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BIOCRUSTS AND PHOTOTROPHIC BIOFILMS ON EARTHEN HERITAGE: BIODETERIORATION OR BIOPROTECTION? A REVIEW WITH IMPLICATIONS FOR MESOPOTAMIAN MUD-BRICK SITES

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ABSTRACT
Earthen architecture is one of the most fragile kinds of cultural heritage. Once excavated and left open, mud brick is worn away by rain, wind, salts and heat. Exposed earthen walls are also colonised by living surface layers, mainly biological soil crusts (biocrusts) and phototrophic biofilms made up of cyanobacteria, algae, lichens, mosses, fungi and bacteria. Conservators have usually seen this growth as a source of damage. Recent field work on rammed-earth walls in China reports something different: crusted surfaces were stronger, less porous and far less erodible than bare ones. This review brings the two bodies of evidence together. We first describe the material and the environmental setting of Mesopotamian mud-brick sites. We then explain how crusts and biofilms form on earthen substrates and summarise the physical, chemical and visual routes by which they can harm them. The protective routes come next: binding of particles by extracellular polymeric substances, shielding from raindrop impact and wind, buffering of the surface microclimate, and carbonate biomineralisation. Previous studies show that the net effect depends on the organisms involved, crust thickness, moisture and salt regime, exposure and time scale. Thin cyanobacterial crusts on dry wall tops appear mostly protective. Mosses, roots and acid-producing communities in damp, salty zones carry real risks. We end with practical implications for Iraqi sites such as Babylon, Ur, Uruk and Tell Muhammad, and propose a monitoring-first research agenda before any biological treatment is tried in the field.

Keywords: *Biological soil crust; Cyanobacteria; Earthen architecture; Bioreceptivity; Nature-based conservation; Mesopotamia.*

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1. INTRODUCTION
Earth is one of the oldest building materials, and a large share of the archaeological record of the Near East is built from it [1,2]. Southern and central Iraq is a clear case. In the Mesopotamian floodplain, mud was the main building material [3]. At Tell Zurghul alone, adobe architecture spans the fifth to the third millennium BCE [4]. Once these walls are excavated, they begin to lose material. Rain cuts gullies, wind abrades the surface and salts break it up from within [5–7]. Exposed earthen surfaces do not stay bare for long. Cyanobacteria, algae, fungi, lichens and mosses colonise them, often as thin crusts or films. Conservation practice has mostly treated this growth as a threat. A large literature, written mainly for stone, links biofilms to staining, mechanical stress and chemical attack [8–11], and removal with biocides has followed from that view [12].

A second view has grown over the last two decades. Geomorphologists described bioprotection, where organisms slow weathering down rather than speed it up [13,14]. The idea was later applied to monuments [15–17]. Dryland ecologists, for their part, have long known that biological soil crusts (biocrusts) hold soil in place [18,19]. The two strands met recently on the Great Wall of China. There, rammed earth covered by biocrusts was stronger and less erodible than bare rammed earth [20].

This raises an obvious question for Mesopotamia. Should living crusts on Iraqi mud-brick ruins be removed, tolerated or even encouraged? The answer matters in practice, because each option leads to a

different way of managing a site. To our knowledge, no field study has yet addressed it. This review has three aims. It summarises how biocrusts and phototrophic biofilms can damage or protect earthen materials. It then asks what earlier studies on earthen sites actually show. Finally, it draws cautious implications for Mesopotamian mud-brick sites and sets out a research agenda.

2. MUD-BRICK HERITAGE IN MESOPOTAMIA

2.1. The material

Mesopotamian mud brick was made from local alluvial sediment. The earth was mixed with water, often tempered with straw or chaff, moulded and left to dry in the sun [2,4]. Recent work at Tell Zurghul (ancient Nigin) in Dhi Qar gives a useful picture of the result. Adobe from the fifth and third millennia BCE contained quartz and calcite as the main phases, together with dolomite, feldspar, gypsum, mica and chlorite [4]. Halite was present too. The authors linked it to later salinisation of the mound rather than to the original recipe. Plant fibres raised porosity, and most samples soaked up water in under a second. The weakest bricks had a clay-rich matrix and were the most prone to weathering, and several lost cohesion under simulated rain [4]. Simple field tests on bricks from the same site pointed to a sandy, uniform material with low shrinkage but limited cohesion [21]. There is also a small but telling detail. When wetted, the archaeological samples smelled of mould and humus, a hint that microbial life was present [21].

At Babylon, ancient bricks from the Ninmah temple had a porosity of about 32%, water absorption of about 23% and a compressive strength of 1.7 N/mm². They were in fact less porous and stronger than the new bricks tested in the same study [22]. These figures describe a porous, fine-grained and weakly bound material. It wets quickly, holds water in fine pores and loses strength when wet. These are also the conditions that favour microbial growth, as discussed in Section 3.2.

2.2. Climate, salts and dust

Central and southern Iraq has a hot desert climate. Mean annual rainfall is about 154 mm. Less than 100 mm a year falls over about 60% of the country, mostly in the south, and almost all of it between October and April [23]. Summer air temperatures usually exceed 43 °C in July and August [23]. The climate is also warming fast. Between 1965 and 2015, minimum temperatures rose by 0.48–1.17 °C per decade and maximum temperatures by 0.25–1.01 °C per decade, two to seven times the global rate [24]. Sand and dust storms have become far more frequent, linked to lower rainfall, drying marshes and land degradation [25]. Soil salinity is widespread across the irrigated Mesopotamian plain [26].

Each stressor acts on mud brick in its own way (Table 01). Short, intense storms cause splash, sheet wash and gullying, especially on wall tops [6,27]. Wind, above all when it carries sand, removes loose grains and pits the surface [6]. In a controlled field experiment at Suoyang, wind-driven rain did the most damage per event, but wind events were far more frequent [6]. Salts move with capillary water and crystallise near the surface. At Tell Muhammad in Baghdad, cycles of salt crystallisation and dissolution, fed by capillary rise, were judged the main conservation risk, and basal erosion affected almost every wall [28]. UNESCO assessments of Babylon, Uruk and Ur describe similar losses from rain and dust storms, made worse by decades of neglect and some incompatible repairs [3,29]. At Ur, cracks in the cement used for the partial rebuilding of the ziggurat in the 1960s now let water into the structure [3]. Ethnoarchaeological studies show how abandoned mud-brick buildings slump and turn back into sediment once roofs and maintenance are lost [7,30]. Climate change is likely to sharpen most of these pressures [31]. Figure 01 shows the sites discussed in this review.

Table 01: Main environmental stressors acting on exposed mud-brick walls in central and southern Iraq and their possible interactions with surface biological growth.

Stressor	Situation in central and southern Iraq	Effect on mud brick	Possible interaction with surface biology
Heat and warming	Air temperatures usually exceed 43 °C in July–August [23]; daily minimum and maximum temperatures rose by 0.48–1.17 and 0.25–1.01 °C per decade in 1965–2015 [24]	Fast drying and repeated heating–cooling of exposed surfaces; climate change is expected to sharpen thermal stress [31]	Restricts active growth to the cool, wet months; dark crusts may add heat (Section 4.3)
Low, seasonal and intense rain	Mean annual rainfall about 154 mm; less than 100 mm over about 60% of the country, mostly in the south; rain falls between October and April [23]	Splash, sheet wash and gullying, above all on wall tops; clay-rich bricks lose cohesion when wet [4,6,27]	Crusts are active only after rain; thin crusts reduce splash and runoff erosion (Section 5.1)
Wind and sand–dust storms	Storms have become far more frequent, linked to lower rainfall, drying marshes and land degradation [25]	Abrasion and pitting by sand-laden wind; wind-driven rain causes the most damage per event [6]	Crust binding raises the resistance of surface grains to wind (Section 5.1)
Salinity and	Soil salinity is widespread in the	Efflorescence and	Poor habitat for most

capillary rise	irrigated plain [26]; halite occurs in Tell Zurghul adobe [4]; salt cycles fed by capillary rise are the main risk at Tell Muhammad, where brick pH is 8.62–8.89 [28]	subflorescence; basal erosion of almost every wall at Tell Muhammad [28]	phototrophs but open to halophiles; extra moisture retention may worsen salt damage (Sections 4.2 and 7)
Neglect and incompatible repairs	Exposed remains at Uruk and Ur were left unprotected for decades and some received incompatible consolidants; cement in the 1960s rebuilding of the Ur ziggurat now lets water in [3]; Babylon needs urgent work to prevent losses during rain [29]	Trapped water, uneven decay and loss of fabric [3,29]; abandoned mud-brick buildings slump back into sediment once maintenance stops [7,30]	Persistently damp spots near failed repairs favour mosses and fungi (Section 3.2)
Human and animal disturbance	Urban encroachment, illegal building and dumping at Babylon [29]; dogs and cattle still enter Tell Muhammad [28]	Impact damage, trampling and disturbance of surfaces [28,29]	Trampling breaks crusts and pushes them back to early stages (Section 8.2)

Section numbers in the last column refer to the discussion in this review.

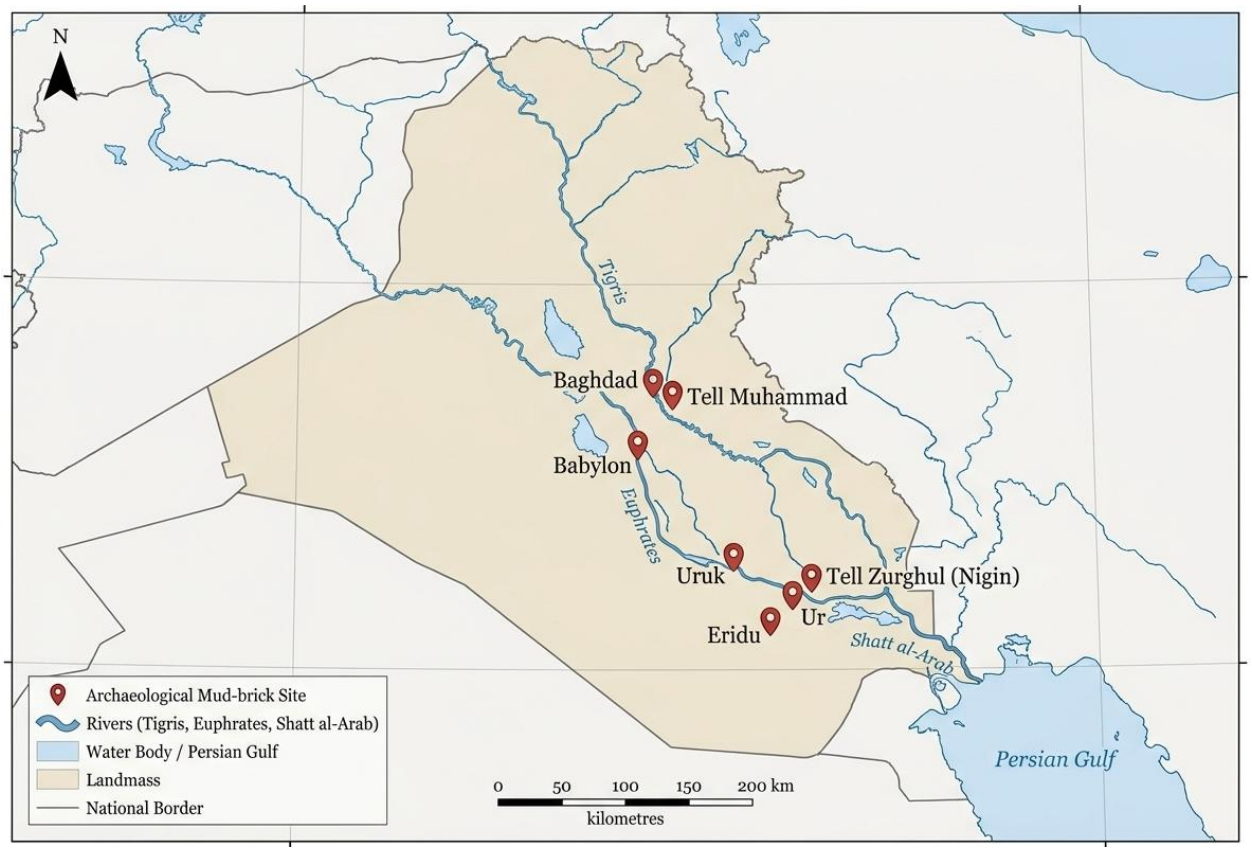

Figure 01: Location of the Mesopotamian mud-brick sites discussed in this review (Babylon, Tell Muhammad, Uruk, Ur, Eridu and Tell Zurghul/Nigin) in relation to the Tigris and Euphrates rivers. Base map: GSHHS shorelines, political boundaries and rivers distributed with the Basemap toolkit.

3. LIVING CRUSTS ON EARTHEN SURFACES

3.1. Biocrusts and phototrophic biofilms

Biocrusts are communities of cyanobacteria, algae, lichens, mosses, fungi and other microbes that live in or on the top few millimetres of soil [32]. They cover a large part of the world's drylands [19,33]. In the Middle East they are well known from the Negev, Sinai and neighbouring deserts [34,35], and recent work in Oman showed that their bacterial and fungal make-up shifts with habitat [36]. Filamentous cyanobacteria such as *Microcoleus* usually start the process. Their sheaths and extracellular polymeric substances (EPS) stick grains together, and lichens and mosses join at later stages [18,37]. Phototrophic biofilms are related but not quite the same. They are thin, often slimy layers of algae and cyanobacteria held in EPS, together with heterotrophic bacteria and fungi [38]. On buildings they belong to the wider group of subaerial biofilms, which must survive repeated drying, strong light and very few nutrients [39,40]. Surveys of

building facades in Europe and Latin America found cyanobacteria, green algae and fungi as the main biomass [41]. Similar groups dominate on Mediterranean monuments [42,43].

On an earthen wall, the line between the two is blurred. A wall top behaves much like a soil surface, while a vertical face behaves more like a facade, and both can host the same organisms (Figure 2). Genetic work on crusts from the Shanhaiguan section of the Great Wall found cyanobacteria to be the dominant phylum, led by *Microcoleus* and *Leptolyngbya* [44]. These crusts were only 1–3 mm thick. Under the electron microscope, however, their filaments formed dense, intertwined nets around the soil grains [44].

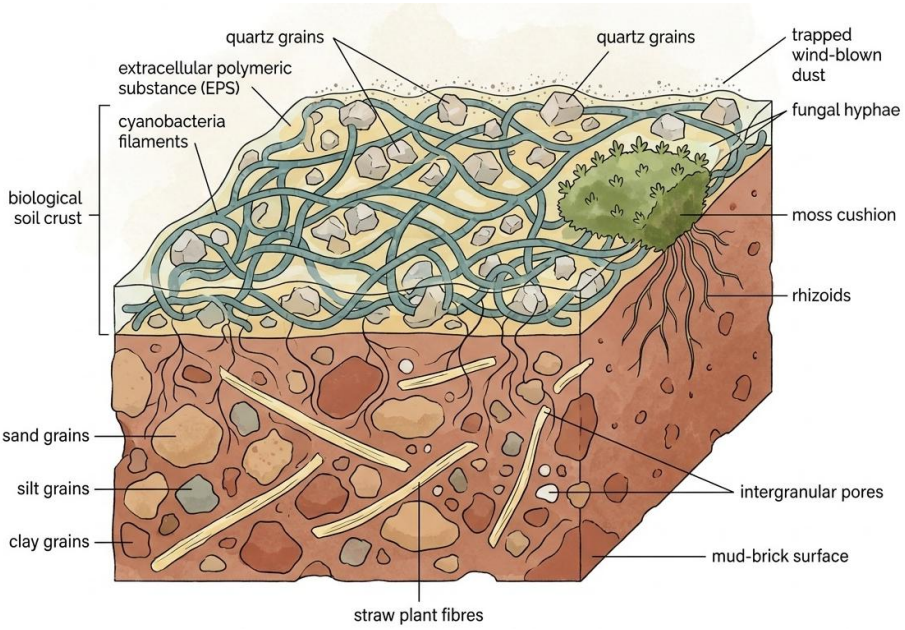

Figure 02: Pictorial cross-section of a biocrust on a mud-brick surface, showing cyanobacterial filaments, extracellular polymeric substances (EPS), trapped dust, mineral grains, fungal hyphae and moss rhizoids. Schematic; not to scale.

3.2. Why earthen surfaces are easy to colonise

Bioreceptivity is the ability of a material to be colonised by living organisms [45]. It depends on porosity, roughness, water retention, pH and mineralogy, and it changes as the material weathers [46,47]. On almost every count unfired earth scores high. It is porous and rough. It keeps water in fine pores long after rain, and it often contains organic temper. Laboratory tests showed that earth materials containing plant aggregates can support fungal growth when humidity stays high [48]. The Tell Muhammad bricks were mildly alkaline, with a pH of 8.62–8.89 [28], a range in which cyanobacteria generally grow well.

Water, though, sets the limit in a dry climate. Colonisation is patchy and follows moisture. On the Great Wall the crest stayed wetter than the lower parts of the faces, and moss crusts occurred where soil moisture was higher [49]. Wall bases near damp ground, shaded faces and spots below broken drains will probably behave the same way in Iraq. These micro-habitats decide where crusts form. As argued below, they also decide whether the crusts protect or harm.

4. ROUTES TO BIODETERIORATION

4.1. Physical effects

Most of the known mechanisms were first described for stone [8,50]. Fungal hyphae and lichen rhizines grow into pores and cracks and widen them [9,51]. Black, melanised microcolonial fungi, typical of sun-exposed rock in hot deserts, are especially well equipped to live on such surfaces [39,51]. EPS swells when wet and shrinks on drying, and this repeated cycling stresses the contacts between grains [8,52]. Biofilms also slow down drying. In an earthen wall, a surface that stays wet for longer keeps its clay swollen and weak for longer, and this is the state in which mud brick slakes and slumps [7].

Mosses add a different risk. On the Weiyuan section of the Great Wall, moss crusts developed large, elongated and well-connected pores that acted as preferential paths for water. Cyanobacteria–lichen crusts, by contrast, had small and poorly connected pores [53]. Faster infiltration may carry water and dissolved salts deeper into a wall. The same authors noted that biocrusts can prepare the ground for vascular plants [53], whose roots open cracks and can destabilise a whole wall head.

4.2. Chemical effects

Microbes release organic acids, chelating compounds and carbon dioxide. These can dissolve carbonates and pull metal ions out of clays and feldspars [51,54]. Lichens add oxalic acid, which reacts with calcium in the substrate to form calcium oxalate [15,54]. Calcite and dolomite are common in Mesopotamian adobe [4], so carbonate binders are a likely target. Yang et al. described a ‘surface protection–internal damage’ paradox on rammed-earth houses in humid

south-eastern China [55]. The crust shielded the surface from rain, but acids released by the algae dissolved calcium carbonate cement underneath it. Salts complicate matters further. Halophilic bacteria have been found thriving in salt-damaged walls and wall paintings [56], and biofilms may change where, and how fast, salts crystallise. For earthen materials these effects remain almost unmeasured.

4.3. Thermal, visual and interpretive effects

Dark crusts absorb more sunlight. Many desert cyanobacteria make sunscreen pigments such as scytonemin [57], and these pigments were shown to warm arid soil surfaces measurably [58]. On a wall that already gets extremely hot in summer, darkening may add to thermal cycling. This has not yet been measured on mud brick, though. Green and black growth also changes how a monument looks, and on stone such colour change is a common trigger for cleaning [59,60]. On excavated earthen walls the loss can be one of information. A crust can hide mortar joints, plaster layers or brick sizes that archaeologists need to read [2]. Figure 3 brings these routes together.

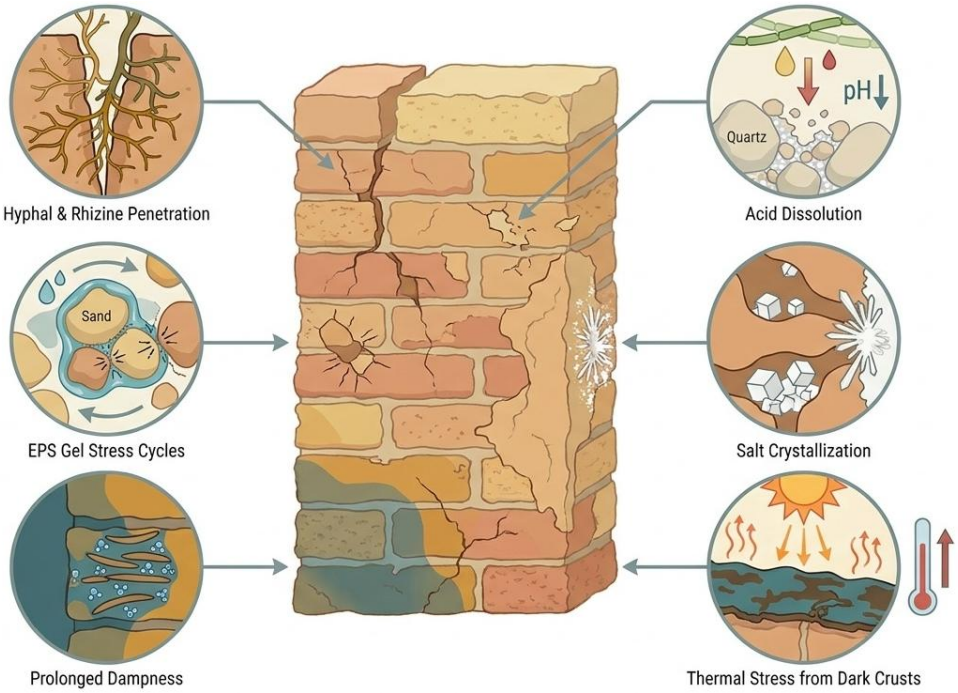

Figure 03: Biodeterioration pathways on mud brick: penetration by hyphae and rhizoids, wet–dry cycling of EPS, prolonged surface wetness, acid attack on carbonate binders, salt interactions and surface darkening.

5. ROUTES TO BIOPROTECTION

5.1. Binding and resistance to erosion

The best-supported protective effect is mechanical. Cyanobacterial filaments form a three-dimensional mesh, and EPS coats and glues grains into stable aggregates [37,61]. Inoculation experiments show how this develops. In sand microcosms, one inoculated cyanobacterium built a polysaccharide matrix that bound the grains into an induced crust [62]. Inoculation also improved surface stability on soils of contrasting texture [63,64]. In the Gurbantunggut Desert, the microstructure of such crusts raised the resistance of sandy surfaces to wind erosion [65].

Results from earthen heritage point the same way. Along the Great Wall, biocrusts covered about two-thirds of the sections surveyed. Crusted rammed earth had lower porosity, water-holding capacity, erodibility and salinity than bare rammed earth, and higher compressive strength, penetration resistance, shear strength and aggregate stability [20]. The numbers from Shanhaiguan are striking. In a five-minute field spray test, about 32.8 g of soil washed off a fully crusted face, against about 2926 g from an uncrusted one [66]. In laboratory rain tests the crust kept 95.3% of its mass, while rammed earth kept only 68.6% [66]. Carbonate content was low (0.25–0.67%), so the authors credited the effect to the living crust rather than to cementation.

5.2. Water, heat and dust

Crusts also change how water enters a surface. Young cyanobacterial crusts can be water-repellent and can clog surface pores [67], and crust microstructure strongly controls how water moves through the top few millimetres [35]. The result is less splash and slower infiltration. At the same time, biocrusts often help soils hold moisture after rain [68]. Their overall effect on dryland water budgets is large, but it varies with crust type and climate [18,69]. For a wall, slower infiltration is mostly good news. Less water reaches the core, and fewer salts are set in motion. It may be no accident that Cao et al. measured lower salinity in crusted rammed earth than in bare samples [20], although the mechanism behind that result is still open.

Living covers can buffer heat as well. Wall caps planted with native vegetation, a larger-scale analogue of a crust, cut material loss by 58–75% under heavy and extreme simulated rain and lowered summer temperature and moisture in test walls [70]. Ivy on historic walls damped temperature extremes and trapped airborne particles [71,72], and soft turf caps on masonry ruins moderated conditions at wall tops [73]. Whether a crust only a few millimetres thick can do the same has not been tested.

5.3. Biomineralisation

Some microbes do more than bind. Photosynthesis raises pH around the cells and can trigger calcium carbonate precipitation in mats and crusts [74,75]. Biofilms have been linked to case hardening of sandstone in arid Jordan [76], and rock-surface microbes stabilised friable sandstone in a dry, wind-abraded setting in Utah [77]. Lichens offer another natural example, as the calcium oxalate films they leave behind are thought to protect some stone surfaces [15]. Engineered versions of this process are now being tested on heritage. Bacterially induced carbonate has been used to consolidate stone [78,79] and to improve other building materials [80]. On soil from Suoyang Ancient City, microbially induced carbonate precipitation raised unconfined compressive strength by 26% at the highest density tested [81]. Denser soil formed more carbonate, so the compaction state of a wall matters for any such treatment [81]. Engineered treatments of this kind are not biocrusts in the strict sense. They do show, however, that microbial cementation is compatible with earthen fabrics. That cannot be said of every synthetic consolidant. At Liangzhu, for example, site microbes degraded an epoxy resin applied as a protective treatment [82]. In the same study, an excess of ethyl silicate changed the particle size of the soil, and the authors warned that heavy use could even speed up weathering [82]. Figure 4 summarises the protective routes, and Table 2 sets them against the damaging ones.

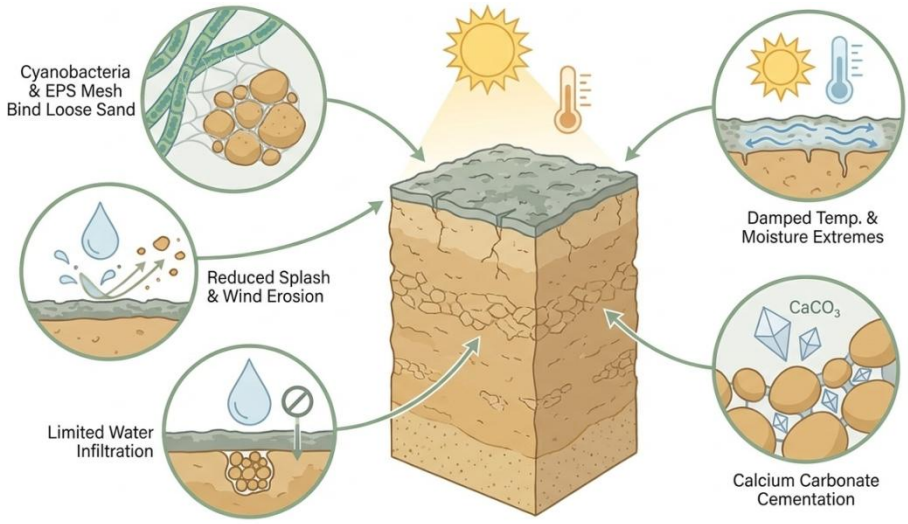

Figure 04: Bioprotection pathways on mud brick: particle binding by filaments and EPS, interception of raindrops and wind-blown sand, reduced infiltration, microclimate buffering and carbonate biomineralisation.

Table 02: Biodeterioration and bioprotection mechanisms attributed to biocrusts and phototrophic biofilms on earthen and related porous substrates, with the conditions under which each is likely to dominate.

Mechanism	How it works	Main agents	Conditions that favour it	Sources
Biodeterioration				
Penetration	Hyphae, rhizines and rhizoids grow into pores and cracks and widen them	Fungi, lichens, mosses	Long wet periods; existing fissures	[9,39,51]
Wet–dry cycling of EPS	EPS swells when wet and shrinks on drying, stressing grain contacts	Cyanobacteria, algae	Frequent wetting and drying	[8,52]
Prolonged wetness	Biofilms slow drying, so clay stays swollen and weak for longer	Biofilms, mosses	Shade, poor drainage, damp bases	[7,8]
Preferential flow	Connected macropores under moss crusts speed infiltration and may carry salts deeper	Mosses	Moist microsites; late-successional crusts	[53]
Acid attack and chelation	Organic and oxalic acids and CO_2 dissolve carbonate binders and mobilise metal ions	Algae, fungi, lichens	Humid or acidic settings; carbonate-rich earth	[15,51,54,55]

Salt interaction	Moisture held by biofilms may feed salt cycles; halophiles thrive in salt-damaged walls	Halophilic bacteria	Rising damp; saline wall bases	[56]
Darkening and heating	Sunscreen pigments darken the surface and raise its temperature	Cyanobacteria (scytonemin)	Sun-exposed surfaces	[57,58]
Visual and interpretive loss	Staining changes appearance and hides joints, plaster layers and brick sizes	Green and black biofilms	All exposed faces	[2,59,60]
Facilitation of plants	Crusts may prepare the ground for vascular plants, whose roots open cracks	Mosses, then plants	Moist wall tops	[53]
Bioprotection				
Particle binding	A mesh of filaments and EPS glues grains into stable aggregates	Filamentous cyanobacteria (e.g., *Microcoleus*)	Thin crusts on dry, exposed surfaces	[37,44,61,62]
Erosion shielding	The crust intercepts raindrops and wind-blown sand, so fewer grains are detached	Cyanobacteria, lichens, mosses	Wall tops and windward faces	[20,65,66]
Reduced infiltration	Water repellency and pore clogging slow water entry	Early cyanobacterial crusts	Young crusts	[35,67]
Lower salinity	Crusted rammed earth was less saline than bare earth; the mechanism is still open	Mixed biocrusts	Arid sites	[20]
Microclimate buffering	Living covers damp temperature and moisture extremes (analogue evidence)	Vegetated caps, ivy, turf caps	Wall tops and caps	[70,71,73]
Biomineralisation	Carbonate or oxalate precipitation cements grains; case hardening of surfaces	Cyanobacteria, bacteria, lichens	Alkaline, calcium-rich substrates	[15,74–76]

Sources are representative rather than exhaustive. EPS, extracellular polymeric substances.

6. PREVIOUS STUDIES ON EARTHEN HERITAGE

Table 3 lists the main studies that have examined living crusts on earthen heritage, together with a few analogue studies on stone. Several patterns stand out.

The first is geographic. Nearly all direct evidence comes from China, where the Great Wall, from Gansu in the north-west to Shanhaiguan on the Bohai coast, has become the main natural laboratory [20,44,49,53,66,83]. We did not find comparable field studies from earthen sites in the Middle East, North Africa or Central Asia. The Getty Conservation Institute and its partners in China and the United Kingdom set out the question explicitly, asking whether biocrusts on wall faces are harmful or protective [84].

The second is that most answers so far favour protection, but with qualifications. Across four defence zones in north-west China, vascular plants covered 13.6–63.9% of the wall tops and biocrusts 36.3–67.8% [83]. On these wall tops, vascular plants and biocrusts together raised soil organic carbon and amorphous iron and aluminium oxides. This promoted stable aggregates and lowered erodibility [83]. The same study, however, found that the crusts reduced the sand fraction, and this change on its own raised erodibility. The protective effect reported by Cao et al. also varied with crust traits, local climate and the way the wall was built [20].

The third concerns organism type. Moss crusts were more porous and let in more water than cyanobacteria–lichen crusts [53]. In the top 50 mm, CT-based porosity was about 12.8% under cyanobacteria–lichen crusts and 21.5% under moss crusts, against 2.1% in bare soil [53]. This sits uneasily with the lower porosity that Cao et al. found under crusts [20], and the gap probably reflects differences in method, depth and crust type. Yet, where moisture allowed, mosses and plants also strengthened aggregates and reduced erosion susceptibility [49].

The fourth concerns climate. In humid, acid-rain-affected Songyang, the same crusts that softened raindrop impact released acids that dissolved carbonate cement [55]. To get around this, the authors proposed a layered composite of a biodegradable mesh, natural fibres, an algal inoculum and calcium carbonate microparticles to neutralise the acid. So far, though, the design exists only on paper [55]. At Liangzhu, another humid site, microbes on the earthen ruins degraded protective resin [82].

The last is time. Most studies are one-off surveys or short tests. At Shanhaiguan, for instance, the case for protection rests on field observation, genetic and microscopic work, and spray and rain tests lasting a few minutes [44,66]. Long records of crust dynamics on walls are rare. Whether nature-based capping lasts for years in semi-arid climates, under freeze–thaw and thermal fatigue, has only begun to be examined [85]. Studies on stone show the same split. Lichens and biofilms damage some monuments but shield others from wind, rain and temperature swings [15–17]. Taken together, the evidence does not support a blanket rule in either direction.

Table 03: Previous studies on biocrusts and phototrophic biofilms on earthen heritage and analogue substrates: site, substrate, dominant organisms, methods, main findings and reported net effect.

Study	Site and substrate	Organisms or agent	Methods	Main findings	Net effect
Earthen heritage					
Cao et al. (2023) [20]	Great Wall, north-west China; rammed earth	Cyanobacteria, lichens, mosses	Field survey; crusted versus bare samples; physical and mechanical tests	Crusts covered about two-thirds of the surveyed sections; lower porosity, water-holding capacity, erodibility and salinity; higher compressive and shear strength, penetration resistance and aggregate stability; effect varied with crust traits, climate and wall type	Protective
Liu L. et al. (2023) [44]	Shanhaiguan, Great Wall; rammed soil	Cyanobacteria (*Microcoleus*, *Leptolyngbya*)	16S rRNA sequencing; SEM	Grey-green crusts 1–3 mm thick; filaments and EPS form nets around grains; protection inferred from field observation	Protective (observational)
Liu L. et al. (2024) [66]	Shanhaiguan, Great Wall; rammed earth	Cyanobacteria and α-proteobacteria (about 60%)	5-min field spray test; laboratory rain test; $CaCO_3$ analysis; SEM; sequencing	Soil washed off: 32.8 g from a crusted face versus 2926 g from a bare one; mass kept in rain tests 95.3% versus 68.6%; $CaCO_3$ only 0.25–0.67%	Protective
Liu Y. et al. (2024) [83]	Great Wall wall tops, four defence zones, north-west China	Mosses, lichens, cyanobacteria; vascular plants	Vegetation and crust survey; soil, aggregate and erodibility analyses	Plant cover 13.6–63.9%, crust cover 36.3–67.8%; more organic carbon and amorphous Fe and Al oxides, stabler aggregates, lower erodibility; crusts also reduced the sand fraction, which raised erodibility	Mainly protective
Liu Y. et al. (2025) [49]	Great Wall; seven positions on both faces and the crest	Mosses, vascular plants	Soil moisture after rain and in dry periods; community and aggregate analyses	Crest wetter than lower faces; moisture shaped moss and plant cover; biota strengthened aggregates and reduced erosion susceptibility	Protective
Yang X. et al. (2025) [53]	Weiyuan section, Gansu; Warring States Qin wall	Cyanobacteria–lichen and moss crusts	Microscopy, SEM, X-ray CT, infiltration tests	Porosity in the top 50 mm 12.8% and 21.5% versus 2.1% in bare soil; moss crusts had connected macropores and the fastest infiltration	Mixed
Yang J. et al. (2025) [55]	Songyang County, Zhejiang; rammed-earth dwellings, humid with acid rain	Cyanobacteria, actinobacteria, α-proteobacteria	Drone survey, XRD, FE-SEM, 16S rRNA sequencing	Crust softens raindrop impact and binds grains, but algal acids dissolve $CaCO_3$ cement; a composite biofilm was proposed but not tested	Mixed
Sun et al. (2020) [82]	Liangzhu City ruins, Zhejiang; humid earthen site	Soil microbial community	SEM; metagenomic sequencing; tests of	Site microbes degraded epoxy resin; excess ethyl silicate changed the particle size of the soil	Damaging to synthetic treatments

			protective materials		
De Vito and Volpi (2025) [21]	Tell Zurghul/Nigin, Iraq; archaeological adobe	Not identified	Empirical field tests	Sandy adobe with limited cohesion; wetted samples smelled of mould and humus	Not assessed
Laborel-Préneron et al. (2018) [48]	Laboratory; raw earth and earth with straw or hemp aggregates	Fungi (*Aspergillus brasiliensis*, inoculated)	Incubation for 12 weeks at 76–93% RH and 20 or 30 °C	Fungi appeared after 4 weeks on earth with plant aggregates and after 8 weeks on raw earth (93% RH, 30 °C); liquid water favoured mould more than humidity alone	Susceptible to fungal growth
Jiang and Yeo (2025) [70]	Scaled rammed-earth test walls modelled on the Ming Great Wall	Native vegetation (natural capping)	Simulated rainfall, four patterns	Material loss fell by 58.24–75.04% and inner moisture infiltration by 5.56–7.52% under heavy and extreme rain; cooler, drier walls in summer	Protective (vegetation analogue)
Li et al. (2024) [81]	Soil from Suoyang Ancient City; compacted specimens	MICP versus EICP	Strength and wave-velocity tests at three densities	Unconfined compressive strength rose by 26% (MICP) and 8% (EICP) at 1.7 g cm^{-3}; denser soil formed more carbonate	Consolidating (engineered)
Analogue substrates					
Viles and Goudie (2004) [76]	Al-Quwayra, Jordan; sandstone	Biofilms	Field study	Biofilms associated with case-hardened sandstone surfaces	Protective
Kurtz and Netoff (2001) [77]	South-central Utah, USA; friable sandstone	Rock-surface microorganisms	Field study	Microbes stabilised friable surfaces in a dry, wind-abraded setting	Protective
Sternberg et al. (2011) [71]	Historic walls, UK	Ivy (*Hedera helix*)	Microclimate monitoring	Ivy moderated wall-surface microclimates	Protective
Viles and Wood (2007) [73]	Masonry ruins, UK	Soft (turf) wall capping	Laboratory and field testing	Soft caps moderated conditions at wall tops	Protective

Net effect as reported or implied by the original authors. EICP, enzyme-induced carbonate precipitation; EPS, extracellular polymeric substances; MICP, microbially induced carbonate precipitation.

7. RECONCILING THE TWO VIEWS

Why should the same organisms act as friends in one place and foes in another? We think the balance turns on five factors (Figure 05).

Crust type and thickness come first. Thin cyanobacterial crusts mainly bind and seal. Lichens, mosses and the plants that follow bring deeper anchoring structures, more water storage and better-connected pores [49,53].The second factor is the moisture regime. Crusts are active for short times after rain and subsequently go dormant in dry environments [18,86]. In central and southern Iraq, where rain falls only from October to April [23], that dormant phase lasts for most of the year. During protracted rainy periods, the release of acid, swelling and sluggish drying become more essential [7,55].The third is salt. Areas rich in salts close to the lower parts of the walls are unsuitable for most phototrophs but can sustain halophiles [56]. Any excess moisture retained there can exacerbate salt damage.The fourth is exposure. Binding is most advantageous on wall tops and windward sides where splash and abrasion are most severe [6,20]. Shaded, protected areas are more likely to remain moist and to support mosses and mushrooms. The highest slopes and borders of previous excavation trenches are the most exposed areas, says On.The last factor is time, and maybe the least researched. Trampling, cleaning or dryness can lead to abrupt loss of crusts, and climate change is already altering their composition [33,87,88]. A protective crust is only good if it lasts. Global change will also unpredictably alter the biology of legacy surfaces [14,31]. Therefore, 'biodeterioration or bioprotection' is not a yes/no question. It is a matter of organism, of place and time.

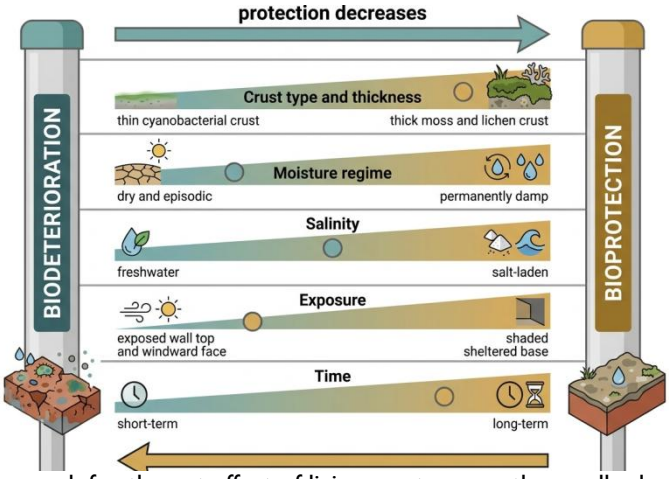

Figure 05: Conceptual framework for the net effect of living crusts on earthen walls along gradients of crust type, moisture, salinity, exposure and time. Conceptual; marker positions are qualitative.

8. IMPLICATIONS FOR MESOPOTAMIAN MUD-BRICK SITES

8.1. Where crusts may help

Most Great Wall sites are cooler and wetter than central and southern Iraq. This should prevent the development of thick moss and encourage thin cyanobacterial crusts on well-drained surfaces, the kind that had the greatest protective impact in China [20, 66]. Wall tops, upper faces and tell slopes are most likely to benefit as these are the areas most damaged by rain splash and wind abrasion [6]. A reasonable first approach is to only leave thin, solid crusts in these areas, unless they contain traits that must be documented. Timing, too, requires thought. In Iraq, crusts would be active mostly in the rainy months, between October and April, and dormant through the long dry summer [23,86]. Thus any field trial should be initiated early in the wet season.

Another tactic is to pass via sacrificial layers. Ruins are capped with new mud brick or clay mortar as a typical practice [5,27]. In simulated rainfall tests on adobe test walls, earthen tops and full coats protected the original fabric much better than patching, even when they too degraded and would need to be renewed [27]. fresh bricks and plaster are being manufactured at Tell Muhammad using local recipes [28]. Such caps could be engineered to contain a biocrust. Native cyanobacteria may be separated, cultured and reintroduced to deteriorated soils [89-91]. The inoculum on a cap would develop into the new layer, not into the old cloth. Polysaccharides and other natural binders already employed in earth building may help with early establishment [92,93]. Any such trial should be undertaken with local strains, compatible earth and should be reversible.

8.2. Where caution is needed

There are times to hold back. Wall bases affected by growing damp and salt efflorescence are not good candidates, since more moisture retention may increase salt degradation, currently the principal concern at Tell Muhammad [28]. Shaded or poorly drained environments may develop mosses, fungus and eventually plants. Feet and hoofs also need protection against crusts. Dogs and cattle continue to access Tell Muhammad [28], and long-term trampling investigations reveal that physical disturbance forces crusts back to early successional stages [87]. Staining and acid assault can damage information that cannot be restored and thus any surface that is plastered, painted or inscribed should be maintained clean [2,55]. Nor should biocides be the knee-jerk response to green or black growth. They may have an impact on non-target animals and leave residues, and their behaviour on earth is poorly understood [12].

8.3. Research and monitoring priorities

What is needed most urgently is a simple description. We are unaware of any published survey of biocrusts or coatings on ancient surfaces in Iraq. Baseline mapping at a few typical sites, from Babylon in the center to Ur and Eridu in the south, should document where crusts occur, what species make them and how they relate to aspect, moisture and salts. Such a work is now inexpensive with DNA-based techniques [44,94]. Simple, repeatable metrics can then be used to track change: colour measurement and photography for surface appearance, chlorophyll-based indices for biomass and erosion pins or close-range photogrammetry for material loss [28,60,95]. Some of the infrastructure is already there. Tell Muhammad uses drone photogrammetry, deterioration mapping and machine learning assisted risk assessment [28]. Biological observations could be added to such systems at little further cost. Paired plots with and without crusts under natural rain would provide the first direct test in a Mesopotamian context. This workflow is outlined in figure 06 and table 04. Training local conservators and site guards, who see these walls every day, will make monitoring viable.

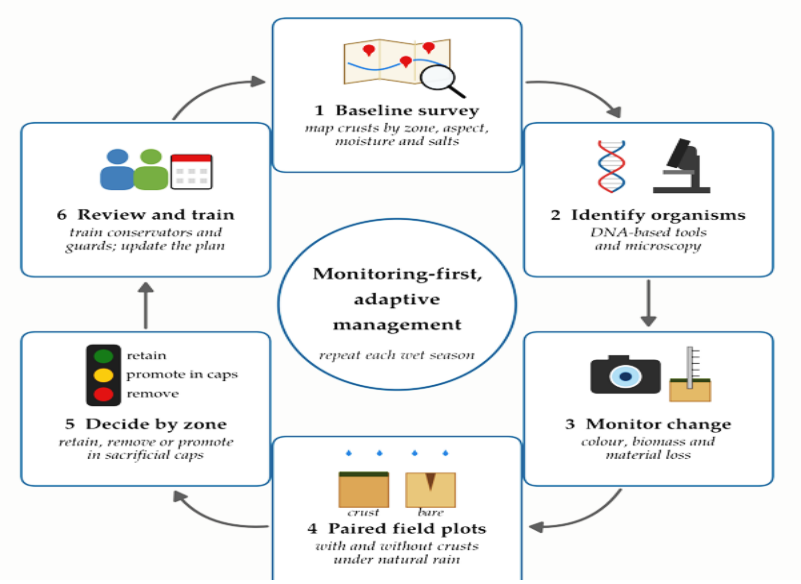

Figure 06: Proposed monitoring-first workflow for managing biological growth on Mesopotamian mud-brick sites, from baseline survey to field trials and adaptive decisions.

Table 04: Proposed decision criteria for retaining, removing or promoting biological crusts on different parts of Mesopotamian mud-brick sites.

Site zone	Typical conditions and growth	Main benefit or risk	Proposed action	What to monitor
Wall tops and upper faces	Dry and exposed; thin cyanobacterial crusts; short wet pulses	Benefit: binding, less splash and abrasion [20,66]	Retain thin, stable crusts; record them before any cleaning	Crust cover and colour; material loss
Tell slopes and trench edges	Loose, exposed sediment; gullies after storms	Benefit: surface stabilisation [20,65]	Retain existing crusts; test inoculation only in small trial strips	Gully depth; crust cover
Sacrificial caps and new repairs	New earth of known, local recipe [28]	Benefit: a crust can form in new material, not in ancient fabric	Main candidate for inoculation with native strains [89–91]; keep the cap reversible	Crust establishment; cap erosion [27]
Shaded or poorly drained faces	Long wet periods; mosses, fungi and later plants	Risk: moisture retention, penetration, plant establishment [53]	Fix drainage and shelter first; remove mosses and plants selectively	Surface moisture; moss and plant cover
Wall bases with rising damp	Capillary rise, efflorescence, halophiles [28,56]	Risk: worse salt damage	Do not promote crusts; control water first (drainage, shelters) [28]	Salt efflorescence; basal erosion
Plastered, painted or inscribed surfaces	Unique archaeological information	Risk: staining and acid attack [2,55]	Keep free of growth; gentle mechanical cleaning by conservators	Colour change [60]
Visitor routes and areas open to animals	Trampling by people, dogs and cattle [28]	Risk: crust loss and return to early stages [87]	Fence, mark paths and keep animals out	Crust condition along routes
Any zone where chemical treatment is planned	Pressure to use biocides or synthetic consolidants	Risk: residues, non-target effects and microbial attack on resins [12,82]	Avoid biocides and resins as defaults; test compatibility first	Treatment performance over time

Proposed by the authors from the evidence reviewed; each action should be tested in the field before wider use.

9. CONCLUSION

Living crusts on earthen heritage are neither simply good nor simply bad. The evidence reviewed here shows that thin cyanobacterial biocrusts can bind grains, shield surfaces from rain and wind, and cut the erosion of rammed earth by large margins. The same communities, or the mosses, fungi and plants that follow them, can also hold water, release acids, open pores and darken surfaces. Which effect wins depends on crust type, moisture, salts, exposure and time. For Mesopotamian mud-brick sites, the hot, dry climate may favour the protective kind of crust on wall tops and upper faces, while damp, salty bases and decorated surfaces need more care. These ideas, however, still rest on evidence from other regions. Iraqi sites lack even a basic inventory of their surface biology. We therefore recommend a monitoring-first strategy: map and identify existing crusts, test their effect in paired field plots, and only then consider inoculating sacrificial caps with native strains. Handled in this way, biocrusts could become a cheap and compatible ally in protecting the earthen heritage of Mesopotamia.

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11. CONFLICTOF INTRST

Not Declered.

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Not Declared.

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