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Trends and opportunities of using local sustainable building materials in the Middle East and North Africa region

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Abstract

In recent decades, most of construction activities have been taking place in developing countries such as the Middle East and North Africa region. The expansion in infrastructure has great impact in the technological, social, economic and environmental transformation of this region. Construction sector contribution to Gross Domestic Product (GDP) varies throughout the region and ranges between 2-10%. Currently, sustainable construction requires integrated and comprehensive sustainable design including careful choice of materials and methods. Materials that are locally available and require less energy to produce and transport would pave the way to more sustainable practices. Many countries in the region have realised the benefits of using local building materials on the economy, society and environment. This paper outlines the key trends and opportunities of using sustainable and affordable local building materials in the region to respond to the global climate change crisis and to promote more sustainable and environmentally friendly practices. The current practice of using various building materials such as bio-based materials, treated municipal solid waste incineration bottom ash (MSWI-BA), construction and demolition waste, gypsum-containing by-products (phosphorgypsum, FGD gypsum, borogypsum and others) and rammed earth will be reviewed. It is concluded that the use of these local building materials in construction activities would foster the development of the society. However, some of these materials are already developed and reached the implementation stage while most of them are still at R&D stage. Therefore, there is an urgent need for a comprehensive local and regional strategies to enhance the utilization of these materials.

Keywords: Bio-based Construction; Gypsum; Construction and Demolition Waste; 3D Earth Printing; Rammed Earth; Solid Waste Incineration Ash

1 Introduction

The population of Middle East and North Africa is estimated to be approximately 500 million [1] living in a land area of about 11.25 million km^2 [2]. The vast majority of the population lives in middle-income countries while 12.5% and 8.6% of the population live in high-income and low-income countries, respectively [3]. The CO_2 emissions per capita of the region is about 5.6 metric tons and forest areas just cover 2% of land area [1]. The climate of this region is dominated by a Mediterranean climate for coastal region and arid/desertic climate for a very large part of the countries both in the Middle East and North Africa. The region is one of the most vulnerable regions to climate change, suffering extremely high temperatures, desertification, water scarcity, degraded marine, coastal ecosystems, and high levels of fossil fuel dependency [4].

Construction industry plays a vital role in the economic growth of the region. However, this contribution varies from country to country. In addition, the political instability and economic pressure in some of these countries alongside the impact of COVID-19 pandemic have largely affected this sector. The industry heavily relies on conventional construction materials, leading to high carbon footprint. However, many existing local and waste materials are greatly overlooked and unutilised. Despite the growing interest of the region about the importance of decarbonising the construction industry, limited attention has been given to the role of local materials and wastes.

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This paper attempts to highlight the potential of using these materials in the construction industry to contribute to the economic growth and sustainable development of the region.

2 Construction Industry and Sustainability in the Middle East and North Africa region

Climate change and global warming is one of the significant pressing challenges across the world and the Middle East and North Africa region. This has become increasingly urgent in the last few years. The population of the region will exceed 1 billion people by the end of the century where most of countries are poor in resources [5]. Therefore, sustainability issues should be addressed at all levels and sectors. A comprehensive review of the progress achieved in the region was recently discussed by Göll et al. [6] and Asi [7]. They highlighted that progress in achieving the United Nations Sustainable Development goals (UN SDGs) in most parts of the region is slow and an accelerated approach is required.

As the construction industry is responsible for emitting large amount of greenhouse gases, using natural resources and generating waste, it should contribute to the region's effort to tackle climate change and build resilient infrastructures. There are many ways the construction industry can assist in achieving the sustainable development goals. One effective way is reducing the carbon emissions by replacing traditional construction materials with more sustainable, greener and low-carbon materials. These include the use of waste and local materials. The role of such materials in the region will be discussed in the following sections.

3 Use of the Bio-based Materials

There are huge unused quantities of agricultural residues around the globe [8]. The use of biomaterials in construction application in the Middle East and North Africa region would be of particular interest. In term of scientific work, it is interesting to note that the first international symposium on the use of vegetable plants and their fibres as building materials was held in Baghdad during 7–10 Oct. 1986 showing that the region was one of the more dynamic in using vegetal in the construction industry [9]. The main aim was to discuss the role of vegetable plants such as bamboo reed, papyrus, rice, paddy or husk, palm leaves and sugar cane bagasse as building materials, and also to evaluate the use of these vegetable plants and their products to improve low-cost housing in different countries.

In addition, several studies showed the potential use of natural fibres (Date palm, Alfa, Cork, Diss, ...etc.) as reinforcement and/or as partial cement and aggregates replacement in cementitious systems (e.g. concrete, mortar) [10–12]. Therefore, depending on the characteristics of fibres and matrix, application of the reinforced composites as structural lightweight materials and/or as insulating materials becomes very attractive as the vegetal fibres can be produced locally with relatively low cost compared to traditional raw materials in addition to their low density and their biodegradability [13, 14]. The advantages of using natural fibre composites are low specific weight, high strength and modulus, low-cost renewable source of material, eco-friendly, easy recycling. There are huge unused quantities of agricultural residues around the globe [8].

The significance of natural fibres in composite application is gaining momentum in the current materials engineering market [15]. This has given boost to the acceptance of plant-based materials in composites to replace synthetic fibres (e.g., glass, carbon, aramid). There has been a lot of work published to improve the shortcomings of natural fibres, especially in the last two decades.

The main typically used vegetal fibres in the region compose Palm, Diss, Alfa, Kenaf and cork. A brief description of the use of these fibres will be presented in the following subsections.

3.1 Palm Fibres

Date palm (Phoenix datylifera) is cultivated in oasis. The date palm is one of the oldest fruit trees in the region and it is extensively cultivated for its edible sweet fruit. It is probably originated somewhere in the desert oases of northern Africa. The number of date palm trees as well as date production and consumption vary from one country to another due to prevailing environmental conditions. The major producers of dates in the world are situated in the Arabian Gulf and North Africa. It was reported that in 2006, world production of dates was about 7 million tons and the top 10 producing countries were Egypt, Saudi Arabia, Iran, United Arab Emirates, Pakistan, Algeria, Sudan, Oman, Libya, and Tunisia [16].

In Algeria, approximately 18 million date palm trees are cultivated on an area of 169,380 ha. Tunisia has more than 4 million date palm trees which occupy nearly 41,000 hectares. In Palestine, the total harvested area of dates in both the West Bank and Gaza was 725 ha in 2012. In the West Bank, there were 85,000 date palm trees spread over 600 ha. In Morocco, the date palm is grown in several areas located on the southern flank of the Atlas Mountains along rivers and around water points. These areas are characterized by a pre-Saharan arid climate. The total number of 5.4 million date palm trees represents about 4.5 % of the palm patrimony of the world [16].

The works of Kriker et al. [17], based on the use of four types of date palm fibres in a cementitious matrix, showed that the increase of lengths and percentages of fibres improve the flexural strength and hardness of the composite, but decreases the compressive strengths. The same trend was observed in the palm-reinforced plaster and gypsum [18, 19].

3.2 Diss Fibres

The Diss (Ampelodesmos mauritanicus, family of Poaceae) is a very luxuriant plant growing in a wild state along the Mediterranean North Africa and dry areas [20]. Its fibrous nature seems to offer improved qualities to the cementitious composites as the traditional fibres. The use of such a fibrous plant in a cementitious matrix leads to a lightweight material with very high tensile behaviour that can be used as filling materials for structures subjected to seismic loadings. For example, Bourahli and Osmani [21] have found an average Young's modulus and tensile stresses of diss fibres of 8,7 GPa and 149 MPa, respectively. This fibrous plant can provide cement materials with reinforcement properties similar to classical steel or polypropylene reinforced concrete. Moreover, the raw diss fibre outside surface is covered with approximately 100 µm-long thorns, which improve adhesion once mixed with binder.

3.3 Alfa

Alfa (plant's scientific name: Stippa tenacissima) belongs to the Poaceae family. The genus Stippa has a hundred of species that grow spontaneously in very poor and dry soils, steppes and rocky slopes in warm temperate regions all around the world. The most common Alfa is the species Tenacissima, which grows as bushes of 1 to 1.2 m height in North Africa and South of Spain [22]. It is a grey-green needle grass made of long stems with seed heads and leaves which acts as a barrier against desertification in Maghreb area [23] and therefore plays an important role in the protection of ecosystems. Nowadays, alfa is mostly used in the paper and rope industry. This plant does not need any additional water to grow or pesticides as it grows in perfect harmony with its environment.

With regards to sustainable development, Alfa is an abundant and renewable resource within arid and rural areas. Its exploitation for construction purposes can contribute towards creating local employment and positive impact on the economy with no significant environmental impact. This would encourage the rural community to stay instead moving to cities and populated areas.

Several studies shows that Alfa can be used for the reinforcement in concrete; thus, producing an environmentally friendly material suitable for housing and infrastructure constructions [22].

3.4 Kenaf

The kenaf plant has recently been exploited in Tunisia. Indeed, the first experience of plantation dates back to the end of the seventies in the Medjerda valley. These trials demonstrated that kenaf can be produced in enough quantities (more than 35 tons/ha). In addition to these classic uses, kenaf fibre is very much exploited in the field of composite materials, specifically bio-composites. Indeed, given its low cost, its density and its easy recyclability, kenaf fibre is finding success as a reinforcement for composites used in the automotive industry and in geotextiles. Also, it can be used in fibrous panels in buildings due to its thermal and acoustic insulation.

3.5 Cork

Cork oak trees can be found in Europe and North-western Africa, including Algeria, Morocco and Tunisia. In order to use cork for insulation, it is necessary to harvest the raw material. Cork is produced from the bark of the cork oak tree, which only grows in warm regions such as the Mediterranean one. Production is not possible in cold areas making this resource less accessible to the rest of Europe. The use of cork is slowly gaining popularity in the architecture industry and could revolutionize the construction industry.

Cork can only be extracted from trees between 20 and 25 years old and the bark is harvested every 9 years with a minimum thickness of 24 mm. It is a limited product which can only be produced on a small scale. it can be used to insulate attics, roofs, walls despite its incompressibility. It can be found in forms of granules, panels or shells. Cork oak forests cover approximately 2.5 million hectares across the Mediterranean region and most of them are located in seven countries including Algeria, Morocco and Tunisia.

4 Raw Earth

Raw earth was used largely as a construction technique over the world [24] (Fig. 1).

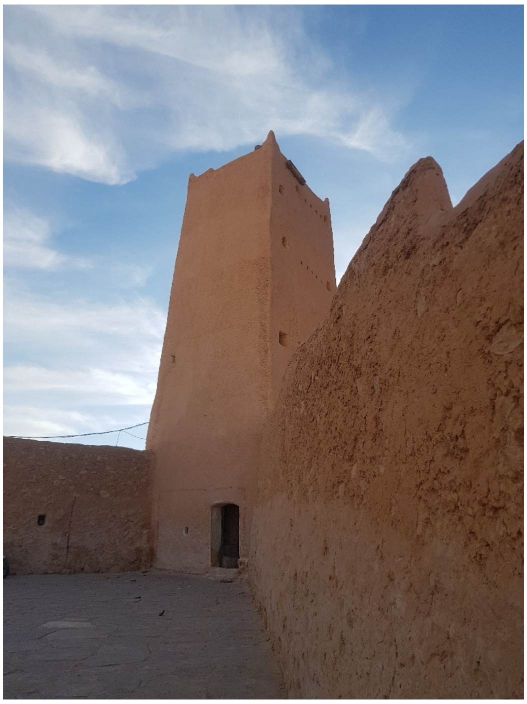

Figure 1. An example of earthen construction (Courtesy; E. Ghorbel, 2022).

Hence, rammed earth is an old construction technique in which local soil is compacted and compressed to form building material for earthen structures [25]. The earthen constructions are well adapted to the climate of the Middle East and North Africa. It should be noted that in the Middle East, rammed earth has been used as building materials for load-bearing posts from 14000 BC. J.-C.

From the 9th millennium BC. J.-C., a new fundamental stage is reached by using earth in layers to build a load-bearing wall. Earth alone can now become the supporting element, first in the form of clods of still damp earth piled directly on the wall [26]. Many sites (e.g., Jericho, Aswad, Nemrik and Qermez Dere) provided semi-buried architectures with stacked earth elevation. Prefabricated materials (sun-dried bricks) bonded with earth was used as building materials appeared since 9000 BC. J.-C (e.g., Jéricho, Aswad, Gesher, Netiv Hagdud, Nemrik, M'lefaat, Ganj Dareh and Ali Kosh).

They are made from "building earth", a mixture of clay, water and most often a vegetable material (grain husk or chopped straw).

This mixture is then shaped with the hands to obtain elements of variable shape which are left to dry in the sun before being arranged on the wall using a mortar elaborated with clay whose composition is close to that of bricks. The interest of the technique of prefabricated elements is obviously to avoid the drying time necessary between each layer of piled earth. One often notes, on the upper surface of these bricks is roughened to facilitate the adhesion of the mortar.

Contrary to the Middle East where the different methods of construction in raw earth have been listed since antiquity, the studies listed on the subject date only from the Punic period (between 264 and 241 BC) for the north of Africa [27–29]. The reported data mainly concerns the medieval, Ottoman and contemporary periods. Whether in Morocco, Algeria or Tunisia, the most used techniques were rammed earth and adobes, clay mixed with water and a small amount of chopped straw shaped into bricks and dried in the sun [30]. Several villages in Kabylie and in southern Algeria are made of rammed earth, while the use of adobes is more in rural areas for the construction of houses with elevations up to 2 floors [29]. Many texts allow the affirmation that almost wherever Muslims did not find, in north of Africa, pre-existing structures adapted to the needs of their strategy, they built first walls in adobe and raw brick and this practice continued until the 10th and 11th centuries [31]. In Tripolitania, in Qastilîya, in Djerid, in Sfax, in Tunis in Tobna, in Msîla, in Belezma and elsewhere, the geographers mention ramparts of cob and adobes.

Unfortunately, these impressive constructions perfectly adapted to the harsh climatic conditions of the desert and the mountains did not survive the cultural shock represented by the invasion of industrial civilization. The concrete has won the most remote valleys and hundreds of earthen buildings threaten to return to their original land if this has not been done.

Recently, the renaissance of building with earthen materials in the Middle East and North Africa is motivated, thanks to the numerous advantages provided by earthen material [32–34]. For example, since 1960, thousands of public housings have been built in rammed earth, earth blocks and adobes in Morocco with the help of French and Belgian architects in Daoudiate & Marrakech in 1962 and in Ouarzazate 1967 [35]. In Upper Egypt, for the Luxor House construction starting In 2019, rammed earth was used for the walls [33].

Earthen materials are eco-friendly materials and present good thermal comfort. A large variety of soils can be used for rammed earth buildings. Preferably, the soil must have a high sand and gravel content, with some silt and clay to behave as a binder and help soil compaction procedure. Combined clay and silt content must exceed 20 to 25% and do not exceed 30 to 35%. The liquid limit of soils should be between 25 and 50% (ideally between 30 and 35%) and the plastic limit should be between 10 and 25% (ideally between 12 and 22%). As for sand content, the minimum percentage should be between 50 and 55% and the minimum percentage between 70-75% [36]. Several research works have been carried out to valorize local soils in order to elaborate rammed earth or compressed earth block. Hence several types of soils and stabilizers were tested and studied in the literature. The main categories of binders used as stabilizers for rammed earth are Portland cement, natural cement, hydraulic lime, hydrated air lime, fly ash with a content ranging between 5 and 15% by weight. Many types of natural fibres (up to 2% by weight) were tested in the literature in order to reduce crack shrinkage caused essentially by clayey fraction existing in used local soil [37].

5 Additive Manufacturing of Earthen Materials

Robotic construction has undergone a dramatic surge in recent years. Since the mid 2000's and the introduction of digital construction, hundreds of construction projects have started and hundreds of scientific papers have been written [38, 39]. The example of digital concrete that has created a broad R&D community can be an example for the development of what can be called digital "earth".

Even if digital earth construction is still in its early development in comparison to digital concrete, some scientific works have shown their potential and demonstrated the technical concept [40–44] and some industrial initiative have shown their applicability as a promising construction methods. In these works, digital earth relies on the adaptation of the 3D printing by extrusion/deposition methods to earth-based materials. The material is deposited layer-by-layer using a robot in order to create a whole structure. During the process of printing, some fresh-state requirements are needed in order to make the earth-based material printable: the material must be extrudable and must be able to sustain the weight of the layers deposited above (this property is called buildability) [42, 45, 46]. This last requirement can be achieved by drying but the kinetics of this natural process cannot be fast enough to allow for a fast printing [42]. In order to fix this issue, the addition of a product that is able to create a fast strengthening of the deposited layer is needed. This addition can be a biopolymer like sodium alginate [42] or bovine blood proteins [47] or an hydraulic binders. It is worth noting that those additions are also able to provide better durability and mechanical strength to the printed materials as shown by study on earth and stabilized earth. Moreover, it has been shown that the hardened properties of printed earth are at least similar to the ones of conventional earth construction materials [41, 42].

It is important to note the local context of the Middle East and North Africa can favour the development of 3D earth printing. First, digital construction has already been introduced in this large area. For instance, Concreative and Besix are 3D printing companies acting in Dubai while Cybe is operating in Saudi Arabi [48]. Also the first printed office building was printed in 2016 in Dubai showing that it is possible to print real scale building in the Middle East [49]. Moreover, it has been established that robotic fabrication can be a solution to answer the needs for fast housing construction [50, 51]. It seems that the technical knowledge and equipment are locally available in different countries of the studied area and can be implemented for digital earth construction. A recent study by Alhumayani et al. [52] has also shown the environmental benefits of 3D printed cob in the context of Saudi Arabia in comparison with concrete construction and conventional cob (even if conventional cob construction remains less impacting in terms of global warming).

Moreover, when dealing with printing of earth, hot and dry local climate of these areas can be turned into an advantage and an opportunity to print a low-cost material. In comparison to Europe, for instance, the arid environment can fasten the drying of the material making it possible to be printed at a high rate without the use of set-mimicking admixtures. Even, if the drying process can last during several days for large structures, the surface drying can provide sufficient strength for the stability of the printed shape as experienced in the work of Bhattacherjee and Santhanam [53].

The substitution of the human workforce by robots can also be one crucial advantage of digital additive manufacture in the context of the Middle East and North Africa where the building sites conditions can be unbearable during the hot season and safety remains a critical point [54]. Therefore, earth robotic fabrication can really improve the safety and workers conditions in the construction industry.

Finally, the question of the structural design and the material reinforcement remains an open question and a challenge that remains to be tackled. One strategy can be the addition of locally available fibres to provide tensile strength or the design of fully in compression structures inspired from vernacular local architecture such as arches and domes.

6 Municipal Solid Waste Incineration Ash (MSWIA)

The generation of solid wastes presents a challenge to many countries in the world, not only the environmental impact that may cause but the availability of landfill space, especially in populated areas in the world. Of these wastes is the municipal solid waste (MSW). The global generation of MSW is expected to reach 2.2 billion tons annually by 2025 with 6% is being generated in the region [55]. The disposal of this quantity requires space which is particularly challenging in urban settings. Waste is normally transported causing more problems elsewhere. The Middle East and North Africa is no exception. While there may be landfill spaces in some countries, there is acute shortage in many other countries. Lebanon, for example, is densely populated and finding landfill spaces is causing major problems to the government and local authorities. The problem is compounded by the fact that most of the population is clustered in big cities and along the coastal strip. Transporting the waste to less dense area is not practical due to the distance and the cost involved. Incineration of the MSW can reduce the volume of the waste by more than 90% which would reduce the need for landfill space. The incineration generates MSW incineration bottom ash (MSWI-BA) and fly ash (MSWI-FA).

Midgley et al. [56] and Radwan et al. [57] suggested that incineration is one of viable option to deal with municipal solid waste generated in Saudi Arabia. The United Arab Emirates (UAE) government intends to build a few incineration plants in order to reduce the volume of MSW produced and to reduce the landfill spaces required for the disposal [58]. MSW Incineration plants in UAE is expected to generate 800,000 tons per year which would be used in value added products such as ceramic production [59]. Egypt, the most populated country in the region, generated around 21.6 million tons of MSW in 2016 and this amount is set to increase in the future [60]. Only 20% of this waste is properly disposed of or recycled. The rest of the waste is illegally disposed of in rivers, canals and open spaces causing major environmental pollution to the soil, water and air. Incineration of the waste and using the ash generated from this process in construction and other applications will reduce the massive volume of MSW and the impact on the environment.

Lebanon, a small and populated country in the Middle East, generates about 2 million tons of MSW [61]. There is only one plant in the Eastern part of the country which incinerate the MSW and the government intends to build more plants in order to reduce the space required for landfilling. In the last few years, there has been some research on the effect of using the waste products from the incineration process (i.e., MSW ash), obtained from the Lebanese plant, in cementitious systems and the results obtained are encouraging. Charbaji et al. [62], Baalbaki et al. [63], Bawab et al. [64] and Khatib et al. [65] examined the effect of using MSWI-BA, obtained from a plant in Lebanon, as partial replacement of fine aggregate on the properties of concrete and reinforced concrete beams. They found that at 20% MSWI-BA replacement, both the compressive strength and modulus of elasticity of concrete increased. Other studies reported similar results [64]. Also, the load bearing capacity of the reinforced concrete beams was the highest at 20% replacement. Similar results on mortar were obtained when MSW-BA partially replaced the fine aggregate [66].

In conclusions, incineration of the MSW will reduce the large volume produced and save much of the needed land space especially in populated urban area in the world including the Middle East and North Africa region. If the ash produced from the incineration process is utilised in construction materials (e.g., concrete, pavement), the environmental impact of the ash will be drastically reduced. Life cycle analysis, including waste management system, should be performed to assess the economic, environmental and social impact of the MSW. Lessons should be learnt from the Netherland where most of the MSWI ash generated is used in construction applications; thus, the MSW should be considered as a resource in many applications to save quarrying virgin materials and to reduce the need for landfill spaces for disposal.

7 Phosphogypsum

Phosphogypsum (PG) is a by-product of phosphoric acid-based fertilizers, obtained by treating apatite with sulfuric acid:

$$Ca_{10}(PO_4)_6F_2 + 10H_2SO_4 + 20H_2O \rightarrow 10CaSO_4{\cdot}2H_2O + 6H_3PO_4 + 2HF$$

From 4 to 5 tons of PG are produced per 1 ton of phosphoric acid [67].

The dominant areas of PG utilization are construction materials, road construction and agriculture [68]. As an alternative source of calcium sulfate-based products, PG can be used to produce modified gypsum binders [69], mineralizing and setting time regulating admixture for cement, binder for supersulphated cement etc. [70].

Whereas gypsum and anhydrite global market estimated at 306.6 million tons in 2020 [71], the annual world generation of PG varies from 100 to 280 million tons [72]. About 14% of worldwide PG production reprocesses, 28% dump into water bodies, but 58% are stockpiled [73].

The main obstacle for processing PG is its contamination, in particular, with radionuclides, it is a worldwide ecological problem. Apart of radioactivity, PG requires neutralization of impurities (remains of phosphorus and sulfuric acids, fluorine compounds) [74]. Due to wet manufacturing processes and subsequent landfills PG has high humidity and non-uniformity.

When stored in dumps over decades, phosphogypsum is subjected to chemical changes to wash out impurities. According to [75] Japan and Germany are the countries which the most use PG. The Middle East and North Africa is the region central to the global phosphate industry in terms of its holding of phosphate resources critical to the world as a whole [76].

Huge amounts of PG are accumulated in damps of Morocco, Syria and Jordan [75]. Fertilizers are among 10 top products in Morocco and Jordan among the region's countries. Egypt has over 17 phosphate fertilizers [76]. The amounts of PG available in some countries are given in Table 1.

According to other data, Morocco is the first world exporter of phosphate and the third producer with a production of 30 million tons per year [77]. The problem of PG landfills is also vital in Jordan and Tunisia [67].

Table 1. The amount of phosphogypsum generated in the region by country (based on aggregated data).

Country	Amount, million tones	Source	Additional notes
Iraq	12	[73]	(Western part of the country)
Jordan	40	[78]	In total (i.e., the total amount in the deposits by the year of estimation)
	60	[79]	In total
Morocco	15	[80]	Annually (i.e., the annual amount of produced phosphogypsum)
	30	[77]	annually
Tunisia	10	[78, 81]	annually
	More than 12	[82]	need to be correctly managed and stored

According to VOSViewer [78] and other aggregated data [68], Tunisia is the leading country in the region on PG researches (Table).

Table 2. Review of accumulated data of PG application in the region by country.

Country	Issue	Source
Algeria	A sustainable method of using in processing the Algerian PG to recover the sulfur, which is imported in huge quantities. Calcined PG residues have a chemical composition almost identical to clinker, which makes a potential for cement production	[75]
Egypt	It is suggested a treatment of PG waste with seawater and acids to recover purified PG as a soil conditioner	[80]
Iraq	Demonstration of the leaching characteristics of Iraqi PG, given the results of the dissolution characteristics of heavy and radioactive elements from PG	[73]
Jordan	Shown no significant difference in concentrations of toxic metals with Jordan PG age. The assessments of the bioavailability of toxic metals indicate that there is no significant number of elements transferred to the surrounding environment	[83]
Jordan	Considered the possibility of application treated and non-treated local PG for construction and agricultural purposes. Treated PG is concluded to be safe	[79]
Morocco	The study of PG purification. Thermal treatment leads to optimizing the elimination of impurities. Thermal behavior of natural gypsum and washed PG was quite similar	[77]
Saudi Arabia	Developed the PG-based heat-insulating construction materials with $\lambda < 0.3 W/m \cdot K$	[78]
Tunisia	The study of the environmental impact of local PG storage during 30 years is demonstrated. The fluorine, phosphate, and heavy metal values exceeded by more than 100 times the specifications of Tunisian standards. There is suggested neutralization of PG with lime and setting up a recovery and recycling system for storage water etc.	[84]
Tunisia	The introduction of PG as a thinning admixture in the manufacture of fired hollow bricks has been studied. 5-30% dosage permits to meet the mechanical properties requirements	[81]
Tunisia	The PG is applicable as clicker admixture after treatment due to available impurities (flotation, calcination, washing with sulfuric solutions). Optimal PG content from the point of setting time OPC is < 0.2%. Washing with H_2SO_4 (40–50%) is considered optimal	[85]
Tunisia	Study of leaching behavior of heavy metal from the PG disposal. Mechanical properties of aged PG are higher than the fresh one. There was observed heterogeneous distribution of heavy metals without visible trend to evaluate the behavior of the elements according to the age	[82]

PG waste management is a huge global ecological problem. Future global trends predict the increase of use of cycled gypsum and gypsum in the construction industry at a slight increase in gypsum mining.

The development of the agricultural industry and phosphate fertilizing companies in Tunisia, Jordan, Syria, United Arab Emirates, Iran, Morocco and others are also key drivers for enlarging the opportunities for using PG. Overall consumption of fertilizers reduces in recent decades in the region [86]. It remains more or less stable in Lebanon, Iraq, Morocco, Egypt. Phosphate plants in Morocco, Egypt, Saudi Arabia are powerful at the market.

The main drivers for growing the use of PG rising activity in the construction industry in the region after COVID 19 due to tourism activation in some countries of the region. At the same time, there are many challenges on the way, in particular, the high radioactivity of PG. Most of the research on PG under review are devoted to either the solving the problems of radioactivity and impurities neutralization or the innovative sustainable construction materials.

8 Gypsum

Gypsum has been used in buildings in the Middle East and North Africa for a long time due to its wide availability, low cost, quick setting, smooth surface, fire resistance and recyclability. Gypsum is one the most mined materials in the world after mainly aggregates, iron ore and lime and the world production of gypsum in 2011 was 148 million tons. Soils containing gypsum formations are wide spread in Egypt and the area is estimated at 382.2 km^2 [87]. The national reserves of gypsum in Morocco are estimated at 10 million tons mostly in Mouissate region (second after phosphate) whereas Tunisia is estimated to be among the top producers of gypsum worldwide [88]. The use of gypsum as a construction material is very old. Gypsum was used in ancient Egypt for several purposes such as vessels from the Predynastic Period (prior to 3100 BC) and later as gypsum plaster [89]. Some towns in the south of Algeria like El-Oued and Ghardaia are known to have used almost solely gypsum, for its quick setting, as a binder in mortar for masonry arches, vaults and domes and as plaster for walls and ceilings.

Gypsum is obtained from natural minerals either in hydrated form with two molecules of water per molecule of calcium sulphate ($CaSO_4.2H_2O$) or in anhydrous form ($CaSO_4$). It can also be produced as a by-product in the chemical industry such as phosphogypsum industry. Building gypsum is obtained from partial dehydration of the calcium sulphate dehydrate ($CaSO_4.2H_2O$) phase through calcination. Gypsum is one of the most environment friendly binders as it consumes less energy in its manufacture compared to lime and cement (firing temperature of less than 200 °C). Gypsum in its anhydrous form is mainly used as an addition to clinker for cement manufacture.

Interest has recently been growing for its uses in a wide range of products. For example, the production of gypsum in Algeria has doubled between 2000 and 2008 from 822 thousand tons to about 1.672 million tons in 45 factories. Gypsum is usually available with different finesses and additions for use as a binder for rendering that could be applied manually or by sprayed on ceilings and walls for its excellent finishing quality and colour. It is also used for internal decorative elements. Building blocks for masonry or plaster boards and panels for walls and technical roofs are also made by gypsum mortar for its lightweight and its low conductivity compared to cement (λ = 0.20 to 0.25 $Wm^{-1}K^{-1}$) to reduce heating and cooling energy demand in buildings.

The main weakness of gypsum is its brittleness, low mechanical properties, low impact resistance and low resistance to water which limit its use to the internal parts of buildings. Gypsum solubility at 20°C is 2.04 g/kg of water. However, higher water resistance gypsum for external walls applications or in humid premises in the interiors of buildings could be obtained by the addition of some filler materials. Mechanical properties and water-resistant improvements have been reported for gypsum composites by the addition of slag and rice husk [90] or by blending the gypsum with Portland cement and pozzolan or silica fume [91, 92]. Polyurethane Foam Waste (PFW) were used in the manufacture of gypsum mortars and resulted in lower mechanical strength but lighter material and better resistance to water-vapour permeability [93].

Synthetic fibres and natural fibres (treated and untreated) such as date palm, jute, sisal, hemp and coir fibres have also been added to improve the flexural strength and toughness, reduce cracking, improve the thermal and acoustic properties and many economic and environmental benefits [94, 95]. Low thermal conductivity of gypsum composite with 20% of date palm fibres of $\lambda = 0.17$ $Wm^{-1}K^{-1}$ and 61.5% reduction of energy consumption as compared to neat gypsum has been reported [95]. The use of cork widely available in North Africa reduced the thermal conductivity by a factor of 3 as compared to the gypsum without cork [96].

Many case studies of innovative use of gypsum are reported in the region. A one floor prototypes building was realized in the research laboratory of the ministry of housing in Algeria (CNERIB) in 1995 using gypsum mortar as material for shuttered walls with no major defects observed until now. Many prototypes of one floor houses of 70 to 130 m^2 using gypsum mortar for 20 cm thick shuttered external walls has also been reported in Morocco [97].

An experimental house was built with local gypsum to promote affordable housing of in Rabat in 1988 with gypsum mortar (Béton banché in French). Sonebi developed the mix design of composition at Laboratoire Public des Essais et Etudes (LPEE) in Casablanca and controlled the quality of gypsum mortar used in the construction of walls and roof. The foundation was made with classic conventional concrete and monitoring during 2 years with LPEE. Mortar was made with 100 kg of gypsum, 40 kg of sand, 40 litres of water and 1% of citric acid. The house was 110 m^2, constructed by slip forming 3 x 1.5 m^2, with compressive and tensile strengths on standard samples of 7.9 MPa and 2.7 MPa, and in-situ 7.2 MPa and 2 MPa, respectively [97].

Using sustainable material as gypsum instead of cement can save up to 22% the material cost [97]. The villa is still standing until now after more than 30 years from 1989 to 2022 (Fig. 2).

Figure 2. Experimental house made with gypsum mortar (beton Banché) (Courtsey; M. Sonebi, 1989 and 2018).

Gypsum was used with dune sand for the manufacture of hollow or solid blocks as a replacement of concrete blocks for better heat and sound insulation in some housing projects of reinforced concrete load-bearing frame buildings of up to three floors in the south of Algeria. Gypsum was also used in these housing projects in mortar joints for infill external walls and roofs and as plaster on the internal walls for its attractive appearance and easy application [98]. In other applications floor to ceilings panels of various thicknesses are used as partition walls or as internal leaf for external walls. National technical documentations were issued in 1993 for construction with gypsum [99] and technical codes were issued in 2004 for the execution of gypsum panels in vertical elements [100] to help spread the use of gypsum as a construction material.

The availability of the material and technical advantages should encourage the growth of the gypsum base materials in the region not only as render, plaster and jointing but also for blocks and panels. Research is still needed for the use of local natural fibres, bio-wastes, construction and demolition waste aggregates and pozzolanic materials to produce more sustainable gypsum material to enhance the quality and insulation performance of the gypsum composites and its resistance to water and widen their applications for sandwich panels and fibre-reinforced panels in the region. In addition, traditional practices and skills in the region need to be reactivated by workforce training for better skilled workmanship and larger use of gypsum in new buildings and for repair of cultural heritage buildings.

9 Construction and Demolition Waste

Most of the countries in the region is considered as developing countries, where a surge in construction and infrastructure projects are still happening. Although the quantities of construction and demolition waste (CDW) varies significantly from country to country as shown in Table 3, the region creates approximately more than 150 million tons of CDW annually. This massive amount of CDW is largely transferred to landfills or illegally dumped on streets. However, there are some initiatives to recycle this waste in different applications, mainly as recycled aggregates (RA) to replace natural aggregates (NA). Natural aggregate (NA) consists of manufactured crushed stone and sand created by crushing bedrock, or naturally occurring unconsolidated sand and gravel while recycled aggregates (RA) come from reprocessing materials that have previously been used in construction. The initiatives to recycle RA, however, are run, in most cases, by the private sector and in few cases by local authorities. Therefore, the level of CDW recycling widely varies from country to country.

Table 3. Annual construction and demolition waste by country.

Country	Annual CDW (million tons)	Source
Egypt	1.5	[101]
Saudi Arabia	4.0	[102]
UAE	42.8	[103]
Syria	20.0*	[104]
Qatar	7.0	[105]
Morocco	42.0	[106]
Algeria	11.0	[107]
Jordan	3.0	[108]
Kuwait	5.0-8.0	[109]
Libya	4.0	[110]

*Estimated total amount of rubbles not yearly figure.

In Egypt, Wagih et al. [111] studied the use of CDW as a recycled aggregate in concrete for structure uses. They found that that the concrete rubble could be transformed into useful recycled aggregate and used in concrete production with properties suitable for most structural concrete applications in Egypt. Another study showed that using CDW as aggregate in pavement for road construction in Egypt was better than pavement with typical natural aggregate [112]. Likewise, in Lebanon, Hassanieh et al. [113] recycled CDW in asphalt mixes and reported that using CDW can replace up to 30% of fine aggregate in hot mix asphalt.

In Saudi Arabia, it was found that CDW conversion into a wide range of aggregates (0–50 mm) can replace 10–100% natural aggregates in backfilling, precast concrete manufacturing, encasements and beddings of water mains and sewers, manholes construction, non-load bearing walls, and farm-to-market roads [114]. In the UAE where around 70% of CDW is recycled, a recent research reported that it is possible to fully replace NA with RA (100%) while maintaining the performance and improving the economic and environmental impacts of concrete produced in the UAE [115].

In Morocco, Raini et al. [116] evaluated the combination of concrete and brick wastes as fine aggregate on mortar properties. They concluded that up to 15% of sand can be replaced by these wastes without compromising the mechanical and microstructural properties of the mortar. Similarly, in Algeria, Debieb and Kenai [117] investigated the suitability of use crushed bricks as coarse and fine aggregate in concrete. They recommended replacement levels of 25% and 50% for the coarse and fine aggregates, respectively, to be used to manufacture concrete with similar properties compared to standard concrete. Complying to the Tunisian national program promote the utilization of CDW, Antit et al. [118] assessed the use of debris of masonry as aggregate in concrete. They reported that it is possible to use recycled waste aggregates in concrete for structural application (beams).

Despite the rise in investigations into the utilization and recycling of CDW in the region, these attempts are still limited. Therefore, a holistic approach and governmental policies are required to fully utilize these wastes and eliminate their hazards to public and environment.

10 Conclusion

This paper reviews the utilisation of local materials in construction in the Middle East and North Africa regions. This includes vegetal and earthen materials, rammed earth, municipal solid waste incineration ash (MSWIA), gypsum and phosphogypsum (PG) and construction and demolition waste (CDW). The trends in using these materials in the region are very diverse. Moreover, the levels of development between countries in the region are highly uneven. The main findings of this review can be summarised as follows:

- The use of vegetable plants and their fibres has a great potential to be used in building materials as reinforcement and/or replacement to cement aggregate.
- The use of earth-based materials for 3D printing could be favourable in the region due to its climate. The use of natural fibres can also improve the properties of the printed materials.
- Earthen materials are eco-friendly materials and present good thermal comfort. A large variety of soils can be used for rammed earth buildings.
- The utilisation of MSWIA in construction materials (e.g., concrete, pavement) contributes to preserving lands in densely populated areas in the region and to reducing the environmental impact of the ash.
- Phosphogypsum can be used to produce modified gypsum binders, mineralizing and setting time regulating admixture for cement as well as a binder for supersulphated cement. However, the radioactivity and contamination of PG should be addressed.
- The availability of gypsum alongside some technical advantages of gypsum should encourage the growth of its use the region not only as render, plaster and jointing but also for blocks and panels.
- CDW can be used in many applications including structural elements. A comprehensive management of these wastes is required to fully utilised their potential in the construction industry.

We believe that the governments, the non-governmental organisations, the academic and research institutions and the private sector in the region should work collectively and collaborate to maximise the use of local materials in the construction industry to achieve the sustainable development goals. Therefore, we suggest the following framework to achieve that.

- Surveying the availability of local materials, by-product materials and wastes that can be used in the construction industry. This can be done by governments and academic institutions.
- Characterisation of these materials and investigation of their suitability in the various construction applications by academic and research institutions.
- Investment in infrastructure and processing plants to maximise the utilisation of these materials by governments and private sector.
- Establishing and developing policies, guidelines, standards and codes on national levels to encourage the use of these materials by governments and legislative institutions.
- Raising awareness of the technical, social, economic and environmental benefits of using these materials.
- Engaging the technical community and local communities in the decision-making process on using these materials by all stakeholders.
- Training and developing workforce to deal with these materials by all stakeholders.
- Improving the regional integration and policy coordination between countries in the region.

Authorship statement (CRediT)

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