions of 40°C, 40% RH, some models are estimating that AWH systems are able to remove approximately 3.8 kg of water in an hour.

Energy consumption is another major parameter, which allows estimating the effectiveness of a facility. For the project to be economically viable, it is necessary to reduce the energy utilized per unit volume of harvested water. Energy requirements differ in the AWH systems that use desiccant materials or those that rely on solar energy; the consumption depends on climate conditions and the particularities of system construction. The heat energy that is required for the extraction of heat from the atmosphere for different systems varies from about 0.38 kW h/kg for absorption system to over 1.16 kW h/kg for conventional adsorption system.

The performance of AWH can be effectively evaluated using thermodynamic assessments. Exergy analysis enables evaluation of the efficiency in using the available thermal and mechanical energies for producing useful work, which is extracting water from the air in a solar still. This analytical method offers an understanding of possible improvements in other temperature and humidity conditions characteristic of Iraq's climate.

In an attempt to enhance system efficiency even more, the relationship between operational parameters must be fine tuned and optimized, including mass flow ratio, daily temperature fluctuations and humidity changes. To this end, different configurations have been modeled, for instance, optimization of the size of the harvester and the power settings to maximize the yield of water while minimizing energy consumption.

Further, the progression in materials science has made refined adsorbent materials to be available in the market, including Metal-Organic Frameworks (MOFs) that can efficiently improve energy optima over several conventional adsorbents for various operational conditions because of temperature responsive adsorption characteristics.

The economic effectiveness of AWH also depends on the life cycle cost per cubic meter of the treated water (LCoW). Decisions related to the precise RH limit below which the system should stop the processes are crucial for minimizing the storage expenses as well as maximizing yield when the climate is stable.

Realizing these efficiency measures will enable stakeholders in Iraq, and other desert environments, to make informed decisions on design, implementation and, possibly, replication of AWH technologies suitable to the regional climate [6], [11], [10], [23] and [7].

5. Performance of Adsorbent Materials in Iraqi Conditions

5.1. Comparison of Adsorbent Materials

This paper focuses on the importance of adsorbent materials to AWH systems and their efficiency and performance when implemented in a country like Iraq. The adsorbents that have been well investigated are silica gel, zeolites, Metal Organic Frameworks (MOFs) and advanced polymers of which these adsorbents possess different characteristics that determines the degree of water adsorption.

Silica gel is probably the oldest adsorbent used for the moisture sealing and is widely recognized by the large surface area and high porosity. They are most effective at capturing water vapour when the relative humidity level rises above 30% but hardly capture where the relative humidity level is low. Likewise, advantages exist within the zeolite structure because the microporous character enables the adsorption of specific molecules only. However they may not be effective in very rapid application due to their slower adsorption kinetics.

Metal-organic frameworks are a novel type of adsorbents that have stirred interest due to their high capacity for water vapour adsorption even at low RH. Studies, in fact, reveal that MOF-303 can take in a large amount of water vapor; it can take 0.7 liter per kilogram of the MOF even at 10% RH. This exceptional capability makes MOFs particularly suitable for the areas of challenging climate similar to that which the Iraq faces.

On the other hand, much attention has been paid to polymer based adsorbents for AWH systems due to their feasibility. It is possible to adjust these materials to improve the desired properties like hydrophilic and thermal conductive. They might not however, achieve the same MOFs total water absorption capacity but they have other benefits such as low cost and easier to process.

The effectiveness of these adsorbents can be evaluated by the means of the water production potential (WPP) and energy consumption (EC). For instance, investigations show that by employing ionogel based adsorbents, WPP of about 1.55 kg/kg/cycle can still be reached even with fairly low energy intake as compared to the conventional systems. In this case, another type of MOF known as MIL-101(Cr) exhibits a slightly lower WPP but performs as excellently under the same operating conditions.

Another factor that is significant is the rate of adsorption and desorption of each material; there are adsorbents that may well and truly employ water but will take some time to release the water through desorption resulting from change in temperatures or some other factor. The design of the systems requires a balance between the absorption rates and the desorption efficiency to be effective.

In conclusion, it is currently seen that each kind of adsorbent has its advantages and its disadvantages and future consequently appear to be in development of hybrid systems or systems that uses different adsorbent materials together or new designs for better performance in these all climates. Further investigation on superfluidity within microporous channels also reveals indications for improved transport speeds in these systems [1], [8], [14], [9], [21], [25].

5.2. Material Suitability for Local Climate

This study reveals that the adsorbent materials in AWH for Iraq are influenced by climatic and operational conditions. Being an arid to semi-arid country, Iraq has relatively low humidity and therefore the chosen adsorbents need to be effective in desiccation of the received air masses. Some of the materials, like Metal-Organic Frameworks (MOFs) are especially attractive because of their large surface area and tunable pore geometry that allows for their optimal performance even in relatively low RH conditions. For instance, MOF-303 demonstrated a great capacity by absorbing about 0.7 liter of water per kilogram from air at 10% relative humidity and at temperature of 27 °C.

However, besides MOFs, other conventional desiccants like silica gel and zeolites also put forth reasonably good prospects in the context of AWH in Iraq. These materials are inherently hydrophilic, meaning that they can capture moisture from the surrounding environment; however, they generally tend to need higher relative humidity than the MOFs. AHW systems designed to be appropriate to the climate in Iraq must not only have a high adsorption capability but also have efficient desorption processes. Choosing an appropriate material in an adsorbent must also take into consideration the kinetics of adsorption as well as the rate at which it can desorb the collected water during diurnal temperature fluctuation.

However, the stability of the adsorbent materials under the cyclic loading condition as well as its chemical stability are the other two factors which define its applicability. The adsorbent must not noticeably lose its performance in cycles of adsorption and desorption, which is especially relevant for Iraq, where the temperature varies greatly throughout the year. Stability is not a direct term, but when it is guaranteed long-term functionality and cost-effectiveness for AWH systems adopted across various areas of the country.

In addition, the use of new MOFs incorporated with the conventional desiccants may have better performance properties for the climatic condition in Iraq. These hybrid systems could take the best of each component in that they could trap moisture during the night when the temperatures are low and the humidity high, but could also immediately release the water during the day when temperatures are high.

Lastly, choice of the right materials for AWH systems in Iraq requires understanding of climatic conditions in the region, the fluctuations of temperature and humidity in seasons and requirements for the operation in the particular tasks like drinking water provision or farming. This way, if better adsorbent options are to be selected for consideration according to the above factors, it will enhance efficiency and sustainability of atmospheric water harvesting technologies in regions experiencing water scarcity challenges more seriously, [21], [14] and [8].

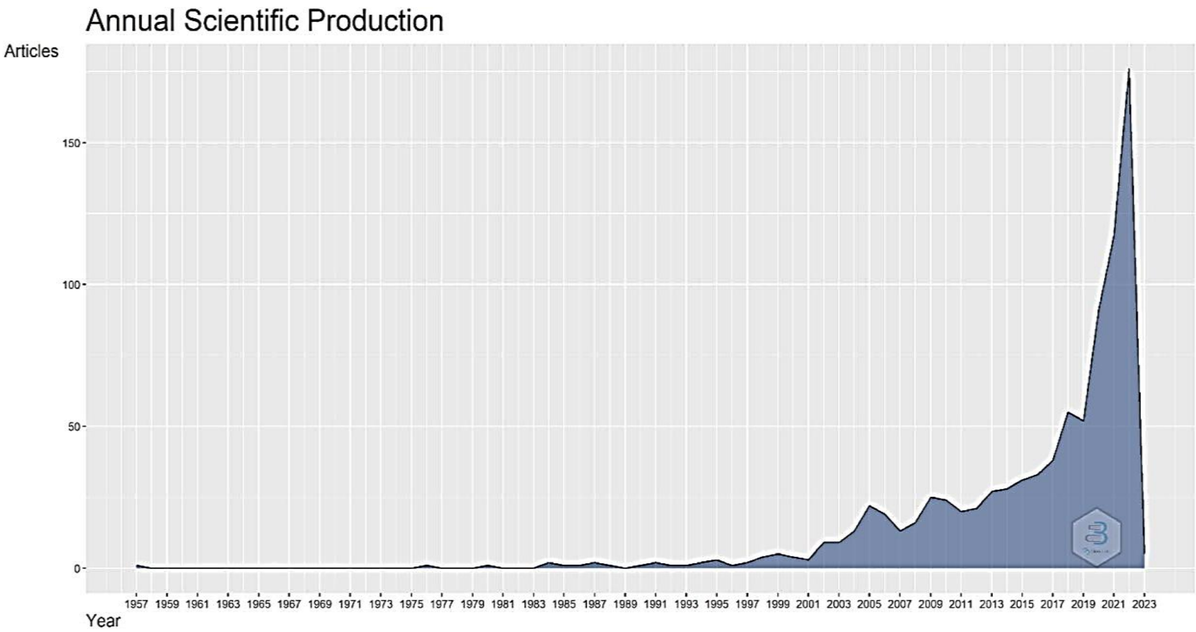

Figure 4. Graph the number of articles per year about water harvesting from air, [8]

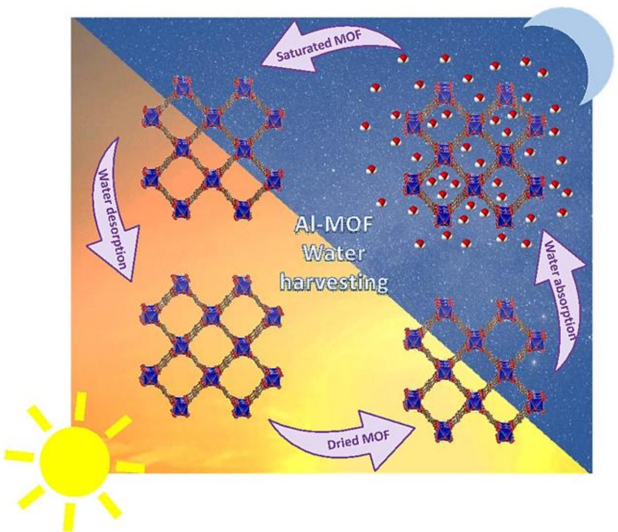

Figure 5. Steps of atmospheric water harvesting used desiccants, [8]

6. Impact of Climatic Variations on Water Harvesting Efficiency

Climate changes play a major role in the efficiency of the AWH systems in Iraq as temperature rises, humidity levels and precipitation change. Higher temperatures rise the rates of evaporation and reduce the level of relative humidity which makes collection of moisture challenging. A prime factor in Iraq is the climate; hot and arid, the temperatures in Iraq during heat periods are over 48°C and this makes it difficult to cool the air to below the dew point, which makes a lot of energy to be used.

It is also good to note that efficiency of AWH is directly linked to humidity; any relative humidity that is below 40% negatively impacts the efficiency of sorbent materials. On the other hand, high humidity is useful in improving the rate of moisture harvesting, though it is sometimes followed by low relative humidity due to the variance of seasons or long dry periods caused by climate change. Hence, it is relevant to devise a strategic plan to address fluctuated changes in order to maximize output.

Seasonal climatic changes also impact on the feasibility of different AWH technologies. For instance, fog harvesting may be optimal in some months and suboptimal when the fog that is needed is not present. They depend on certain weather conditions in order to implement AWH; this means that there is need to constantly monitor and or adjust the strategies in order to ensure that there is a constant availability of water all year round.

The other long-term forecasts point to escalating climatic conditions as a result of global warming, as being compounding factors that will make AWH systems prove even more difficult in Iraq. Rising levels of evaporation and changed patterns of precipitation have led to the decline of conventional water resources such as the Tigris and Euphrates rivers, and therefore such options as AWH are essential. Because the river flows vary with upstream dams and climate changes, AWH technologies have to correspond to change.

More strategic innovations like incorporating solar energy into the already established AWH systems could help reduce on energy issues regarding high temperature requirements while at the same time making systems sustainable. The research carried out in an attempt to identify ways through which effectiveness of the system designs can be achieved based on climate data is crucial in enhancing the the performance in various conditions. Knowledge of regional climatic conditions shall assist in identifying, appropriate adsorbent material for the prevailing climatic condition in Iraq thus helping in future changes, [1], [36], [22], [4], [30], [3], [23], [7] and [16].

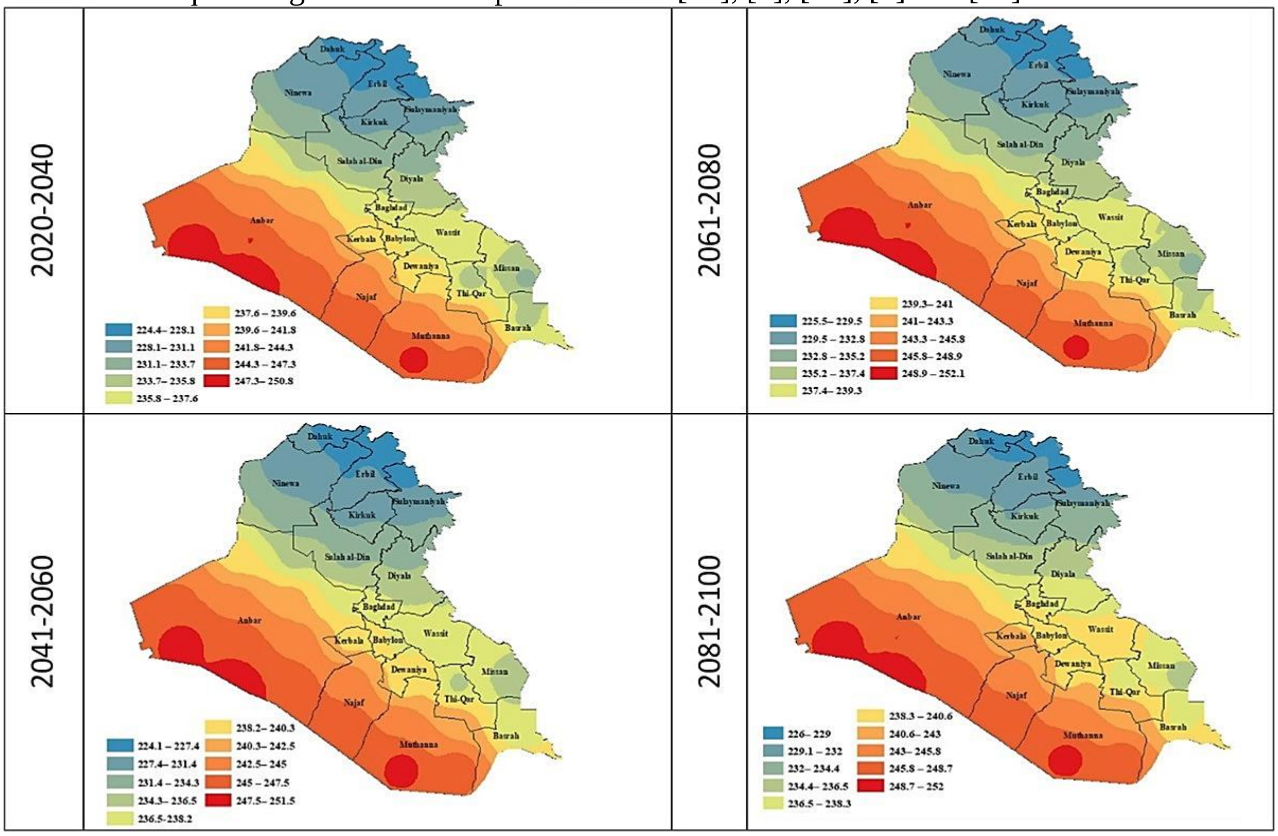

Figure 6. Projected annual average changes in solar irradiation for the periods of 2020-2040, 2041-2060, 2061-2080, and 2081-2100 based on the climate model RCP2.6, [16]

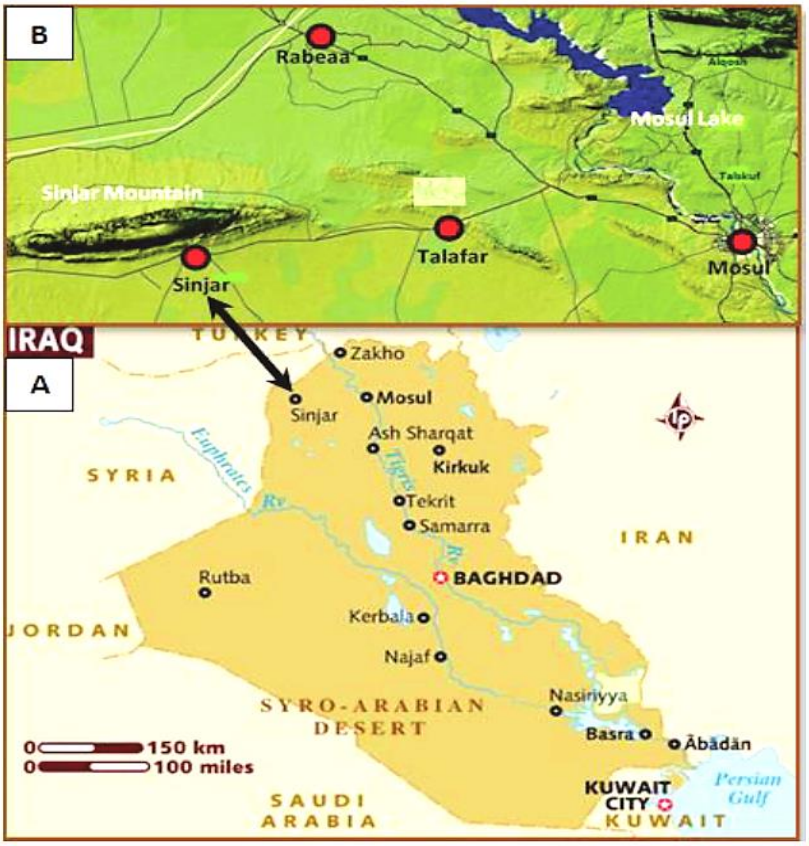

Figure 7. (A) Map of Iraq shows the Sinjar District, (B) Meteorological stations: Rabeaa, Sinjar, Talafar and Mosul, [30]

7. System Design Considerations for Iraqi Conditions

7.1. Sizing and Scaling of AWH Systems

If the physical and economic characteristics of the AWH systems are to be defined and its applicability at a large scale in Iraq is to be assessed, the knowledge of the local climatic conditions, technological possibilities, as well as users' demand and expectation is crucial. Therefore, the technical feasibility of AWH systems calls for an evaluation of the required future water harvesting volume to maintain the system's sustainability and functionality. This sizing process begins by evaluating the usual humidity and the temperature variation common to every area of Iraq and focusing on the arid or semi-arid zones.

The adsorption methods for the selection of suitable technologies involve the basic technologies used for the extraction of water at its highest levels, as well as hybrid technologies that incorporate the most effective techniques. The study reveals that the adsorption systems using metal-organic frameworks or zeolite as the adsorbent material can increase moisture removal efficiency. These materials are highly efficient in the dry climatic conditions which prevail in many regions of Iraq and they are able to maintain a high rate of output even in low humidity conditions – which are not conducive for dew formation – that characterizes many parts of this country.

Extension of these systems for broader applicability involves increasing the sizes of such systems from modularity to sizes that can serve water needs of a given community. This transfer usually requires change in such parameters as the absorptive area of the adsorbent material and general layout to incorporate better air movement and heat exchange. Furthermore, expansion of the system calls for a determination of the energy consumption per liter of produced water; research currently shows that though AWH systems may consume more energy than desalination systems, for example, with technological development, AWH systems can be made cheaper in the long run.

In practice, the extent to which AWH systems can be scaled for other uses – from domestic to agricultural – can also improve scalability. For example, establishment of modular units enables a gradual build up as estimated by the demands and resources available. Another advantage of integrating renewable energy systems also enhances operation capacity yet decreasing reliance on conventional energy resources.

Furthermore, site surveys often using GIS that allows surveyors to determine suitable areas of installation depending on hydrological data and other physical characteristics. This strategic method ensures that identified locations enable efficient operation and correlate with local infrastructural options.

Therefore, in order to size and scale up AWH systems in Iraq, it is necessary to assess the technologies available, the needs of the users, the environmental conditions, and the overall prospects for strategic development of the systems to meet short-term and long-term water needs for addressing climate change variability, [36], [8], [14], [20] and [23].

Table 1: ABAWH technology roadmap, [14]

		Short-term	**Medium-term**	**Long-term**
General	adsorbent	increase adsorption capacity improve kinetics improve thermal properties	design new materials tailored to the applications (MOF & hydrogel design with high sorption rate and low generation temperature)	reduction in costs, 1~10 USD/kg possibly (MOF, hydrogel, or porous silica gel and Composite sorbents)
Household	discontinuous passive	system design with a capacity of 3~5 L per day (solar thermal driven)	utilizing methods to improve the condensation rate, 10 L per day (coolant for equipment or radiation cooling)	utilization of intelligent materials in the control system, 10–20 L per day (fully automatic generated)
	discontinuous active	system design with a capacity of 20 L per day	diversification of energy sources (any kind of heating source)	portability and easy to install (water cost reasonable)
	quasi-continuous	design of units with a capacity of 20 L per day (with daily solar generation 3~5 times)	hybridize with existing devices such as dehumidifiers or refrigerators, or heat pumps (water generation	portability & ease of installation, 50 L per day (with water cost close to mineral water)

		Short-term	Medium-term	Long-term
			cycle 10~60 min)	
Industry and Agriculture	water recovery	identify applicable cases (such as desalination with adsorption)	design dedicated units Using waste heat or DCHE based electric heat pump (capacity 1~10 ton per day scale)	integrated water supply system, a commercialized product with various AWH production series
Environment and Agriculture	distributed irrigation	design of units for 2~10 L per day (solar thermal driven, hydrogel is preferred to store liquid water)	integration with modern irrigation methods Identify suitable plants (capacity 10~20 L per day scale for moderate water demand plants)	utilization of intelligent materials in the control system (thermal or heat pump driven for AWH with low cost of energy per liter water)

7.2. Integration with Existing Infrastructure

The improvement of AWH in Iraq requires integration of systems into the infrastructure. AWH technologies should incorporate local resource and an existing framework, while an innovation in using such systems could be in incorporating these systems into architectural designs that incorporate renewable energy like PV/T. These configurations are capable of producing electricity and at the same time collecting moisture from the atmosphere and therefore minimize resource costs.

Another successful approach is to integrate AWH with current HVAC systems in residences as well as business spaces. These integrations can sharply rise, water output and improve energy performance by harvesting condensate water wasted from air conditioning units. The studies prove that indicated systems could supply a significant part of daily water requirements without significant changes in the basic infrastructure.

The use of waste heat from industrial and transportation sectors also improves the feasibility of AWH in Iraq. Some industries generate excess heat, which can be used in another process of moisture desorption from the adsorbent material so that water formation is easier for the industries during high operational heat like in food industries.

Portable AWH devices come in small and highly mobile system options that make them suitable for use in urban and rural regions that have not been able to establish a stable source of water supply. These devices can supplement home appliances for generating clean water for drinking without bringing significant changes into homes.

Localized community based approaches encouraging neighbourhood-based implementation of AWH can ensure that solutions are relevant to the community and awareness creation can increase people’s engagement in AWH technology.

Such integration strategies have to incorporate socio-economic factors that determine the citizens’ uptake of integrated systems. Greater acceptance and sustainability will be achieved if such properties such as user-friendliness and affordability are embraced.

There is a need to convene a multiple stakeholder approach involving government institutions, private organizations, and research institutions to facilitate the policy environment that supports AWH integration in environmental management in Iraq. Institutional support or innovations incentives in form of policy support or financial support can help foster sustainable water management practices across the region [14], [23], [9] and [35].

8. Environmental and Socioeconomic Impacts

This study established that AWH technology in Iraq offers massive environmental and socio-economic benefits. AWH responds to acute water shortage due to climate change and mismanagement, and offers a new source of fresh water needed for rural people with no access to clean water. This technology enhances the use of independence and adaptation to some of the changing climatic conditions.

On the ecological side, AWH can decrease the water consumption from Tigris and Euphrates rivers to bring more stability to these sources and environments. Furthermore, AWH can refine atmospheric moisture that signifies that it can help in purifying air within the same region and thus boosting public health.

Economically, a large-scale use of AWH technology might lead to job opportunities in system installation and maintenance as well as encouraging local manufacturing industries. Promoting training with local people especially the young generation can ensure development of a competent workforce that will ensure sustainable water projects. Use of AWH may also reduce the cost of bottled water and cost of transporting clean drinking supplies.

Nevertheless, barriers are still there as far as larger-scale AWH implementation is concerned because of the relatively high costs of implementation and lack of awareness of the community about the new technologies. This means that other educational initiatives should also focus on the revelation of operational impacts as well as long-standing advantages. This integration will be important since farmers shall be able to use the harvested moisture to water crops hence reducing the strain on local aquifers.

Because of various factors including environmental displacement, the socio-economic context in Iraq is relatively diverse. Displaced population’s needs for basic services remain unmet in urban settings; therefore, incorporating AWH into urban design will help meet immediate water needs and reinforce community stability.

Due to Iraq’s regional situation including the sharing of water resources with neighboring countries, incorporation of AWH technologies can support diplomatic procedures for equal water sharing. It could promote regionalism through solution-oriented approaches which would suit different stakeholders.

In conclusion, AWH has potentially positive social, environmental and economic effects for Iraq in relation to environmental management and socio-economic development but to optimise the effects of the approach in all the sectors of the society efforts need to be made to overcome the initial challenges through education and investment.

9. Challenges and Opportunities in AWH Implementation

Challenges coexist with the benefits of Atmospheric Water Harvesting (AWH) technology in Iraq while implementing the technology. Lately, the availability of fresh water resources has become a severe problem due to climate changes and affecting Iraq most. Rising temperatures, lesser availability of precipitation, and heavier sandstorm activity reduce the availability of conventional water resources for agriculture and proper drinking water supply systems.

Furthermore, the degradation and inefficient management of existing water systems due to prolonged conflict and poor governance deprive the integration of AWH technologies a smooth way. AHW could prove to be a useful option in rural areas where traditional water sources are limited; nonetheless, this calls for massive investment in technology besides allowing for sufficient training of the community on correct usage.

On the other hand, the use of AWH technologies has the following possibilities: In conditions of further degradation of climate, extraction of moisture from the atmosphere is critical for AWH systems in regions with a critical shortage of water. This technology has been found useful in arid regions where other methods may not produce similar results. New developments in the adsorption based AWH technologies indicate promising innovations of low energy innovative solutions that could be adopted in the local setting.

Socio-economic factors also contribute to innovation through multisectoral partnership solutions to water problems. Inclusion of local communities in the models is critical for replicability so that participants can sustain their businesses and strengthen the economic base of their respective regions for the targeted disadvantaged groups. Water saving educational programs may help to increase acceptance of such innovations as AWH among people and organizations involved in educational processes.

International support is therefore necessary in order to realize such opportunities. Funding however might be scarce because of changing global trends or conflict of interest; however, collaborations with NGOs and government agencies can result in the allocation of funds for AWH projects relevant to Iraq. The integration of global best practices with local solutions may help ensure that sustainable implementations are viable in both the socio-political environment and with regard to physically pressing issues.

Overall, it is crucial to mention that despite the given conditions, such as Iraq’s climate vulnerability and problematic infrastructural prerequisites, there are more opportunities to improve AWH deployment with the help of community and international support, [27], [14], [28], [22], [4], [33] and [17].

10. Future Directions for Research and Implementation

The trend for research and the practical use of AWH technologies in Iraq is considered relevant along with perspectives for its development since Iraq is characterized by specific climatic conditions and critical problems of water shortage. One of the areas of improvement essential for creating smart building materials is the improvement of complex and advanced materials such as MOFs that proved to have a high rate of extracting moisture from the surrounding air. Further research should be directed towards the improvement of these materials to provide them with the necessary resistance to the change in humidity as experienced in Iraq. It would be possible to build up a database of local climatic conditions, helping optimize MOF properties to the conditions of Iraq and thus increase water production.

In addition, more research needs to be done in relation to how AWH systems may be connected to existing structures, for example; watering systems in urban areas and agriculture. This integration could help to foster other forms of water production that are less centralised and more sustainable than some of the currently widely used models which may be reaching peak capacity. In addition, using the renewable energy sources such as solar energy could help to significantly increase the practicality of AWH systems, thus making it easier for it to be commercially produced and used without negative impacts on the environment.

One such direction of future research is related to the enhancement of the system designs by integrating the AWH technologies together. For example, combining passive technologies like a fog net with adsorption techniques can greatly enhance the comprehensive system’s effectiveness and its ability to function in various climactic conditions throughout Iraq. In addition, the search for new efficient energy conservation technologies will also be relevant; studies relating to the fundamental limits of heat transfer could yield ideas in boosting efficiency requirements for AWH equipment.

Closely related to this is the assessment of the community engagement mechanisms as well as the technological solutions. Sensitization of the local populace to the AWH technologies and their participation in the implementation will go a long way in making the systems adopted to fit the local demographics. Such activities should aim at educating the public about the need for sustainable use of water and at the same time make, them understand that atmospheric water harvesting is a perfect solution for poor water supply.

Moreover, favorable g policies from government structures can enhance the spread of AWH technologies. All of these policies should encourage funding for research endeavours directed towards creating solutions that address Iraq's needs and promote partnership between universities, companies, and government organizations.

Last but not the least the issues of maintaining and operation sustainability must be addressed to ensure long-term success. Future studies should focus on the creation of effective and dynamic surveillance tools through which the performance of the AWH system can be monitored continuously, as well as creating and implementing training for the local technicians to maintain the functionality of these technologies in the end, [1], [12], [14], [37], [10], [5], [32] and [17].

11. Conclusions

This clearly call for the development of new approaches in handling water problem due to shortage because environmental factors are a real big issue this is realized by looking at countries like Iraq. The use of technology to obtain water has come up as one of the most innovative solutions for water scarcity, with the best known solution being the Atmospheric Water Harvesting (AWH), which harnesses moisture from the air. Because the Iraq climate varies drastically in temperature and humidity, AWH techniques can be modified to gather more water during the rainy season when the humidity is highest.

The vast variety of available adsorbent materials is an excellent chance to increase the effectiveness of AWH systems. To this effect, it would be necessary for us to find and use materials that would be in harmony with the climate of a particular region to facilitate proper capture and storage of moisture in the atmosphere. Moreover, comparison of the various adsorbents helps decide on the right course of action that will be applicable to the Iraqi environment.

However, it important not to downplay the fact that although AWH can reduce water scarcity by up to 90%, it has to be done in a way that is compatible with the current system and structures of a community. The incorporation of these technologies into today's agricultural and urban systems will increase the effectiveness of such systems in satisfying local needs for clean drinking water and irrigation. Strategies will be adopted in line with the prevailing design considerations in Iraq and will help enhance the scalability and performance of AWH systems.

Further, this study needs to consider other socio-economic factors that shape the adoption of the AWH technology in order to gain support and share the technology's harvested water resources equitably. Through its policy interventions in addressing economic inequalities, Iraq can turn towards AWH not only as the method of environmental conservation, but also as the approach to social advancement.

Overall, therefore, it would be pertinent to argue that addressing the complex problems posed by climate change, there is a need to pursued further research on the sustainability of water harvesting techniques. Focusing on the continuous improvements and flexibility of water management will contribute to the creation of a more robust system in Iraq that will be capable to respond to the rising challenges in the future climate change, [1], [31], [14], [30], [30], [30], [24] and [21].

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