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REVIEW ARTICLE

Assessment of the potential effects of plants with their secreted biochemicals on the biodeterioration of archaeological stones

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Abstract
Archaeological sites and structures suffer from several factors of deterioration. The present survey focuses on the biodeterioration by plants, which is not less important than the rest of the deterioration factors; moreover, in many cases, it leads to their occurrence. Despite the importance of plants in our lives and their aesthetic appearance around stone monuments, they pose a threat to their survival. Therefore, it is necessary to have such a review to detail this topic and understand its severity by identifying the most common and harmful plant species, the co-factors for their existence, and the mechanism of damage. Physical damage through causing cracks, detachment, and loss of structural integrity and chemical damage from root secretions-biological damage by encouraging microorganisms and insects supported by examples of sites that have been damaged by plants. The results will help to apply appropriate methods of prevention and control by mentioning the advantages and disadvantages of each method.

Keywords Biodeterioration · Plants colonization · Stone monuments · Archaeological sites · Control methods

1 Introduction

Biodeterioration is a chemical or physical alteration in archaeological material caused by biological organisms. Biophysical damage is the mechanical degradation of the surface through separation and penetration, causing pressure by growth and increasing porosity. Biochemical damage is the direct action of metabolism. Furthermore, the aerobic organisms produce carbon dioxide respiratory, carbonic acid that decays and dissolves stones and contributes to forming soluble salts [1–3]. Notably, the biodeterioration caused by organisms is more dangerous than that by microorganisms such as fungi, bacteria, algae, and lichens [4].

Analogous biodeterioration by plants is one of the most significant deterioration factors of monuments and structures [5]. Undoubtedly, Egypt is one of the ancient countries, which has a significant cultural heritage that is still so attractive and charming [6]. Plant colonization of stone monuments is a worldwide issue and several archaeological sites in Egypt were damaged by plants such as Behbeit el-Hagar Temple, Keman Fares Temple, and Sarabium site [7–9]. In addition, the Kom el Dikka site at Alexandria City, Egypt, is displayed in Fig. 1. Moreover, several sites in Turkey, Spain, Italy, and India suffer from it too [10–13]. At the Petra site in Jordan, vegetation was observed on the façade of the Corinthian tomb; therefore, these plants must be eliminated to prevent unrecognizably weathered or collapsing in the future [14]. Plants belonging to families Asteraceae, Poaceae, Apiaceae, and Scrophulariaceae were identified from the biodegradation of Kasbahs of the Gharb Region, Mehdia and Kenitra Kasbahs, Morocco, which were fitting into joints or cracks on the stones, by acid chemical action and mechanical action by the growth of roots inside cracks [5]. Plants pose a major danger to stones and structures due to their ability to cause serious types of deterioration [15, 16]. With the presence of plants in many archaeological sites, the resulting damage may not be visible yet but is potential due to root extension under the ground [17].

The deterioration changes depending on whether it is a climbing plant from soil or sprouted on the structure. In the first case, the damage is caused due to the weight of

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Fig. 1 An example of plant colonization at Kom el Dikka site Alexandria, Egypt (**a** and **b** showing the growth of the plants between stone blocks, **c** showing plants under the ribbed vault, **d** showing plants growing on the mosaic (Photos were taken by the co-author Yomna M. Elgohary)

the aerial part, and in the second, it extends to include the damaging effect of the roots, which may lead to the fall of the plaster if it grows on the stucco wall [11]. Notably, plants that grow without soil in urban structures can adapt to harsh conditions [18].

Sometimes the roots penetrate to a depth of about 8–10 m and sometimes cover distances of more than 50 m, as in the case of one specific *Ficus carica* L. (the common fig) [19]. Plants have been classified as one of the weathering types that historical buildings are exposed to, because they develop easily, especially with the availability of appropriate conditions [20]. Furthermore, plants are more urgent to edaphoclimatic conditions, as they act as bioindicators for the microenvironment where they grow [15, 21]. On the whole, the deterioration degree highly relies on growing conditions, which makes it easier to predict potential damage to the site [22, 23].

Therefore, this review aimed to illustrate the plant genera that cause the biodeterioration of archeological stone monuments and their mode of action and furthermore, the possible ways to preserve and prevent the deterioration caused by plants.

2 The harmful colonized species

2.1 Woody species

Plants whether woody species like trees and shrubs or herbaceous species including grasses, wildflowers, and weeds can cause damage to stone blocks and structures. But woody species are more harmful due to their root system that can grow for several meters in width, depth, and length as such it poses a danger by extending in the joints and trapping moisture in these openings, resulting in their enlargement [15, 24–28].

Woody species or higher plants like *Olea europaea* L., *Ailanthus altissima* (Mill.) Swingle, *Asparagus albus* L., *Ceratonia siliqua* L., *Rubus ulmifolius* Schott, and *Ficus carica* L. with their large root sizes can cause a chemical and mechanical breakdown of phanerophytes by creating deep fissures that can end in destruction with appreciation to their vigorous roots and their high alimentary needs [17, 29–31]. Indeed, they can develop their root system at a far distance from the rooting point [23]. Moreover, woody species can induce noticeable dimensional changes because of the secondary growth in their stems and roots [32]. Ornamental trees disperse their seeds from birds, wind, water, insects, mammals, and even humans as such they are prevalent on monuments, not only that but its danger is represented in its reproduction on the upper parts, which is difficult to control [33, 34].

2.2 Perennial weeds

Perennial weeds such as *Erysimum cheiri* (L.) Crantz, *Cynodon dactylon* (L.) Pers., and *Dittrichia viscosa* (L.) Greuter is responsible for further damage than annual weeds through their ability to make the structure vulnerable by affecting the stability resulting from their root system and the biomass [25, 35]. Perennial weeds are resistant, adaptable, and can populate with seeds and reproduce vegetatively, which is a unique way to survive, consequently becoming difficult to control [34, 36].

2.3 Climbing plants

Climbing plants have unique adaptations and possess high tensile strength and flexibility, which allows them to use natural and man-made structures for support and growth [37]. Additionally, climbing plants require to attach themselves to external support from nearby trees and shrubs to facilitate their growth as well; they are responsible for the climber diversity [38]. Climbers do not only cover up the whole view, but they stifle the substrate or the structure, and shortly by their increasing weight pull down parts of it, in addition to the stout woody climbers of liana, which can produce roots at every node of their stem and then cling to the walls and the sides of the structure [39]. In a comparatively short time, the plant's roots, tendrils, suckers, and roots of creepers like ivy can cause significant mechanical and chemical deterioration of stones and structures [40, 41]. Besides, vines can pose severe damage compared to other species because they tend to create damp areas between the leaves and the walls, which can cause moisture build-up and rot as it prevents the sun from drying the wall [42]. Furthermore, the roots enzyme can attack the stability of lime remains only in the sand [15, 24–27]. In occupied buildings, mature creepers may cut out light, inhibit drying out, and obscure the condition of the walls [43].

The weathering process by small $H+$cation produced by the root systems of higher plants and climbing vines like Virginia Creeper (*Parthenocissus quinquefolia* Planch.) and Boston ivy (*Parthenocissus tricuspidata* Planch.) can easily exchange negatively charged nutrient metal cations with minerals and soils. This exchange is also important in the dissolution of the CO_3 anion to carbonate [44]. Climbing plants such as ivy (*Hedera helix* L.) pose a threat due to their ability to establish easily on walls and form an intensive cap causing Surface loss and fragments lost [22, 33]. *Hedera helix* L. intrudes into joints and rubble fill, converting originally substantial walls into an unstable mass of loose stones and decomposed mortar [43].

Likewise, ivy roots can be very invasive and destructive when allowed to penetrate pre-existing fissures and gaps [45]. Moreover, ivy can interact with brick and mortar causing loss of structural integrity and by extension, intervention by the consolidation process becomes required [22]. Overall, vines should be denied the freedom to climb the walls, which could be achieved by periodic weed trimming maintenance [15, 24–28]. The order of the most harmful plant species is shown in Fig. 2.

3 Co-factors for plant invasion and colonization

In general, plants need Mn, B, Zn, Cu, Mo, Cl, Na, Si, Co, V, and Ni as essential mineral nutrients (in the case of wall vegetation if the nutrient is organic, it could be an impurity from the substrate or formed through humus if it is inorganic so they are often the mineral constituents of the stone), water, adequate temperatures and humidity, light, and oxygen, which are the key factors for plant growth and reproduction whether in the soil or on the monuments [32, 46–48].

Soil pH indicates hydrogen ion activity in the soil solution; it plays a significant role in plant health through mineral nutrient supplies in addition to most of the soil processes. The optimal soil pH for plant growth is between 5.5 and 7; on the contrary, most plants cannot grow in acidic soils because of the amount of aluminum and iron, which are toxic to them [49, 50]. Most wall materials are alkaline pH in the range of 7–9, while mortars are highly alkaline such as Portland cement pH between 11 and 12 [51].

But some other promoting factors (Fig. 3) make the structure of buildings suitable for plant colonization, such as stone facades that suffer from moisture retention and stagnation of rain for prolonged periods as well as the condition of the surface, porosity, and chemical composition [52–54].

Moreover, the size of the stone can affect the type of plant colonization as it seems that more xerophilous species

Fig. 2 The order of the most harmful plant species

grow between smaller blocks, which is likely due to higher moisture in the cracks of the larger blocks [53], while trees require large surface areas compared to the walls to grow effectively [51, 55]. Another factor is the age of the wall and the presence of lime mortar [11, 51, 56]. The age of a wall that can enhance variegated flora ranges from one hundred to five hundred years, where the age is associated with the dissolution of walls, creating crevices, and sediment accumulation in this context promotes more botanical communities [51, 56, 57].

Commonly, plants prefer growing in porous stones and lime mortar in the case of bricks due to their ability to retain water and are more easily invaded compared to compact materials like granite and other siliceous rocks [25, 28]. However, by extension, when comparing the attack of acid gasses on the surface of dry and wet limestone, it will of course be greater in the presence of a wet limestone surface [43]. As it was underlined, lime mortar represents the weakest resistance area, the easiest to penetrate, and therefore the fastest to deteriorate [32]. Although the walls are covered with plaster, they may play the role of a surface protector in the short term. Plasters retain their physical and mechanical strength, as well as their dissolution, which supports the growth of roots and the reproduction of woody species, resulting in promoting the growth of the most dangerous species of flora [23].

The climate of the monument area is highly significant for plant growth especially humid and warm conditions that are favorable and exposed to drought factors such as wind and sun [32, 58]. Wall vegetation develops when the conditions for settlement are appropriate such as exposure to weathering long enough and accumulated soil particles [56, 59].

Notably, the degree of deterioration is determined by the plant growth conditions [22]. Damage is not highly dependent on plant size; it was found that in some cases, although there were large plants, little or no damage was observed, while the small stems caused severe damage to the wall, but the larger stems caused more damage than the small stems as observed in the case of the *Ailanthus altissima* (Mill.) Swingle tree [17].

Cracks and cavities that appeared in stones are favorable habitats for plant establishment or regeneration because of dust and humus accumulating and depositing of seeds by wind and birds [24, 29, 35, 44]. Especially smaller seeds that can easily dispersal [60].

Based on previous studies, plant colonization is higher on horizontal surfaces like walls and roofs than on vertical surfaces due to providing better growth conditions [11, 23, 25, 51, 61]. The presence of these plants on the horizontal and inclined surfaces reduces the resistance of the stone against external deterioration factors, and thus, conservation management becomes supremely important [61].

Close distance is not required to cause damage, because even when trees grow four meters from the wall, they can

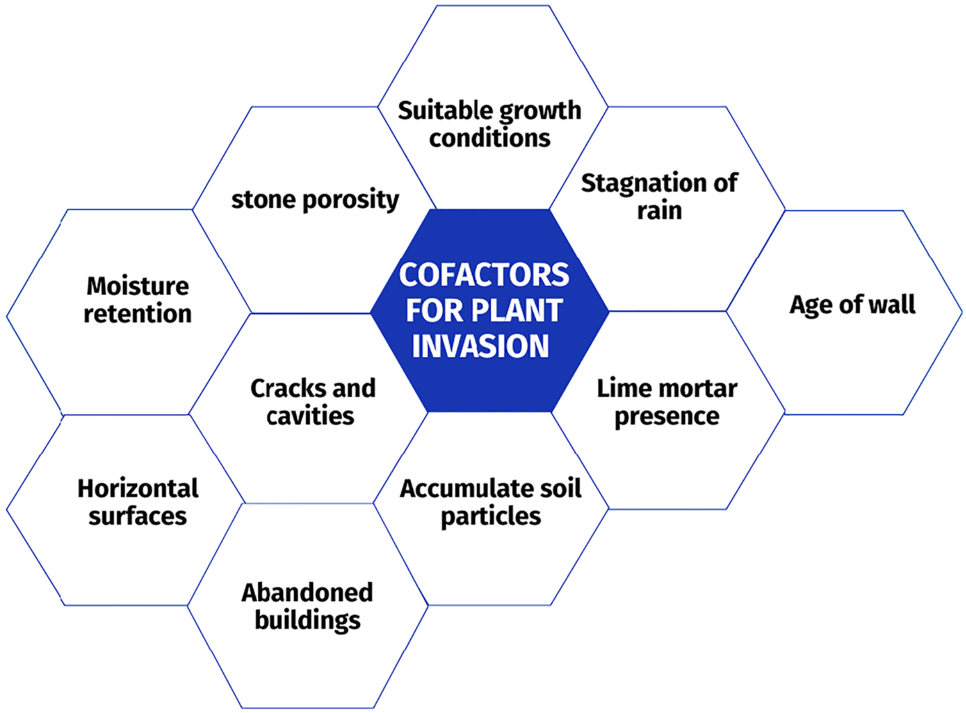

Fig. 3 The most important promoting factors for plant invasion

cause deterioration [17]. It was previously concluded that the plant growth was concentrated in abandoned and unused buildings with a lack of restoration and maintenance practices such as cleaning [10, 18, 20, 23, 62–69]. Besides, the presence of bryophytes and lichens can support vascular plant colonization [10]. It can even be considered one of the preliminary stages leading to the later invasion [70].

4 Types of deterioration

All plant parts (Table 1) like roots or climbing and adhering parts of leaves and stems cause chemical, esthetic damage, and structural alterations to stones as well as a hindrance to displaying the site to the public when dense vegetation affects the visibility of the monument like graveyards and archaeological buildings [32, 71, 72], especially in the case of the significant details on the surfaces like colors and decorations [71].

The presence of plants, whether herbaceous or woody species, can promote the risk of fire, increasing deterioration that may lead to the destruction of the stone monuments [61, 73].

4.1 Mechanical and physical damage

Vascular plants pose physico-mechanical deterioration of buildings and structures by root growth, causing an overload on the surface and when allowed to continue without

Table 1 The parts of plants and their deterioration effect

Plant parts	Deterioration symptoms
Roots	Roots are remarkably responsible for causing damage to stones. The damage can be mechanical by the roots' force, chemically through the chemicals accompanying the secretions of the roots, or biologically as the roots encourage insects and microorganisms [74]
Stems	• Vascular plants with the aerial vegetation apparatus formed by stem cause a serious role in the damage, whether biophysical or biochemical [32] • Trees like mulberries, tree-of-heaven, and catalpa can produce more stems, even after cutting [24, 75] • In the case of poison ivy, the stems of the plant can reach in some places a diameter of 6 to 8 inches resulting in crumbling at the touch of a hand [24, 75]
Leaves and branches	• The ground can be dehydrated by the transpiration of leaves that extract moisture from the ground [76] • The branches and leaves can hide the buildings; furthermore, they cause static damage because of their weight which leads to the fall of stones or large portions of the wall [11]

checking may result in affecting the contacted section with the growth or in some cases can threaten the stability of the entire structure [19, 23, 32, 61]. In agreement with previous studies, fast-growing tree species can reduce the humidity level in the surrounding clay soil, causing sufficient shrinkage that can damage the nearby building's foundations and affect the building's balance [77–81]. Some woody species can damage the underground monuments as happened in the Jewish catacombs of Villa Torlonia in Rome [82]. When the roots die and decay, this becomes a weak point in the wall, which can lead to collapse, creating gaps and cracks inside the material where water can easily penetrate and render the structure vulnerable [83]. Furthermore, when the stone surface is reduced to small fragments, it can be deteriorated by wind, rain, chemical compounds particularly in the case of the outdoor environment, and the detachment of the paint layer that resulted from the fungal growth [4, 84].

When tree roots extend for seeking moisture sources, old lime mortar loosened, and the stone blocks may fall away ultimately. If the tree is not removed, it will become more dangerous because the adventitious roots will eventually attack many weak points in the mortar system and the tree will add a major weight of the weak parts of the wall [43].

Roots of plant species induce significant loss of materials affecting the long-time stability of the structure, deformation, and new cracks, and more fracturing facilitates the growth of new trees and shrubs. Notably, the resulting mechanical damage may be one or a combination of all of them [13, 17, 35, 67, 85]. Plant roots have adverse effects that lead to physical pressure, which was clear in Saint George Church in Diyarbakır [86]. Root growth and its radial thickness are the main reasons for physical deterioration which increases the pressure on the areas surrounding the building [32, 87]. This pressure can reach more than 15 atm [88]. Roots become stronger in time and by their physical force, they can open cracks and joints, which in turn expand to allow more moisture to enter [11, 44, 58]. Whether plant roots or weeds on the mortar surface can accelerate the mechanical weathering of the stone by widening the fissures and causing soil pressure and stone reaches to 1–1.5 MPa [74, 89, 90]. Hence, tumefaction and the growth of these plant colonies on the substrate (rhizomes and bulbs) can promote physical confinement and mechanical ruptures [29].

4.2 Chemical damage

The rhizosphere is the size of soil affected by the existence of the growing plants' roots. The general change can be considered biological, but the physical, chemical, and biological features are affected to different degrees [91]. Root secretions of organic acids react chemically with the substrate resulting in chemical degradation or may cause surface erosion due to the absorption of calcium or other ions present in the substrate in addition to increasing the number of cracks induced by the wedge effect, and eventually will facilitate the deterioration process [32, 61, 92]. Indeed, most of the excretions are carbon and can be categorized into two groups of compounds, low-molecular-weight compounds like organic acids, amino acids, phenolics, sugars, and volatile compounds and high-molecular-weight compounds like proteins and mucilage [93].

In general, compounds secreted by roots are carbohydrates, enzymes, amino acids, flavonols, lignins, coumarins, aurones, glucosinolates, anthocyanins, indole compounds, sterols, volatile organic compounds (VOCs), allomones, proteins, and organic acids [93]. The organic acids considered producers of the most direct effect on stone weathering involve malic, oxalic, citric, salicylic, aspartic, gallic, and succinic [94]. Carbonic acid is produced through the respiration process [19]. The oxalic acid secreted by plants reacts with the structure and performs a destructive role as it is a vigorous and complex acid which has chelating and acidic properties, more active than other organic acids [4, 86]. Table 2 shows some plants and their destructive compounds on the stone monuments.

The roots cause chemical damage by the acidity of their secretions, whose pH values are between 4 and 6 [106]. The pH of the rhizosphere becomes lower, which promotes weathering through cation capture by the roots. Thus, the areas surrounding root systems participate basically in the total soil weathering when these roots are in the vicinity of the weatherable rock material but not if the roots are growing within the organic layer of the soil [107]. Some creepers (especially in maturity) and trees are undesirable in enhancing the appearance of masonry walls because their root systems feed on the wall core and disrupt stones. The *H. helix* should not be left on walls, because of its rapid growth and the searching effect of its aerial roots [43].

One of the previous studies discussed the enhancement of weathering by plants, which rates at least ten times greater than those with only lichens or microorganisms in the studied environments [108, 109]. During the transpiration process of plants, roots can extract water from joints or capillary pores [110]. In addition, the bulk dissolution of plagioclase accounts for most of the weathering observed under higher plants on basalt stones [110]. Further studies prove through the examination of stones in contact with plant roots that some marks are developed, which were produced by the solvent action of root secretions and appeared clearly on limestone and marble [58, 94].

Plant species can alter soil chemistry, structure, stability, and site hydrology [111, 112]. Plant colonies keep the

Table 2 Plants and their destructive compounds on the stone monuments

Plant	Compounds	Deterioration mechanism
Phragmites australis (Cav.) Trin. Ex Steud	Gallic acid (tri-hydroxybenzoic acid) [95]	Can react with calcium carbonate, the main mineral of limestone, and dissolve it [15, 24–27]
Sonchus oleraceus L	Phenols, flavonoids, tannins, saponins, and alkaloids [96]	Has an allelopathic effect on the surrounding plants Can affect the chemical composition of the building substance [96]
Ailanthus altissima (Mill.) Swingle	Ailanthone, 18 alkaloids, 62 terpenoids, 15 steroids, 30 aliphatic components, 7 flavonoids, and several coumarins, organic acids, and lignans [19, 97, 98]	It can cause chemical weathering of stone materials, through the chelating effects of Calcium ions, and the emission of H + ions [36]
Hedera helix L	Unsaturated sterols, oils, tannins, phenolic compounds, terpenoids, glycosides, alkaloids, flavonoids, carbohydrates, reducing sugars, and saponins [45, 99]	Ivy can adhere by secreting a glue-like substance to the surface of several types of stone such as limestone, sandstone, and calcite crystals, the main mineral in marble and limestone [45, 99]
Portulaca oleracea L	Malic, fumaric, oxalic, and glutamic acids [100, 101]	Acids cause erosion phenomena due to their interaction with substrate molecules, the subsequent formation of salts, and many reaction products [100, 101]
Ficus carica L	Phenolic acids include cinnamic, gallic, vanillic, coumaric, syringic, caffeic, and chlorogenic [102, 103]	Considered the most common, the most adaptable to wall habitats, and are insensitive to the type of building material [102, 103]
Ocimum basilicum L	Rosmarinic, cinnamic, caffeic, sinapic, and ferulic acids [104]	It can cause chemical weathering like acid erosion on siliceous rocks [105]

stones in a damp state, which promotes the attack of air pollution gasses and salts on the surfaces [80]. Indeed, plant roots absorb mineral salts from the stone materials supporting their presence [113].

4.3 Biological damage

Although the influence of plants falls under biological damage, it leads to the encouragement of other biological factors indirectly. As such the roots of plants can increase the biological weathering of the rocks [74]. Weed growth acts as a shelter for harmful insects, rodents, and microorganisms [29, 72]. Root area even after decaying attracts microbial activity and insects like ants, termites, and pests and these insects increase further crack volume leading to disturbance to the substrate [11]. Table 3 shows some weeds as alternate hosts of some pests. By accumulating humus from dead mosses or the prolonged plant presence, they can promote the development of other plant species, which further degrades the stone structures [24, 60, 114]. In addition, the roots can cover huge areas after the first growing season and regrow new species of plants and these roots continue growing over the years; thus, it becomes stronger and more difficult to eliminate [11, 29].

5 Managing the biodiversity and biodeterioration

The vegetation cover—both natural and cultivated—of the archeological site contributes to its characterization and provides points of interest for visitors. Moreover, it enriches the value of the archeological site, and in some cases offers insight into human actions. On the other hand, plants' presence on the site should not be underestimated as a threat deterioration factor to the stone monuments [121]. Managing the biodiversity of archaeological sites is an ongoing issue, especially when considering preserving historical structures and biodiversity. As a result, there is an urgent need to take measures to preserve cultural landscapes while considering the conservation of biodiversity within archaeological sites [122]. To manage this component, a collaboration between botanists, agronomists, and archaeologists appears to be necessary, but they must provide directions and tools to facilitate work [123].

6 Methods of control and prevention

As mentioned in previous studies, the management and restoration factors are extremely important to prevent the growth of plants [61, 69]. Control methods aim to eliminate biological growth or may delay neo-colonization and

Table 3 Examples of weeds as an alternative host for pests and pathogens

Weeds as an alternative host	Pests
Bidens pilosa L	Bean insect pests [115]
Parthenium hysterophorus L	*Ferrisia virgata* (Ckll.) (Hemiptera: Pseudococcidae), *Helicoverpa armigera* Hübner (Lepidoptera: Noctuidae), *Clania crameri* Westwood (Psychidae: Lepidoptera), and *Diacrisia obliqua* Walker (Lepidoptera: Arctiiade) [116]
Xanthium strumarium Lour	*Zygogramma bicolorata* Pallister (Coleoptera: Chrysomelidae) [117]
Armoracia rusticana G.Gaertn., B.Mey. & Scherb	Black rot bacterium (*Xanthomonas campestris pv. campestris*) [118]
Hordeum murinum L *Agropyron scabrum* (R.Br.) P.Beauv	Rust fungus *Puccinia graminis* [119]
Bidens pilosa L *Cenchrus echinatus* L *Emilia sonchifolia* (L.) DC *Solanum americanum* Mill *Tridax procumbens* L *Waltheria indica* L *Tridax procumbens* L	*Protortonia navesi* Fonseca (Hemiptera: Monophlebidae) [120]

cleaning artifacts, which involves the removal of vegetation as one of the first steps to be taken in restoration measures [71]. Regular maintenance like mechanical cleaning, laser cleaning, and herbicides can conserve the stone surfaces from biological activity [124].

Vegetation becomes a hazard in the future if proper prevention is not applied to the sites [24]. Plant controlling is costly, complex, and difficult due to its dispersal, vegetation regeneration after mowing, and the ability to grow in high habitats; in addition, consideration must be given to the appropriate conservation of man-made structures, the environment, and the landscape [75, 125]. The methods of control differ depending on the species of plant identified, building structure, state of conservation, and its location [11, 15, 25].

The knowledge of the ecological behavior of wall plants is necessary for better control and management of these species; a case-by-case evaluation is necessary to assess the size and length of the root and then plan the specific intervention [23, 126]. Therefore, the most common plant species at archaeological sites and their reproduction methods are collected in Table 3. Thus, understanding the natural habitat of the wall is important for choosing the best method for controlling colonial species of plants [127].

The colonization of plants is closely related to the ability of the species to adapt and the efficiency of the method of reproduction. Worth mentioning is that vegetative reproduction allows plants to have an alternative method in case of sexual reproduction failure. Thus, plants capable of vegetative reproduction are the most dangerous of all [25]. Likewise, the most destructive plants are those with vegetative reproduction as rhizomes and stolons induce an increase in colonize species in size and propagate over great areas to the obvious detriment of building structure [128]. The damage caused by this type of vegetation is especially destructive to statues.

By understanding the way plants reproduce and spread, it becomes possible to plan a successful weed management strategy [34]. It is recommended that control techniques be applied to sites and monuments with optimal environmental conditions for the invasive species [22]. Total removal of plants with their roots is the best method of control with long-term advantages [11]. It is preferred to use environmentally friendly methods [59].

On the other hand, traditional methods can induce additional deterioration to the monument and the environment [126]. In the case of ivy, it is advised not to remove it because it can lead to the collapse of the structure, and it is preferable to cut the roots and leave them to die on their own [72]. In all cases, burning the vegetation is not an acceptable method particularly in the field of archaeology because it causes severe and irrevocable damage [72, 129]. In many cases, especially when the roots penetrate deeply into the structures of the walls, after the completion of the removal of vegetation, the consolidation must be followed, because some damage may arise after the removal process [83]. Furthermore, from Table 4, it can be said that the plant species that reproduce in more than one way are more dangerous especially if they are woody species, and therefore difficult to deal with.

6.1 Mechanical (manual) methods

Manual methods such as grubbing, weeding, and hand pulling are appropriable ways for herbaceous species but do not guarantee the definitive cessation of the vegetative activity and they can cause damage to the wall structure [24, 59,

Table 4 Short list of some plant species growing on the stone monuments; they were chosen as most of them are common in several archaeological sites * reproduction methods are from http://www.worldfloraonline.org/. As for the families and species, the references taken from them are mentioned in the table below

Families	Species	Reproduction	Damage	References that refer to the plant's presence at the archaeological sites
Simaroubaceae	*Ailanthus altissima* (Mill) Swingle	V/S	+ + +	[17]
Amaranthaceae	*Amaranthus viridis* L	S	+	[5, 11, 29]
	Amaranthus retroflexus L	S	+	
	Amaranthus spinosus L	S	+	
Moraceae	*Ficus carica* L	V/S	+ + +	[29]
Araliaceae	*Hedera helix* L	V/S	+ + +	[22]
Poaceae	*Desmostachya bipinnata* (L.) Stapf	V/S	+ +	[62, 75, 113]
	Dactylis glomerata L	S	+	
	Cynodon dactylon (L.) Pers	V/S	+ +	
	Phragmites australis (Cav.) Trin. Ex Steud	S	+	
	Arundo donax L	V/S	+ +	
	Avena fatua L	S	+	
Capparaceae	*Capparis spinosa* L	V/S	+ + +	[23]
Plantaginaceae	*Cymbalaria muralis* G.Gaertn., B.Mey. & Schreb	S/R	+ +	[62]
Fabaceae	*Alhagi maurorum* Medik	V/S	+ +	[130]
Meliaceae	*Azadirachta indica* A.Juss	V/S	+ + +	[32]
Oleaceae	*Olea europaea* L	V/S	+ + +	[131]
Cyperaceae	*Cyperus rotundus* L	V/S	+ +	[29]
Convolvulaceae	*Convolvulus arvensis* L	V/S	+ +	[130]
Asteraceae	*Sonchus oleraceus* L	S	+	[23]
Cannabaceae	*Celtis australis* L	S	+ +	[10]
Euphorbiaceae	*Euphorbia hirta* L	S	+	[32]
Ulmaceae	*Ulmus minor* Mill	RS	+ +	[69]

V, vegetatively propagated; *S*, seed propagated; *R*, removing rooted sections of the stem; *RS*, root suckers. Damage ranges from + + + (major) to + (minor).

125, 132]. For higher plants, the best time for their mowing or defoliation is the germination season when these plants need a lot of energy to send up new leaves and stems [133]. In addition, food reserves in the roots are usually at their lowest before developing full leaves [32].

The mechanical method is effective when it relies on eradicating plants during the initial stages of growth by cutting them with suitable sharp tools, but it is temporary because there are plants that get stronger and grow again even after cutting, and new suckers can sprout, such as peepal (*Ficus religiosa* L.) and *Ailanthus altissima* (Mill.) Swingle [17, 58]. This method prevents the presence of unwanted chemical residues, which might affect the surfaces of the building; besides taking time and being a cumbersome process, the method has some risks in the form of deterioration to adjacent surface areas if growths are unwisely pulled [32].

6.2 Chemical methods

Chemicals are used in the form of liquids, emulsion formulations, and dispersible powders. Biocides can be applied depending on the situation as an aerosol, poultice, by brushing, injection, or immersion [71].

Using herbicides is harmful to the health and integrity of the restorer and may lead to serious ecological problems in addition to the potential deterioration of long-term; as well, applications for the use of herbicides must meet current requirements and must be specific to the intent of the project [24, 75]. Archaeological stones need more appreciation, especially when using herbicides that can interact with the stones or induce deterioration, and then turn from a method of treatment to a source of damage but neutralization of herbicides can decrease the deterioration degree [134]. Furthermore, examining various physical and chemical changes in masonry proved to be the cumulative application of herbicides that can result in mechanical deterioration as well as staining of stones and mortar [129].

Notably, some plant species evolved their resistance to herbicides and the reason for this is the excessive reliance on herbicides to control weeds [135]. Relying on herbicides alone for weed management is unsustainable and will fail in the long term even when we use several herbicides with different mechanisms of action; resistant biotypes will be selected by either improving metabolism or stacking multiple resistance traits [136]. Selective herbicides in limited quantities can be suitable to avoid mechanical deterioration of the structure, and while using herbicides, it is necessary to prevent their spread to architectural parts and the environment [125, 126].

Glyphosate is one of the most widely used herbicides at archeological sites [4, 64, 125, 129]. Despite the use of glyphosate, it has been proven that it has disadvantages in some cases such as acidic degradation, the formation of salts, the discoloration of the stone surfaces, and it can expand the materials resulting in widening fissures [129, 137].

Many control methods can be used depending on the type of growth and characteristics, but often a combined program (mechanical and chemical methods) is required to solve the problem and gives the best results [28, 32]. Repeated mowing accompanied by localized herbicide is a good control method [23].

6.3 Biological methods

Likely, the use of bioherbicides is an effective method to control weeds through fungi, bacteria, and natural material extracts because they are of low cost, permanent, and eco-friendly, but it needs more research and experimentation, especially in archeological sites [134, 138]. *Cochliobolus lunatus* is a fungal pathogen of plants and can kill barnyard grass seedlings [34]. The fungus *Alternaria destruens* L. Simmons, strain 059, can eliminate various plant species, crops, and ornamental plants which are commonly in archeological sites [139]. Plants are used as the most promising biocides and a better alternative to chemical biocides, due to their low toxicity and ease of handling [140, 141].

Ailanthus altissima (Mill.) Swingle is one of the most dangerous invasive species at archeological sites and can grow rapidly causing great damage thanks to its root system [17, 71, 142]. Surprisingly, *A. altissima* leaf extract can be used as a bioherbicide to hinder the growth of *Medicago sativa* L. and prevent it from seed germination and thus transform from a source of damage to a treatment method, and this promising method needs further study and experiment at archaeology sites [143]. There is an urgent need to use natural herbicides because they are safe for the environment and have proven great effectiveness, especially acetic acid, citric acid, clove oil, and corn gluten meal [144].

6.4 Prevention

Ignoring plant problem, planting trees paying no attention to distances between walls and plants, and neglecting the tree pruning practice lead to interventions that are not only useless and expensive but also dangerous, and it is preferred to repeat mechanical mowing and gardening rather than the frequent use of herbicides [71, 82]. Prevention, caution, and regular monitoring are the most effective methods for dominating plant communities around archeological sites and structures [58, 134]. By prevention, we can avoid both weed propagation and the introduction of new species [145].

More research and interventions must be available through follow-up to prevent future invasion by plants, considering the development of new management strategies through the integration of multidisciplinary approaches whose goal above all is to restore the monuments themselves [33]. After removing vegetation from the site, it is necessary to start planning for periodic conservation, so the controlling process is not lost in vain [72]. Table 5 shows some practical

Table 5 Some practical examples of plant control methods

Control method	Mechanism	Archaeological site	Plant species	References
Mechanical (manual)	Systematic mechanical grubbing to all plant parts over several periods	Chellah site in Morocco	Herbaceous species, shrubs, and deep-rooted plants were not removed because they may damage the structure	[35]
Chemical (Herbicides)	Selective herbicide "Round Up" application showed that treatments were highly (100%) effective as stump causes death and prevents further damage while avoiding dispersion to architectural parts of the monument or the environment	Seven sites selected throughout Greece	Perennial woody species (*Capparis spinosa* L. and *Ailanthus altissima* (Mill.) Swingle	[126]
Integrated program using mechanical and chemical methods	Applying dense suspension of glyphosate locally on shrubs after severe pruning had 100% success	Eleusis site in Greece	Woody species shrubs and small trees (*Olea europaea* L. and *Nerium oleander* L.)	[64]
Biological (bioherbicides)	To our knowledge, bioherbicides have not been applied in eliminating plants at archaeological sites, papers just suggest using them			

Table 6 Advantages and disadvantages of the control methods*

Control method	Advantages	Disadvantages
Mechanical (manual)	Effective Safe Reduce the use of chemical methods (Herbicides) Easily managed [136]	Requires time Excessive cost Can promote the growth of new, stronger plants Need suitable soil and climate conditions to be effective Skilled workers are required Temporarily should be repeated Can damage wall structure [136]
Chemical (herbicides)	It is fast and low cost Effective on perennial weeds Effective in the short term [136]	Toxic Leading to ecological problems Need trained operators for handling Can interact with stone monuments Some plant species are resistant to herbicides Staining of stones and mortar [136]
Biological (bioherbicides)	Self-perpetuating Low cost Permanent Eco friendly Ease of handling [136]	Should feed strictly on the target weed Must be controlled early before reproduction It is a slow process Needs more research and experimentation [136]
Prevention	The most basic and effective of all methods of control [34, 134]	Does not have any drawbacks [136]

examples of plant control methods. Table 6 summarizes the advantages and disadvantages of methods used for the control and prevention of growing plants in archeological sites.

In addition, it was reported that there is no perfect weed management system that works all the time, and in all situations, diversity is key. This is what we should strive for [136].

7 Conclusion

The biodeterioration of stone monuments by plants should not be underestimated. From the aforementioned, it is evident that the plants did not leave any kind of damage without causing it. It is difficult to apply a single control method for all plants because it varies according to the type of soil and environmental conditions in addition to the state of the site and the type of stone, but the best solution is to rectify the plant's problem and prevent the future threat by following up the preventive maintenance of sites regularly, such as filling cracks and joints with lime mortar and eliminating the plants at the beginning of their growth, as well as preventing the accumulation of dust, organic materials, microorganisms, and humus materials on stone surfaces, and reducing moisture and prolonged stagnation of rainwater. As it is too late, it is better to intervene by mechanical methods and use environmentally friendly methods while avoiding the use of chemical herbicides or applied minimally because of their ability to cause deterioration for stones and their toxicity to humans and the environment. Finally, it is advisable to look for new and promising methods that will reduce the shortcomings of various control methods, eliminate harmful plants with non-toxic methods, be inexpensive, and fast, and preserve stone monuments should have priority.

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