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Tracing human–fire relations in early sedentary communities: Fire installations and micromorphological insights from combustion-related deposits at Pre-pottery Neolithic B Tell Halula (Syria)☆

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ABSTRACT

Fire installations are key in archaeology for understanding the organisation of social spaces in past societies, as they provide valuable insights into domestic activities, production and consumption practices, and the creation of spaces of belonging. During the transition from mobile hunting-gathering to sedentary agricultural strategies, concepts of space changed, with buildings shifting to rectilinear, multi-roomed structures. In this context, combustion structures were less frequently placed in communal and external areas and were instead incorporated within individual architectural units. This shift suggests that fire-related activities became more segregated within distinct social units, which, along with other socioeconomic transformations, emphasised the household as a central unit of production and consumption. This study explores the technology of fire installations and interrelations between fire use, waste management and cultural practices at the Pre-Pottery Neolithic site of Tell Halula (Syria). The analysis integrates excavation data reporting on distinct morphotypes of combustion structures with a high-resolution micromorphological study of midden deposits. By combining these datasets, the research explores how the emergence of more permanent and densely populated settlements affected the design, management, and spatial organisation of fire installations; how choices of fuel and combustion technology were shaped by evolving economic strategies; and how the use of fire contributed to the definition of household and community within early sedentary lifeways. Together, these lines of evidence provide new insights into human–fire relations in the earliest farming societies.

1. Introduction

Fire installations are key archaeological features for investigating domestic organisation, use of space, and social interaction in past communities, given their close association with everyday activities such as production, consumption, heating, lighting, and food preparation. As focal points within inhabited spaces, combustion structures provide insights into the organisation of domestic life, the social use of space, and broader economic, technological, and symbolic dimensions of human behaviour across different cultural and historical contexts (Brown et al., 2009; Shahack-Gross, 2018; Conati Barbaro et al., 2021; Clark et al., 2022; Fuchs-Khakhar, 2022; Sisa-López de Pablo et al., 2022; Belarte et al., 2023; Kalogiropoulou et al., 2025).

The transition from mobile hunter-gatherer lifeways to increasingly sedentary farming communities was accompanied by profound transformations in settlement layout, architecture, and household organisation. As settlements became more permanent and architecturally complex, domestic buildings shifted from predominantly circular or oval forms towards rectilinear and multi-roomed layouts (Byrd, 2002; Düring, 2006; Stordeur, 2015; Duru et al., 2021; Watkins, 2024), reshaping the organisation of production, consumption, storage, and food preparation practices within households. Within this broader process, combustion structures, together with other food-processing features, became progressively integrated into domestic architecture and associated with individual dwellings rather than communal or open-air contexts, reflecting the growing importance of households as primary units of production, consumption, and social reproduction (Byrd, 1994, 2002; Bogaard et al., 2009; Kuijt et al., 2011; Wright, 2014).

Previous research on Early Neolithic fire installations has primarily focused on the morphology, construction, and spatial distribution of

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combustion structures, highlighting key technological developments, including the introduction of new construction materials (i.e., lime plaster) and designs (i.e., ovens), and the increasing intra-site standardisation of fire installations within domestic architecture across Southwest Asia (Molist, 1986, 1989, 1998b; Wright, 2000; Albukaai, 2014; Uzdurum, 2018; Fuchs-Khakhar, 2021). These changes coincided with intensified sedentism, cereal cultivation, and greater household autonomy in production and consumption, when fire-related practices became increasingly embedded in domestic and economic activities. However, the relationships among fire installations, fuel selection, combustion performance, and waste management remain insufficiently understood, as fuel types and combustion conditions are usually not determinable from macroscopic evidence alone.

Over the last decade, microarchaeological analyses of combustion-related deposits have substantially expanded our understanding of fuel selection, use of space, and human–environment interactions in Early Neolithic settlements (Matthews, 2010, 2016; Shillito and Matthews, 2013; Portillo et al., 2014; Allcock et al., 2023). Nevertheless, such studies remain comparatively limited in number of case studies, especially considering the increasing complexity and diversity of the social and economic transformations associated with early sedentary lifeways (Gebel, 2004; Ibáñez et al., 2018; Fuller and Lucas, 2025). Moreover, relatively few studies have integrated high-resolution micro-archaeological data with macroscopic excavation evidence in order to examine combustion technologies, fuel practices, and household organisation within a unified analytical framework (Shahack-Gross, 2018).

Against this background, this article examines human–fire relationships at Tell Halula during the Pre-Pottery Neolithic B. It explores how permanent, densely populated settlements changed the design, management, and layout of combustion structures. By combining excavation data on construction techniques, morphology, dimensions, and spatial distribution with high-resolution micromorphological analysis of accumulated combustion by-product deposits, the article investigates how early sedentary lifeways influenced combustion technologies, fuel use, and waste-management practices.

Within this analytical framework, particular attention is given to the location of fire installations in domestic buildings and adjacent open areas to assess their integration into household organisation and daily practices. The analysis also examines how fuel selection and fire management strategies were influenced by local environmental conditions and by social or economic changes associated with Neolithic lifestyles. Through this integrated approach, the study explores the relationships between combustion technologies, fuel use, domestic organisation, and waste management, offering insights into the social, economic, technological, and symbolic transformations associated with early sedentary communities in Southwest Asia.

2. Case-study: Tell Halula

Tell Halula is located in the Middle Valley of the Euphrates River, approximately 150 km east of the modern city of Aleppo, on the right bank of the river (Fig. 1). The site forms a roughly circular artificial mound covering about 8 ha, with a maximum height of approximately 11 m. Its geographical position in the Mesopotamian lowland steppe at the junction of several ecological zones, including the riverine environment of the Euphrates, nearby hills, and the open steppe characterised by xeric grasslands and shrublands, provided the settlement with access to a wide range of natural resources, constituting a key factor for understanding subsistence strategies, availability of building materials, and potential fuel sources.

Tell Halula was identified during archaeological surveys in 1989 and subsequently excavated between 1991 and 2011 as part of a long-term interdisciplinary research project led by the SAPPO research group at the Universitat Autònoma de Barcelona. Excavations allowed the identification of thirty-eight occupation phases, documenting a practically continuous sequence from c. 7800 to 5700 cal BC. These phases span the Middle and Late Pre-Pottery Neolithic B (hereafter MPPNB and LPPNB), the Pottery Neolithic (Pre-Halaf), and the Neolithic–Chalcolithic transition (Halaf culture). For the purposes of this study, particular attention is paid to the earliest occupations, that is, the MPPNB and LPPNB, during

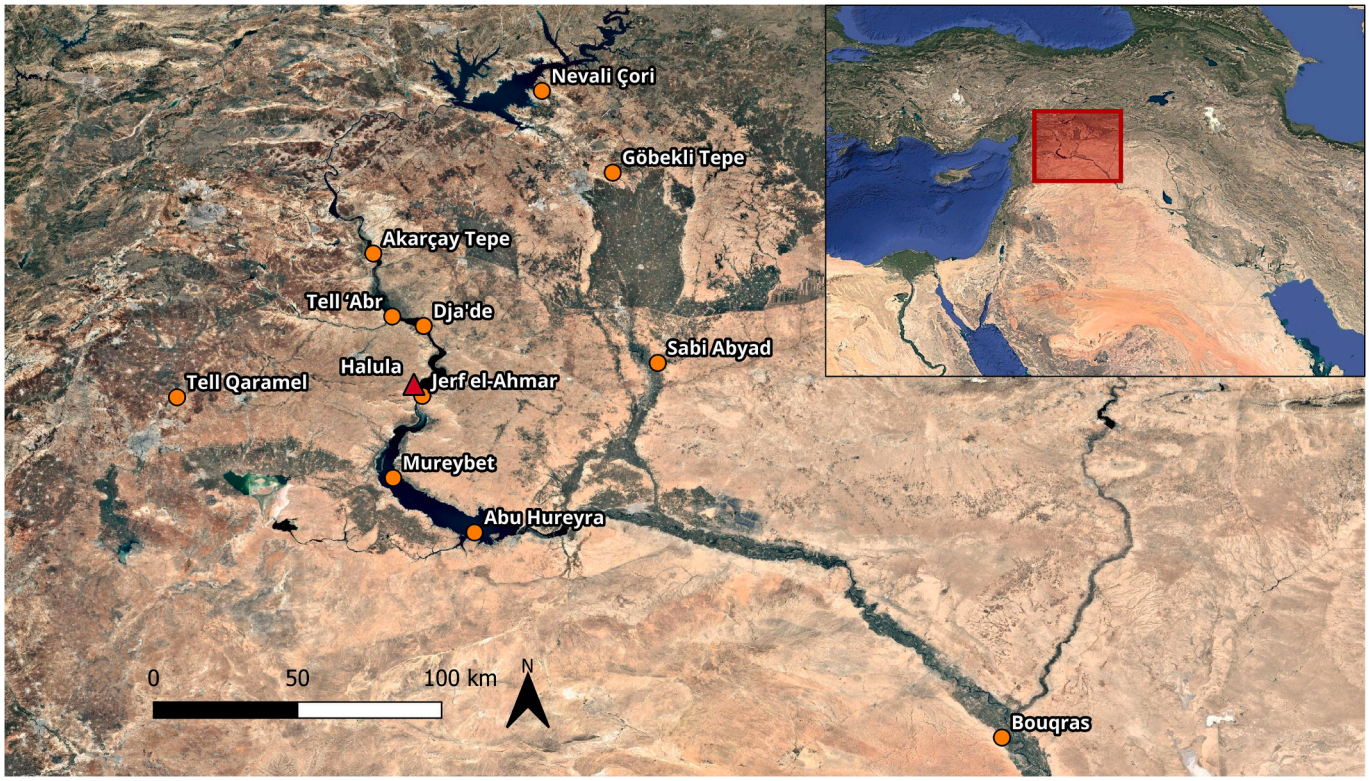


Fig. 1. Location of Tell Halula and neighbouring Early Neolithic sites in the region.

the 8th millennium cal BC, when Tell Halula functioned as a large sedentary settlement (Molist, 1996, Molist, 2013; Molist et al., 2020).

The settlement pattern at Tell Halula is characterised by a high degree of regularity and organisational consistency. Excavations in Trenches 2 and 4 have revealed a dense, agglutinated village layout, with domestic units arranged in parallel alignments following a dominant east–west axis. Within these alignments, individual houses are predominantly oriented north–south, with entrances consistently located on the southern façade. Narrow circulation corridors, ranging from approximately 0,4 to 1,8 m in width, separate the houses, while larger open areas are located in front of the entrances (Fig. 2).

Domestic architecture is notably standardised across the PPNB sequence. Houses are rectangular and pluricellular, typically consisting of three sections: the porch, the central room, and two small back rooms, arranged according to a consistent plan (Fig. 2 and Fig. 3a). Construction mainly relies on earth, used as moulded mudbricks. Stone is used sparingly, mainly as foundations or reinforcements for walls, especially when new buildings are erected directly on top of earlier structures, while wood is only indirectly evidenced through post-holes and impressions preserved in construction materials, indicating its use in roofing systems.

The central room constitutes the core of the domestic unit. It displays a high-quality finish, with carefully plastered floors and walls coated with lime, and it systematically includes two distinct fire installations (Fig. 3a). Drainage systems for wastewater evacuation have been documented in several houses, consisting of sloped floors and channels that direct fluids towards the exterior. In contrast, the smaller adjoining rooms and the porch exhibit greater variability in size, shape and construction quality and are interpreted as multifunctional spaces for storage, craft activities, or food processing, as attested by the presence of silos, grill-plan structures, and occasional hearths. These features were commonly constructed using cob bricks and shaped-earth techniques (Sisa-López de Pablo, 2023).

Another characteristic feature of the domestic buildings at Tell Halula is the presence of burials. Funerary deposits are systematically located beneath house floors, mainly in the entrance area of the central room, where floors are typically constructed of earth rather than lime plaster. These burials consist of individual inhumations placed in pits dug directly into the floor surface, comprising infants, subadults, and adults of both sexes where sex determination was possible (Guerrero, 2006; Anfruns et al., 2013). The pits are generally small, circular in plan and characterised by straight walls and a flat or slightly concave base. The deceased were usually deposited in a flexed or seated position, with limbs folded against the body, and subsequently sealed by a visible cover, often leaving a void between the body and the pit walls (Anfruns and Molist, 1996; Guerrero et al., 2009; Kuijt et al., 2011). The high degree of morphological homogeneity observed in these funerary structures suggests a shared set of practices, with no significant variation by age group or sex.

In addition to funerary practices, some domestic buildings exhibit evidence of symbolic activities through paintings. These appear on both lime-plastered floors and the plastered surfaces of the walls of the central room. The motifs include geometric and figurative representations, as well as simple spots without clearly recognisable forms (Molist, 1998a; Molist and Vicente, 2013). These are predominantly executed in red pigment derived from hematite, with occasional use of black (Navarro, 1998). In some cases, high-resolution physicochemical analyses indicate that a white lime wash was applied prior to the execution of the red paint (Pérez and Sanz Rodríguez, 2008). The recurrent presence of pictorial decoration in the central room highlights the symbolic

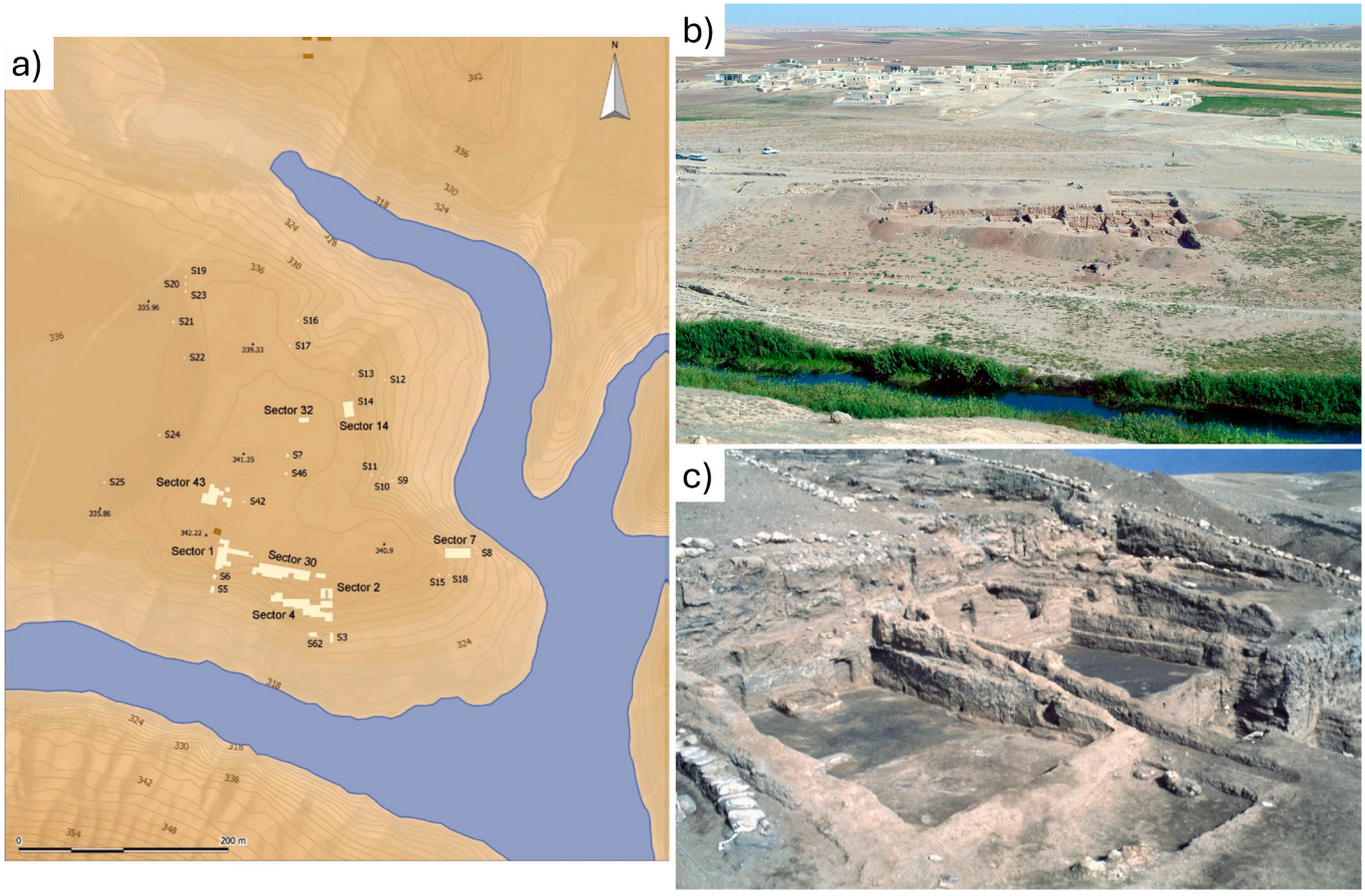


Fig. 2. Site plan and views of Tell Halula: a) Plan of the site showing the location of the excavated trenches; b) General view of the site from the south, showing Trenches 2 and 4 in the foreground; c) Detail of PPNB domestic buildings.

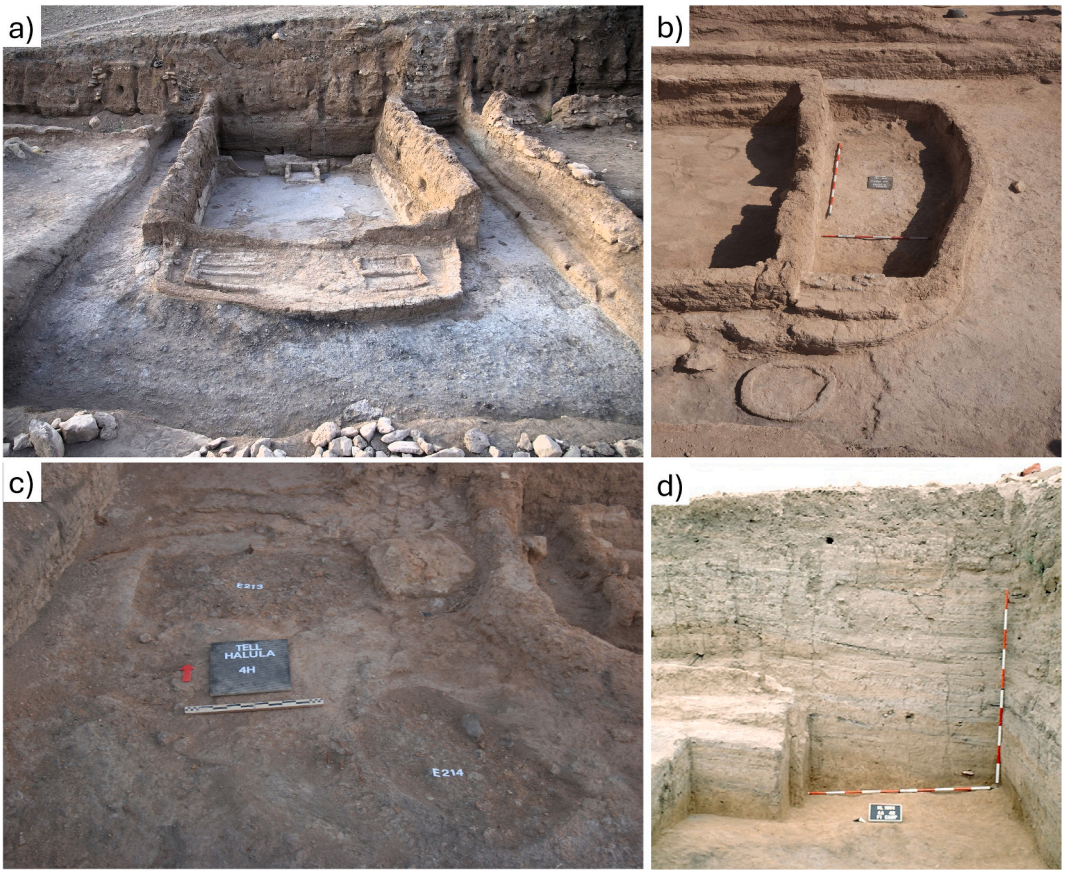


Fig. 3. Example of a domestic building and adjacent exterior areas at Tell Halula. a) PPNB domestic building showing lime-plastered floors and walls. Note the presence of ashy deposits in front of the house and the laminated stratigraphy visible in the profile of the corridors between buildings; b) Domestic cob feature in an exterior area adjacent to a building; c) Fire pits in an exterior area adjacent to a building; d) Midden-like deposits in exterior areas between buildings.

significance of this space within the household.

The vertical superposition of houses, involving the systematic reuse of earlier walls and foundations, reflects both economic considerations related to the recycling of building materials and a strong continuity in spatial organisation over time. As noted above, domestic units consistently exhibited the same spatial pattern, likely due to their advantages in terms of climatic, environmental, and social factors. Despite numerous repairs, refurbishments and minor modifications, the overall settlement layout and domestic architecture remained highly consistent throughout the PPNB sequence, underscoring the long-term stability in social organisation and household practices at Tell Halula.

A marked contrast is observed between interior and exterior spaces. The main rooms of the houses were deliberately kept clean, as evidenced by repeated floor resurfacing and the scarcity of refuse, also attested through high-resolution micromorphological analyses (Sisa-López de Pablo et al., 2024, 2025a). Domestic waste, combustion residues and abundant artefacts are instead concentrated in the exterior open areas located in front of the houses and corridors, where numerous hearths and other activity-related structures adjacent to domestic buildings have been identified (Fig. 3a–c). These areas represent key contexts for understanding daily practices, including fuel use and waste management.

3. Materials and methods

A total of 71 combustion structures have been considered in this study, selected on the basis of their state of preservation and the availability of sufficient archaeological evidence for their characterisation. The first stage of the analytical methodology consists of a morphological and typological analysis of the fire installations documented at Tell Halula. This approach is based on the systematic integration of excavation and report data, including detailed stratigraphic information and contextual documentation, as well as previous analyses of fire installations (Molist, 1998b; Albukaai, 2014). For each combustion structure, data were collated regarding construction materials and techniques, dimensions, morphology, and spatial location within domestic buildings and adjacent open areas. Based on this combined dataset, the fire installations were identified, classified, and characterised into distinct morphotypes. Particular attention was paid to their stratigraphic position, use-life, and evidence of repair or abandonment, allowing a multi-scalar assessment of both short-term household practices and longer-term changes in fire installations throughout the PPNB sequence.

The morphotypological analysis is complemented by a high-resolution micromorphological study of midden deposits from exterior areas, where residues generated by daily activities were primarily accumulated and where waste produced within interior domestic spaces was routinely discarded (see Fig. 3d). In this study, micromorphology is employed to investigate occupation deposits dominated by combustion by-products, characterised by the abundance of heat-altered remnants of fuel sources and other burnt materials. Observation of these deposits at the microscopic scale allows for the high-resolution distinction of individual depositional events and the detailed characterisation of bio-archaeological, mineral and micro-artefactual components, as well as their spatial and temporal associations within depositional units (Matthews, 2005). This approach provides refined insights into fuel procurement, fire use and discard practices, and complements more routine archaeobotanical studies through the identification of diverse plant remains, including parts typically missed by flotation (e.g., stems, leaves, roots) (Matthews, 2010, 2020).

A total of thirteen large-format thin sections (14 × 7 cm), prepared

from twelve undisturbed sediment blocks, were included in the present study (supplementary material, S1). These samples derive from midden sections comprising deposits associated with combustion waste and were selected following a comprehensive review of archive micromorphological thin sections from Tell Halula (Sisa-López de Pablo, 2023). The selected samples were collected during the 1992, 1993, and 1996 field seasons and originate primarily from Trench 4, with a single sample from the adjacent Trench 2, all of which are assigned to the PPNB. Together, they comprise thirteen different archaeological deposits documented during excavation. Details on samples and contexts are provided in Table 1.

Samples for micromorphological analysis were collected by cutting intact sediment blocks from exposed midden profiles and carefully wrapping them in tissue paper and tape to prevent disturbance. Thin sections from samples collected in 1996 were manufactured at the UMR 5199-PACEA laboratory, Université de Bordeaux (Bordeaux, France), while those made from samples collected in 1992 and 1993 were produced at the soil laboratory of AgroParis-Tech (Grignon, France), following in both cases the method described by Guilloré (1980).

Micromorphological thin sections were analysed using a petrographic microscope under plane-polarised light (PPL), crossed polarised light (XPL), and oblique incident light (OIL) at the GRAMPO-SAPPO laboratory in the Department of Prehistory, Universitat Autònoma de Barcelona. Description and interpretation followed standard guidelines (Bullock et al., 1985; Courty et al., 1989; Stoops, 2021), complemented by specialised reference atlases for the identification of micromorphological features when required (Nicosia and Stoops, 2017; Stoops et al., 2018; Verrecchia and Trombino, 2021).

Microstratigraphic units (MSUs) identified in thin section were classified into distinct deposit types based on diagnostic attributes including groundmass characteristics, microstructure and porosity, organic and inorganic constituents, and pedofeatures. Interpretation procedures involved the qualitative and semi-quantitative description of MSUs across the sample assemblage, providing a comparative framework for assessing depositional processes and combustion-related activities.

Table 1
Summary of micromorphological samples, stratigraphic units and field descriptions.

Sample	SU	Trench	Field description
HA92-11	A6b	2D	Thick grey ash accumulation with a charcoal-rich band overlying a brown layer with charcoal inclusions
HA92-15	B1c	4C	Thick brown homogeneous deposit with thin black lenses rich in charred plant material
HA92-17	A6a/A6e	4B	Unit A6a: Deposit comprising finely laminated units rich in charcoal inclusions; Unit A6e: layered brown-greenish deposit with black burnt lenses
HA93-56	A4a	4C	Layered deposit including black charcoal-rich horizons
HA96-7	A2f	4D	Finely laminated grey ashy deposit with charcoal-rich bands; upper part disturbed
HA96-12	C1/C5	4B	Unit C1: homogeneous brown deposit with dark burnt-rich band; sharp boundary with underlying C5 marked by a horizon with burnt materials
HA96-13	C1/C5	4B	Unit C5: layered brown deposit with black burnt lenses
HA96-14	D2/D6c	4B	Unit D2: brown deposit with frequent burnt and domestic inclusions; underlying D6c is defined by a dark organic-rich horizon with ash and charred remains
HA96-17	D13a/D14a	4B	Unit D13a: dark brown deposit with abundant charcoal, burnt inclusions and grey ash
HA96-19	D14a	4B	Compacted accumulation of burnt domestic debris
HA96-22	B4	4B	Thick, homogeneous brown deposit with very thin white ash bands
HA96-23	B4	4B	Thick, homogeneous brown deposit with very thin white ash bands

4. Results

The terminology used to describe combustion structures presents several challenges due to the wide variety of terms employed across archaeological literature. In some cases, identical terms have been applied indiscriminately to different types of fire installations, or even to non-constructed features (e.g., fireplace), as noted by several authors (see Mentzer, 2012; Fuchs-Khakhar, 2021; Vandevelde et al., 2024). In other instances, site-specific terminology has been developed based on local characteristics, which can hinder comparative analyses across settlements.

In the present study, a classification framework is adopted that employs general terms applicable to fire installations across different archaeological contexts, while more specific terminology is used where distinctive morphological or functional traits are observed. Based on the morphotypological analysis, three main categories of fire installations have been identified at Tell Halula: 21 ovens, 14 hearths, and 36 fire pits (n = 71). Details on the main characteristics of each type of fire installation are provided in Table 2.

4.1. Macroscopic analysis of fire-installations

4.1.1. Ovens

Ovens are defined here as fire installations characterised by a built superstructure, often domed and potentially equipped with a ventilation flue, or alternatively featuring one or more open faces. At Tell Halula, ovens display a highly standardised morphology. They are rectangular structures with a single frontal opening and a flat superstructure, as indicated by the recovery of fragments from collapsed covers within oven fills.

Within domestic buildings, ovens are systematically located in the main room, specifically in its central area and abutting the rear wall (see Fig. 2b and Fig. 3a). This position likely enhanced heat retention and placed the oven opposite the entrance, aligned along the main axis of the building. As a result, ovens occupied a visually and functionally dominant position within the room. This spatial configuration remains remarkably consistent throughout the PPNB sequence.

Table 2
Comparative summary of fire installation types identified at Tell Halula (PPNB).

Attribute	Ovens	Hearths	Fire pits
Plan morphology	Rectangular	Quadrangular with rounded edges	Oval, elongated or circular
Dimensions (approx.)	90–120 × 70–100 cm	45–65 × 41–50 cm	20 × 10 to 140 × 100 cm
Depth / elevation	Slightly raised above floor level	At floor level; central depression 5–15 cm deep	Depth 5–30 cm (occasionally up to ~ 50 cm)
Construction materials	Earth with vegetal fibres; occasionally recycled mudbricks, limestone pebbles and lime plaster	Earth-built rim; lime plastered surface	Excavated sediment; occasional earthen lining and stone pebbles
Combustion surface	Pebble base coated with earth and lime plaster	Plastered surface within shallow depression	Natural sediment or stone-lined base
Location	Main room, central position abutting rear wall	Main room, usually on western side	Exterior open areas; occasionally in porches and back rooms
Spatial relation to architecture	Aligned with main axis of house; opposite entrance	Adjacent to western roof-support post	Variable; dependent on space
Inferred combustion intensity	High and sustained	Low-intensity combustion (embers or small controlled fires)	Variable

In terms of size and construction, these structures measure 90–120 cm in length and 70–100 cm in width and are generally slightly raised above floor level (Fig. 4). The lateral walls and superstructure were built using earth mixed with vegetal fibres, while in some cases, the vertical walls were constructed from horizontally laid mudbricks. Construction involved several stages. A basal platform was first prepared to isolate the combustion area from the floor and to provide structural stability. This base was coated with well-processed earth and bordered by small limestone pebbles set vertically around its perimeter (Fig. 4a). The oven walls were then erected, leaving an open frontal access. The combustion surface was subsequently prepared by laying limestone pebbles flat across the base (Fig. 4b). An earthen coating was applied to the rear of the structure to seal the interface with the supporting wall, ensuring insulation on all sides except the opening. Finally, the interior of the oven, including walls and combustion surface, was finished with a lime plaster coating.

Clear evidence of intense thermal alteration, together with repeated episodes of maintenance, usually up to three, indicates sustained and regular use. Repairs typically involve resurfacing the combustion area with a new fill layer, followed by the placement of limestone pebbles and a renewed lime plaster coating (Fig. 4a). In some instances, repairs also entailed the construction of new internal walls built against the inner face of the previous phase, resulting in a gradual reduction in oven dimensions. These reconstruction events were often, though not systematically, associated with the resurfacing of the main room floor.

4.1.2. Hearths

Hearths are defined as deliberately constructed fire installations that lack a built superstructure or cover, in contrast to ovens. At Tell Halula, hearths exhibit a set of recurring morphological, spatial and constructive characteristics.

They are exclusively located within the main room of domestic buildings and consistently positioned in the medial area of the room, towards its western side, at an average distance of approximately 0,5 m from the western wall (Fig. 5a). In all documented cases, hearths are directly associated with a post hole corresponding to one of the wooden posts supporting the roof.

Morphologically, hearths are quadrangular features with rounded edges and a narrow opening on one side. Their dimensions range from 45 to 65 cm in length and from 41 to 50 cm in width. A shallow depression, between 5 and 15 cm below floor level, occupies the centre of the structure (Fig. 5b–c). Unlike ovens, hearth orientation varies slightly between buildings (N–S or E–W) (Fig. 5b-c). The combustion area is defined by a low raised rim, not exceeding 10 cm in height, interrupted only at the opening, which measures approximately 10 cm. This access likely facilitated fuel loading, particularly when a container was placed above the hearth.

Construction involved excavating a shallow depression in the floor, around which a low cob layer was applied directly to the floor surface. This rim was subsequently coated with lime plaster identical to that used on the surrounding floor, indicating that hearths were conceived as an integral component of the room surface rather than as independent installations.

The consistent placement of hearths adjacent to the western roof-support post suggests a functional rationale despite the apparent fire risk. This location may have protected the flames from draughts or facilitated smoke evacuation through a roof opening near the upper part of the post. In a limited number of cases, fragments of arched lime plaster suggest that the wooden post may have been partially coated to reduce the risk of ignition, an interpretation supported by the occasional preservation of circular lime-plaster linings within post-hole negatives. Additionally, the abundance of ash, combined with the scarcity of charcoal, suggests that hearths hosted low-intensity fires or embers rather than high-temperature combustion (Courty, 1984; Wattez, 1992; Mentzer, 2012), consistent with a brazier-like function. Compared to ovens, hearths show fewer episodes of repair, generally associated with floor resurfacing events. Their proximity to funerary areas and to spaces with floor paintings (Molist, 1998a; Molist and Vicente, 2013) further suggests a role extending beyond purely functional activities, potentially linked to social reproduction and symbolic practices.

4.1.3. Fire pits

Fire pits are defined as combustion structures elaborated through the excavation of a portion of the ground surface, within which combustion takes place, without the construction of any above-ground superstructure. At Tell Halula, fire pits display the greatest morphological variability among the identified fire installations (Fig. 6a-b).

They exhibit oval, elongated and circular plans, listed here in decreasing order of frequency, and present a wide range of cut profiles, including concave, convergent and straight walls with generally flat

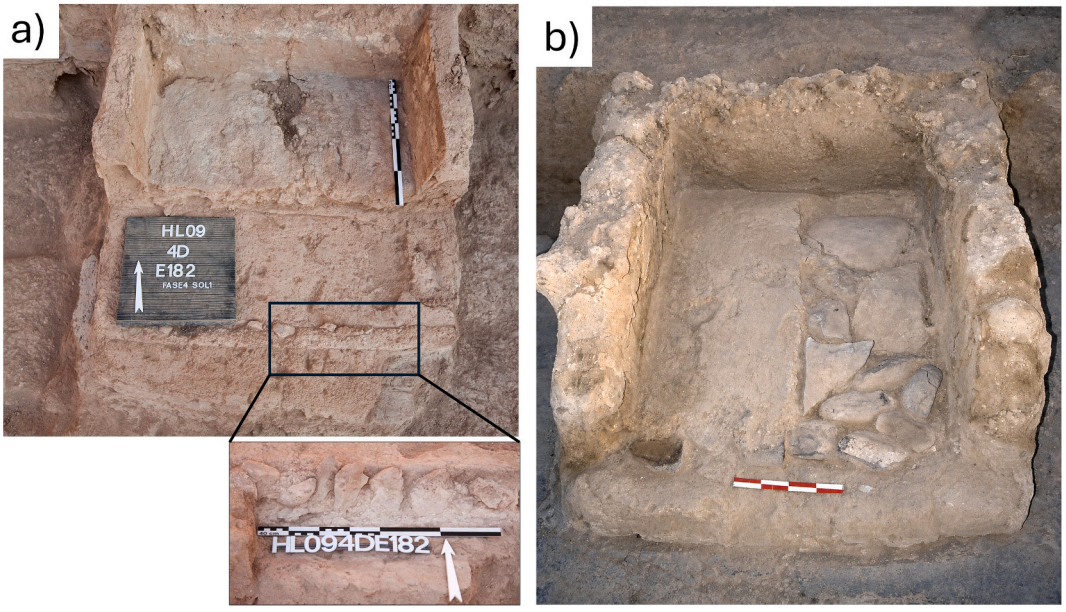


Fig. 4. Ovens at Tell Halula: a) Sectioned Oven E182 showing different construction episodes; b) Oven E25 showing the combustion surface composed of flat-laid pebbles finished with plaster.



Fig. 5. Hearths at Tell Halula: a) View of a domestic building showing the typical location of a hearth; b) Hearth E67, oriented E–W, adjacent to posthole E68; c) Hearth E20, an example of a N–S-oriented hearth.

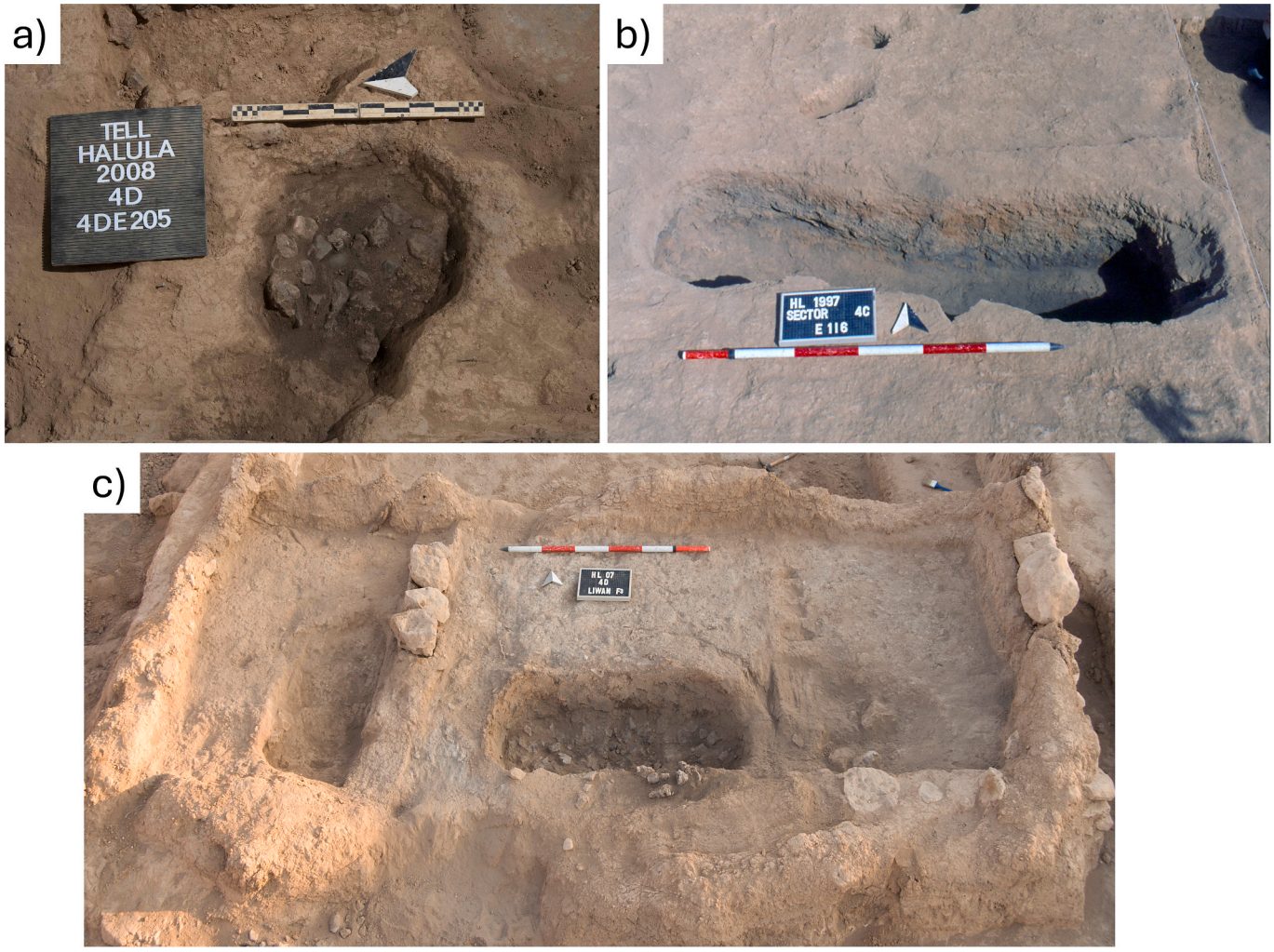


Fig. 6. Fire pits at Tell Halula: a) Circular shallow fire pit E205; b) Elongated deep fire pit E116; c) Oval fire pit with earth-lined walls located in the porch area of a domestic building.

bases. Their dimensions and depths are highly variable, ranging from small features measuring approximately 20 × 10 cm to large pits reaching up to 140 × 100 cm. Depths typically range between 5 and 30 cm, although exceptional examples approach 50 cm. In some cases, a thin earthen lining is preserved on the inner walls, with no clear correlation to size or morphology (Fig. 6c).

Despite overall heterogeneity, a common characteristic of most fire pits is the presence of stone pebbles in the fill, particularly concentrated at the base. These stones vary in size and consistently exhibit thermal alteration, suggesting intentional use in the combustion process. They may have functioned as refractory elements to enhance heat retention during cooking activities and/or as a means of separating fuel from the upper level, possibly supporting food processing or cooking practices, among other potential uses.

In contrast to the strong standardisation observed in ovens and hearths, fire pits exhibit considerable flexibility in form and construction. This variability is nevertheless structured by clear spatial patterning. Fire pits are predominantly located in exterior open areas

surrounding domestic buildings and constitute the only fire installation type systematically documented outdoors (see Fig. 3c, Fig. 6a-b). More rarely, they occur within domestic buildings, specifically in porches and rear rooms, but are never found in the central room (Fig. 6c). The largest and deepest examples within buildings are concentrated in porches, whereas those in rear rooms tend to be smaller and shallower, likely reflecting constraints related to ventilation, smoke management, and fire risk.

Fire pits are best interpreted as installations complementary to ovens and hearths, associated with specific domestic activities carried out in exterior, semi-open or secondary indoor spaces. Their distribution highlights the functional differentiation of domestic space at Tell Halula and the role of porches and rear rooms in supporting distinct household practices.

4.2. Micromorphological insights into combustion residues from midden deposits

Micromorphological analysis of midden deposits revealed the presence of five distinct deposit types among the 30 MSUs identified in thin section dominated by combustion by-products (see supplementary material, S1): (i) deposits rich in charred plant remains; (ii) deposits rich in silicified plant materials; (iii) deposits rich in both charred and silicified plant remains; (iv) deposits rich in herbivore dung; and (v) deposits rich in burnt earthen aggregates. Micromorphological attributes of each deposit type are summarised in Table 3.

4.2.1. Deposits rich in charred plant remains

Accumulations rich in charred plant remains usually consist of units ranging from 0,5 to 3 cm in thickness and represent the most common deposit type among the samples analysed. The microstructure is predominantly crumby, and porosity is dominated by vughs, packing voids and, to a lesser extent, planes. Charred plant remains are present across all contexts studied, typically occurring at abundances of c. 2–5%. However, in this deposit type, the groundmass is dominated by charred plant remains (>20%), weakly to moderately oriented and moderately to strongly parallel-distributed, usually interbedded between heat-altered subangular massive earthen aggregates consisting of earth-building materials likely deriving from the inner surfaces of fire installations, and calcitic ashy aggregates (Fig. 7a–b). Additionally, within these deposits, charred plant remains and charcoal fragments reach their largest recorded dimensions, occasionally attaining centimetric size. Although taxonomic identification is generally hindered by fragmentation, in specific cases where large, charred wood fragments were preserved, charcoal identification proved feasible (Fig. 7c) (see section 5.2). Other inclusions present include phytoliths and burnt bone fragments, a proportion of which exhibit degrees of thermal alteration consistent with exposure to temperatures of approximately c. 300–400 °C (Villagran et al., 2017).

These deposits are likely formed through the discard and redeposition of charred fuel residues, corresponding to rake-out or clearance deposits derived from fire installations. Fuel-related evidence indicates formation under moderate- to high-temperature combustion conditions, probably in the range of c. 500–600 °C. This interpretation is supported by micromorphological indicators such as the presence of calcitic ashes, the absence of bulliform voids within charcoal fragments and the opacity of the clay fraction, consistent with sustained exposure to elevated temperatures (Wattez, 1992). The occasional presence of bones burnt at lower temperatures indicates that at least part of the osseous assemblage was exposed to heat after peak combustion temperatures had been reached, further suggesting that these deposits may also incorporate domestic refuse discarded into fires, potentially associated with consumption and cooking-related activities.

4.2.2. Deposits rich in silicified plant materials

These deposits range between 1 and 1,7 cm in thickness and

Table 3
Summary of micromorphological attributes following deposit-type. Classification of frequencies according to Stoops (2021). C/f limit is 50 μm.

Deposit-type	Particle size	Microstructure and porosity	Groundmass	Sorting	Coarse components fabric	Anthropogenic inclusions	Sample
Dominated by charred plant remains	Silty clay loam and medium-coarse sand	M: vughy/crumb microaggregate P: c. 25–30% vughs, packing voids, planes	c/f ratio: 1/2 c/f r.d.p: porphyric/enaulic b-fabric: calcitic-crystallitic	Poorly sorted	Weakly to moderately oriented Moderate to strong parallel distribution	Charred plants (>20%) Burnt earthen agg. (5–10%) Calcitic ashes (5%) Phytoliths (2–5%) Bones (<2%)	HA92-15; HA92-17; HA93-56; HA96-7; HA96-12; HA96-13; HA96-14; HA96-17; HA96-22; HA96-23
Dominated by silicified plant materials	Silty clay loam	M: platy P: c. 15–20% vughs, planes	c/f ratio: 1/3 c/f r.d.p: close porphyric b-fabric: calcitic-crystallitic	Moderately to well sorted	Moderately to strongly oriented Strong parallel distribution	Charred plants (2–5%) Burnt earthen agg. (1%) Calcitic ashes (10%) Phytoliths (>60%) Bones (1%)	HA96-22; HA96-23
Dominated by charred and silicified plant remains	Silty clay loam and sand	M: vughy P: c. 20–25% vughs, packing voids, planes	c/f ratio: 1/2 c/f r.d.p: close porphyric b-fabric: calcitic-crystallitic	Poorly to moderately sorted	Weakly to moderately oriented Moderate parallel distribution	Charred plants (25–35%) Burnt earthen agg. (2%) Lime plaster (1%) Calcitic ashes (20–25%) Phytoliths (25–40%) Bones (1%)	HA92-11; HA92-15, HA96-7
Dominated by burnt herbivore-dung	Silty clay loam and medium-coarse sand	M: granular/intergrain microaggregate P: c. 25% Packing voids, vughs	c/f ratio: 1/2 c/f r.d.p: close enaulic b-fabric: calcitic-crystallitic	Poorly sorted	Weakly oriented Random distribution	Burnt herbivore dung (>40%) Charred plants (5–10%) Burnt earthen agg. (5%) Calcitic ashes (2%) Phytoliths (15%) Bones (1%)	HA96-14
Dominated by burnt earthen aggregates	Silty clay loam, sand	M: granular/vughy P: c. 20–25% vughs, planes, packing voids	c/f ratio: 1/3 c/f r.d.p: porphyric b-fabric: calcitic-crystallitic	Poorly sorted	Weakly oriented Random distribution	Charred plants (5–10%) Burnt earthen agg. (>25%) Phytoliths (2%) Bones (<1%)	HA93-56; HA96-12; HA96-13; HA96-17; HA96-19

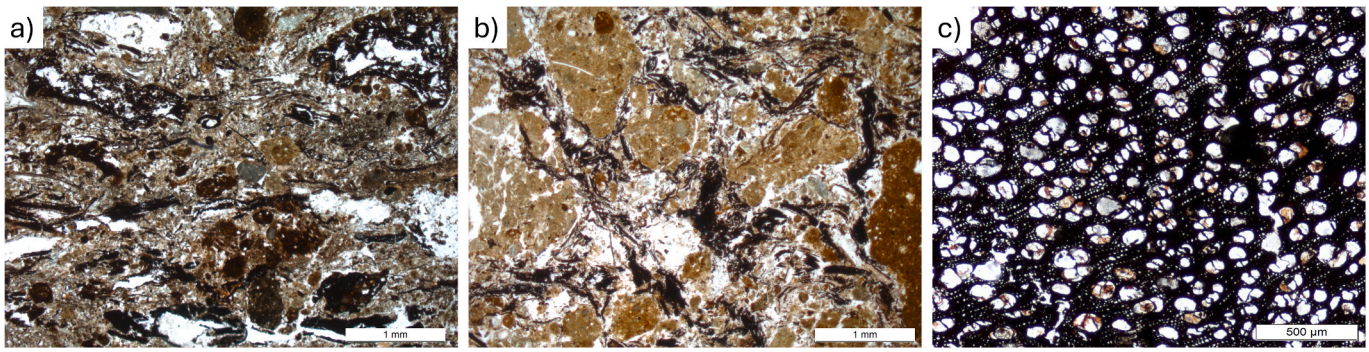


Fig. 7. Photomicrographs of MSUs classified as deposits dominated by charred plant remains: a) Charcoal fragments moderately to strongly oriented embedded in an ashy matrix, PPL; b) Charred plant remains weakly to moderately oriented interbedded between heat-altered subangular earthen aggregates, PPL; c) Large charcoal fragment of Salicaceae identified in thin-section, PPL.

constitute the second least frequent deposit type within the analysed sample set. They are predominantly composed of articulated, although sometimes locally disturbed, siliceous plant remains (>60%), primarily derived from grasses and reeds (Fig. 8a-b). These remains display a marked parallel orientation forming laminated accumulations, and are associated with grass-derived microcharcoal, ashy aggregates and occasional black carbonised particles. Experimental and archaeobotanical studies demonstrate that different plant tissues (stem, leaf, husk) respond variably to heat exposure. While some phytoliths may begin to exhibit slight colour alteration at temperatures as low as c. 250 °C, others remain unaltered up to c. 600 °C (Fritzsch and Röpke, 2025). In general terms, blackening of phytoliths typically occurs between c. 400 and 600 °C (Boardman and Jones, 1990; Matthews, 2010; Fritzsch and Röpke, 2025). An additional thermal indicator is the presence of melted silica, which forms at combustion temperatures exceeding c. 650–850 °C (Canti, 2003; Portillo et al., 2021; Fritzsch and Röpke, 2025).

In the analysed units, no melted silica was observed. However, a proportion of phytoliths display darkened or blackened colouration (Fig. 8c), suggesting exposure between low and moderate combustion temperatures (<600 °C) or to short-duration, weakly sustained fires (Boardman and Jones, 1990; Canti, 2003; Matthews, 2010; Fritzsch and Röpke, 2025). These features are consistent with partially charred herbaceous plant remains rather than fully combusted fuel residues.

The underlying substrate layers show no evidence of *in situ* burning (Mallol et al., 2007; Mentzer, 2012; Vera Aldeias et al., 2016), suggesting either very low-temperature combustion or the redeposition of fuel residues originating from nearby combustion areas, as the degree of phytolith articulation indicates limited disturbance. Nevertheless, the level of phytolith articulation in some cases also leaves open the possibility that some of these accumulations formed *in situ*, reflecting open-air combustion episodes that produced a rapid build-up of herbaceous fuel residues.

Altogether, these deposits are interpreted as deriving from the use of herbaceous plants, particularly grasses and reeds, as fuel in low-intensity or short-duration combustion episodes. Alternatively, they may reflect the burning of waste generated through the disposal of plant remains from cooking or craft-related activities, as part of routine cleaning practices.

4.2.3. *Deposits rich in charred and silicified plant remains*

These deposits typically measure between 1,5 and 3 cm in thickness and constitute the third most frequent deposit type. The microstructure is predominantly vughy/spongy, while porosity is defined by vughs, some of which are elongated. Phytoliths, mostly unarticulated and in some cases blackened, and charred plant remains occur in broadly similar proportions (c. 25–35%). However, in certain units, silicified plant remains, specifically derived from grasses and reeds, constitute the dominant inclusion, reaching overall abundances of c. 45% (Fig. 9a). Inclusions are moderately to strongly oriented parallel to the depositional surface and are embedded within an ashy groundmass. Other components occurring in lower frequencies include grass-derived microcharcoal and bone fragments, the majority exhibiting thermal alteration around c. 300 °C, with some fragments burnt at 500–600 °C (Villagran et al., 2017), as well as burnt earthen aggregates and lime plaster fragments, likely derived from fire installations (Fig. 9b).

These deposits are interpreted to have formed through the discard and redeposition of mixed fuel residues, as well as through fire installation clearance and maintenance practices, as indicated by the presence of redeposited structural materials. The association of wood charcoal and grass-derived phytoliths suggests the combined use of woody and herbaceous fuels. Fuel-related evidence suggests formation under moderate- to high-temperature and/or relatively short-duration combustion events. This interpretation is supported by the co-occurrence of charred plant remains, typically associated with burning at c.

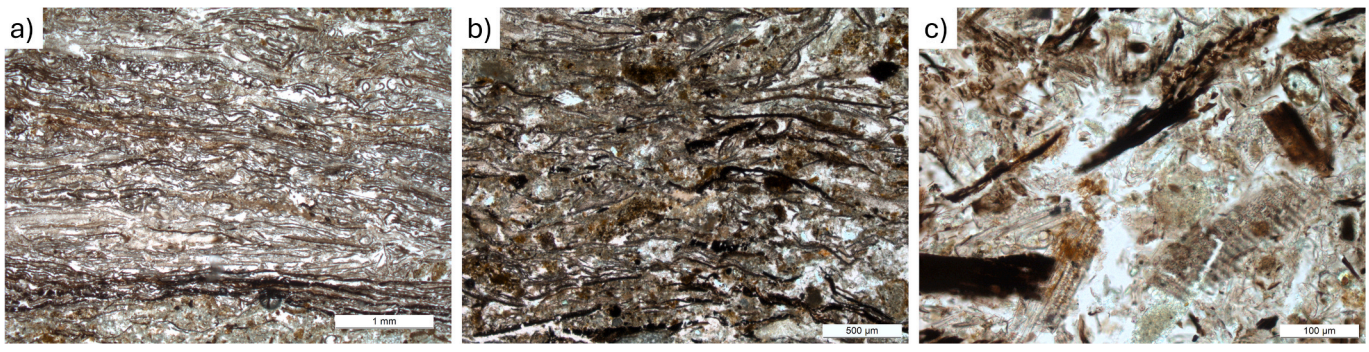


Fig. 8. Photomicrographs of MSUs classified as deposits dominated by silicified plant remains: a) Highly laminated grass-derived silicified plant materials, PPL; b) Partially articulated silicified plant materials embedded in ashy matrix, PPL; c) Blackened plant tissues and phytoliths indicating burning activities, PPL.

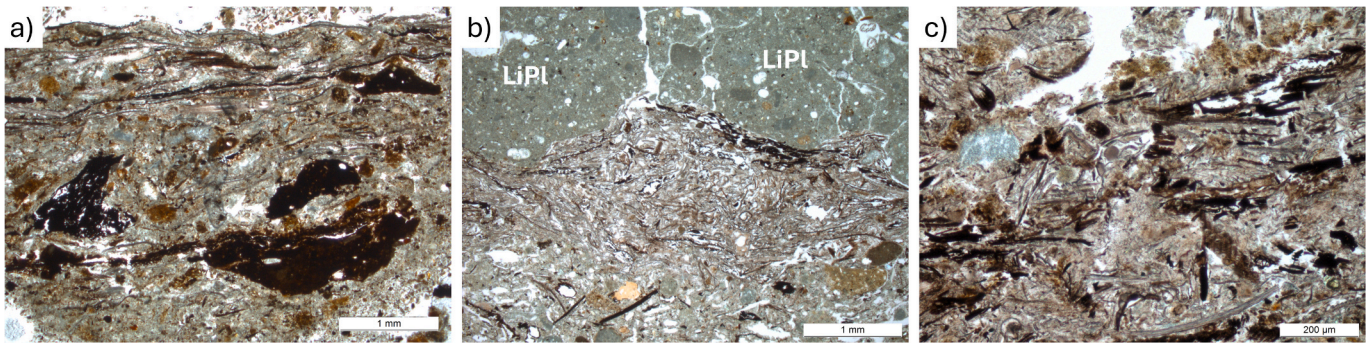


Fig. 9. Photomicrographs of MSUs classified as deposits rich in charred and silicified plant remains: a) Moderately to strongly oriented charcoal and silicified plant materials within an ashy matrix, PPL; b) Accumulation of charred plants and unarticulated grass phytoliths along with a lime plaster fragment (LiPl), PPL; c) Detail of (a) showing blackened plant tissues and phytoliths, indicating burning activities, PPL.

400–600 °C (Wattez, 1992; Matthews, 2010), and blackened phytoliths (Fig. 9c), which begin to develop darkened colouration between c. 400 and 600 °C (Boardman and Jones, 1990; Matthews, 2010; Fritzsch and Röpke, 2025).

4.2.4. *Deposits rich in burnt herbivore dung*

These deposits measure up to 4,5 cm in thickness and represent the least frequent deposit type among the samples analysed. The microstructure is granular with some intergrain microaggregates, and porosity is defined by packing voids and vughs. Dung fuel remains in thin-section were identified by analysis of dung morphology, internal structure and contents, including calcareous spherulites that form in the guts of animals during digestion (Brochier et al., 1992; Canti 1999; Shahack-Gross 2011). These deposits are dominated by > 40% burnt herbivore dung, which is weakly oriented, accompanied by minor proportions of charred plant remains and occasional traces of burnt bone fragments and burnt earthen aggregates (Fig. 10a). In contrast to the previous deposit types, calcitic ashes are poorly represented.

The excrements are subrounded, reaching up to 2 cm in size, and display a fibrous, micro-laminated microstructure with abundant spherulites. Colour varies according to the maximum temperatures attained, ranging from reddish-brown to pale greyish-brown for calcined fragments under plane-polarised light (PPL) (Fig. 10b). Approximately 10% of the spherulites exhibit thermal alteration (Fig. 10c), suggesting that temperatures of c. 500–700 °C were reached (Canti and Nicosia, 2018; Portillo et al. 2021).

The lack of compaction, the predominance of packing voids, the low sorting degree, and poor accommodation of the components, along with the absence of thermal alteration in the underlying substrate, indicate that these units represent the discard of burnt herbivore dung, most likely used as fuel, as indicated by minor related inclusions.

4.2.5. *Deposits rich in burnt earthen aggregates*

These deposits are relatively thin, ranging from 0,5 to 2,5 cm in thickness, and constitute the second most frequent deposit type. The microstructure is granular with occasional inter-grain micro-aggregates, while porosity is characterised by vughs, planes and packing voids. These units are dominated by subangular silty clay granules (>25%), exhibiting reddish to dark-brown colours under PPL and generally massive microstructures, indicative of their origin as earth building materials (Fig. 11). This interpretation is further supported by the presence of plant impressions in some aggregates, likely reflecting the use of vegetal fibres as stabilisers. Minor inclusions comprise charred plant remains, phytoliths, heated rock fragments exhibiting enrichment in iron oxides near their exterior surface, and occasional burnt bone fragments; notably, calcitic ashes are almost absent. Inclusions are generally randomly distributed and unoriented.

These deposits are interpreted as primarily resulting from the raking-out or cleaning of fire installations, where fuel residues are poorly represented, possibly due to their fragility and displacement or fragmentation during cleaning. An additional possibility involves the dismantling and/or collapse of combustion structures, whereby burnt aggregates derive from the walls or surfaces of ovens or fire pits. The reddish colouration of the aggregates provides a proxy for temperature exposure. Experimental and observational studies suggest that the onset of reddening may occur at c. 400 °C (Berna et al., 2007), whereas other studies indicate higher thresholds, up to 800 °C (Mathieu and Stoops, 1972). More recent research places colour changes in sediments between 600 and 1000 °C (Röpke and Dietl, 2017), although thermal responses vary considerably depending on material properties and composition, preventing a clear assignment of specific temperatures (Canti and Linford, 2000; Berna et al., 2007).

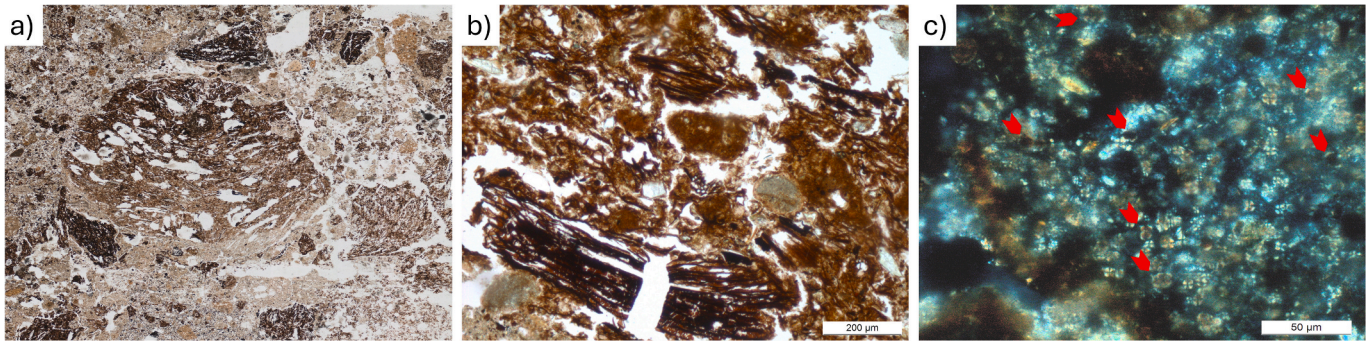


Fig. 10. Photomicrographs of MSUs classified as deposits rich in herbivore dung: a) Weakly oriented and randomly distributed burnt animal dung fragments, PPL; b) Detail of a burnt dung pellet showing an internal structure dominated by plant remains, note the reddish-brown colour resulting from burning, PPL; c) Calcitic spherulites within dung pellet, some of them showing traces of burning (red arrows), XPL.

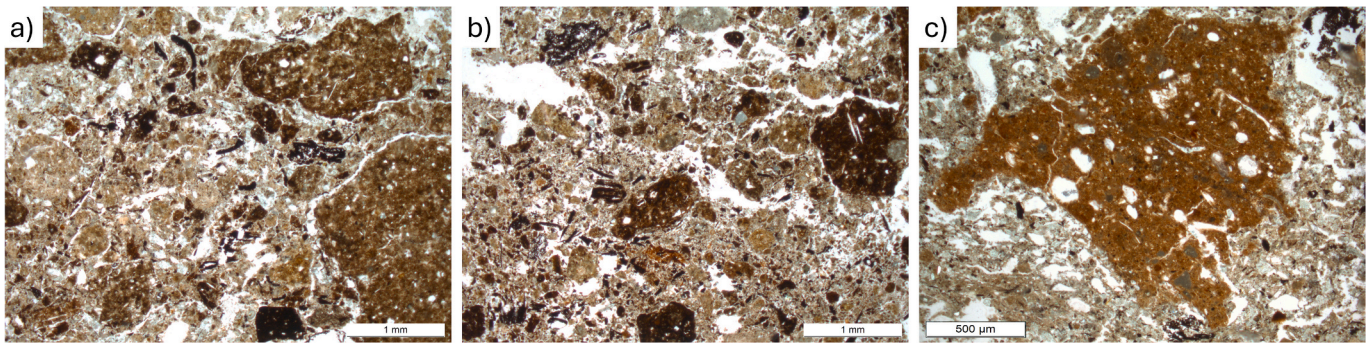


Fig. 11. Photomicrographs of MSUs classified as deposits rich in earthen aggregates: a) and b) Weakly oriented and randomly distributed burnt earthen aggregates, PPL; b) Detail of a heat-altered earthen aggregate showing a massive microstructure with rounded vesicles and moldic voids (plant impressions), likely indicating its origin as building material, PPL.

5. Discussion

5.1. Spatial location and technology of fire installations

The transition from mobile hunter-gatherer lifeways to sedentary farming-herding life-ways involved changes in social organisation, including the emergence of new forms of spatial and social interaction. Among these transformations, the increasing segregation and compartmentalisation of fire-related and domestic activities have been widely documented across Early Neolithic sites in Southwest Asia. This process has been interpreted as part of broader socioeconomic changes that emphasised the household as a primary unit of production and consumption (Byrd, 2002; Bogaard et al., 2009; Kuijt et al., 2011), as well as a key arena for social relations (Hodder, 1990; Watkins, 2006; Souvatzi, 2012).

In this context, features associated with food processing, storage, and combustion were progressively incorporated into built domestic spaces, rather than located in open or communal areas. This shift coincides with the disappearance of communal buildings and changes in architectural design, from small, unicellular structures to larger, multi-roomed rectilinear buildings capable of accommodating a broader range of activities and social practices (Byrd, 1994, 2002; Banning, 1998; Kuijt and Goring-Morris, 2002; Kuijt et al., 2011; Duru et al., 2021).

This process is particularly well documented in the Middle Euphrates valley through evidence from earlier PPNA-EPPNB sites such as Tell 'Abr, Dja'de and, most notably, Jerf el Ahmar. At these sites, combustion structures in earlier phases, associated with circular architecture, are predominantly located in exterior spaces. Only in later phases, characterised by rectilinear multi-cellular buildings, do fire installations begin to appear consistently within architectural units (Stordeur and Abbès, 2002; Albukaai, 2014; Stordeur, 2015). These installations are relatively standardised in form, typically circular and excavated, often raised and lined with stones, and occasionally finished with mud plaster.

In contrast, from the MPPNB onwards, at Tell Halula, combustion structures are predominantly located within interior domestic spaces, a pattern widely attested across Southwest Asia, including the southern Levant, the Zagros region and central Anatolia (e.g., Byrd, 1994; Matthews, 2016; Fuchs-Khakhar, 2021). Fire installations also display high morphological standardisation combined with strongly structured spatial patterning. Ovens are consistently positioned in the central area of the main room, abutting the rear wall, a location that likely enhances heat retention while placing the structure opposite the entrance. This configuration may have reduced direct exposure to incoming air currents while maintaining stable combustion conditions. Hearths, by contrast, are also located within the main room but occupy a more lateral position, near the entrance and adjacent to one of the posts supporting the roof. Despite the potential fire risk, this placement may have helped shield the fire from air currents. Fire pits, by contrast, are less common and primarily located in exterior areas surrounding domestic buildings. When present within houses, they are never found in the main room, where floor disturbance appears to have been restricted only to burial practices, but rather in porches or rear rooms. This clear spatial segregation suggests functional differentiation between indoor and outdoor combustion practices, and also between rooms within domestic buildings.

Beyond these functional considerations, the organisation of combustion features also reflects broader constraints related to building aerodynamics and smoke behaviour within enclosed spaces. Factors such as prevailing winds, building layout, and roof construction would have affected combustion efficiency and smoke evacuation. In this regard, the recurrent placement of hearths and ovens in relation to entrances or structural elements may have facilitated airflow, while features such as roof openings or gaps between wall tops and roofing elements could have enabled smoke release. Alongside functional and social considerations, these factors suggest that health-related constraints associated with smoke exposure likely contributed to the organisation of fire installations within domestic spaces.

The MPPNB also sees an increased investment in the construction and maintenance of fire installations, particularly those located indoors. At Halula, this is reflected in the emergence of new designs, such as ovens and brazier-like hearths, that require different control and management of fuel loadings, combustion temperatures, durations and applications. It is further expressed in more complex sequences involving the application of multiple layers and the careful selection of materials, including alluvial sediments rich in quartz and feldspar sand fractions used in ovens to enhance thermal shock resistance (Marchiori, 2015). This technological development is further evidenced by the widespread use of lime plaster, a resource-intensive material requiring substantial fuel input and implying technical knowledge and possibly craft specialisation within the community (Garfinkel, 1987; Kingery et al., 1988; Goren and Goldberg, 1991; Friesem et al., 2019). These innovations resulted in more heat-resistant structures with improved thermal performance.

Fire installations were also subject to repeated maintenance and rebuilding. New structures were often constructed directly over earlier ones, enabling material recycling and continuity of domestic layouts. Archaeological evidence usually indicates up to three reconstruction events within single domestic units, particularly in ovens. These episodes are not uniform across the settlement, suggesting that maintenance responded to specific functional requirements rather than to standardised cycles. Similar patterns of renewal have been observed in plaster floors through micromorphological analysis (Sisa-López de Pablo et al., 2024), reinforcing the close relationship between combustion features and broader architectural dynamics, mirroring the life-cycle of the house. Fire pits, by contrast, show no evidence of systematic rebuilding or replastering, suggesting different operational roles. A similar case is that of Aşıklı Höyük, where differences in spatial location, hearth maintenance and renewal, and hearth typology are interpreted as

indicative of different fire uses, with indoor and outdoor uses distinguished (Uzdurum, 2018). However, high-resolution studies at sites such as Çatalhöyük have documented variations in soot accumulation on internal versus external wall surfaces, which are interpreted as evidence of seasonal patterns in the use of indoor and outdoor combustion structures (Matthews 2005, 2012).

Altogether, the evidence from Tell Halula and the wider Middle Euphrates region indicates a significant transformation in both the spatial organisation and technological investment of fire installations during the MPPNB. Fire installations became increasingly integrated into domestic architecture, particularly in interior spaces and the main room, where they required greater labour investment and repeated maintenance, underscoring the growing emphasis on the household (Byrd, 2002; Hodder and Cessford, 2004; Kuijt et al., 2011).

5.2. Fuel sources and selection strategies

The environmental setting of Tell Halula provides a key framework for interpreting fuel procurement strategies. Located in proximity to the Euphrates and surrounded by two wadis, the site would have benefited from direct access to riparian vegetation, including woody taxa suitable for fuel, while the surrounding steppe environments offered complementary biomass resources such as shrubs, grasses and other herbaceous plants. This ecotonal position enabled the exploitation of multiple ecological niches and supported a flexible, diversified approach to fuel acquisition, reflecting both environmental availability and social practice.

Micromorphological analysis of combustion-related deposits reveals a marked diversification of fuel types, including wood, herbaceous plants, and herbivore dung. Notably, individual depositional events are generally dominated by a single fuel type, whereas mixed assemblages are rare, indicating structured patterns in fuel selection linked to environmental availability and resource-use strategies.

Woody fuel is the most identified resource. Microscopic analysis confirms the presence of Salicaceae, *Tamarix* sp. and *Pistacia* sp., consistent with archaeobotanical evidence from the site (Piqué et al., 2013). The predominance of riparian taxa indicates a sustained reliance on vegetation growing along watercourses, emphasising the economic importance of the riverine environment, also highlighted by previous bioarchaeological studies at the site (Willcox, 1991; Helmer et al., 1998). At the same time, the occasional presence of taxa such as *Pistacia* sp. suggests that wood resources from surrounding steppe areas were sometimes also exploited.

Herbaceous fuels are represented by deposits rich in silicified plant remains, mainly derived from grasses and reeds, indicating the exploitation of local wetland environments as a source of combustible biomass. Similar patterns have been documented in Early Neolithic sites across the Zagros region and central Anatolia through micromorphological analysis, demonstrating the widespread use of grasses, reeds, and sedges as fuel (e.g., Shillito and Matthews, 2013; Matthews, 2016, 2020; García-Suarez et al., 2018). In addition to their role as fuel, these plants may also have been procured for other activities, including roofing, matting, basketry, foddering, or the processing of edible plants, thus reflecting a multifunctional exploitation of plant resources.

Animal dung represents an additional, though comparatively less frequent, fuel source during the PPNB at Tell Halula. The relatively limited occurrence of dung-rich deposits contrasts notably with the later Pre-Halaf and Halaf periods, when dung fuel becomes more prominent (Sisa-López de Pablo et al., in prep). Micromorphological evidence for dung fuel has been documented across various Early Neolithic contexts in Southwest Asia (e.g., Shillito and Matthews, 2013; Matthews, 2016; García-Suarez et al., 2018; Sisa-López de Pablo et al., 2025b). The use of dung as a fuel is often associated with closer proximity between humans and animals and the development of herding practices. At Tell Halula, despite evidence for domesticated species such as sheep and goats in earlier occupations, no clear indications of penning areas have been identified. As a fuel, dung has several advantages, including slow, even burning and the capacity to sustain relatively high, stable temperatures, making it suitable for a range of domestic and craft activities (Sillar, 2000; Matthews, 2010).

The range of identified fuel sources implies variability in combustion properties and fire performance. Both wood and dung can sustain high-intensity fires, reaching temperatures of c. 800–1000 °C under controlled conditions (Matthews, 2010; Gur-Arieh et al., 2013; Vergès et al., 2016; Portillo et al., 2017). However, these fuels exhibit different combustion dynamics. Animal dung generally requires a longer time to reach peak temperatures but is able to maintain stable heat output over extended periods (Sillar, 2000; Matthews, 2010; Vergès et al., 2016). Micromorphological evidence suggests that dung combustion at Tell Halula reached temperatures of at least c. 550–750 °C, as indicated by the thermal alteration of faecal spherulites (Canti and Nicosia, 2018; Portillo et al., 2021), likely under reducing conditions. This may point to its use in enclosed or semi-enclosed fire installations, such as ovens or covered fire pits.

Similarly, charred plant remains could also have reached those temperatures, as shown by the presence of charcoal and related features such as heat-altered sediments and calcitic ash, which indicate that wood-based fuels attained comparable temperature ranges (Wattez, 1992; Berna et al., 2007; Mentzer, 2012; Röpke and Dietl, 2017). In contrast, deposits dominated by silicified plant remains suggest lower combustion intensities, with estimated temperatures around c. 400–500 °C, as indicated by the presence of blackened phytoliths (Boardman and Jones, 1990; Fritzsch and Röpke, 2025). The absence of melted silica further implies that these fires did not exceed temperatures of c. 650–850 °C (Canti, 2003; Portillo et al., 2021; Fritzsch and Röpke, 2025) and were therefore likely short-lived and of lower intensity.

Overall, the range of combustion-related deposits identified at Tell Halula indicates diversified energy sources, including riverine and, to a lesser extent, steppe woody taxa, herbaceous, and animal-derived resources. This variability suggests flexible procurement strategies adapted to environmental availability, combustion efficiency, the operational demands of different fire installations, and possibly smoke production and indoor air quality constraints.

5.3. Fire use and waste management

A notable characteristic of many early sedentary settlements in Southwest Asia is the relative absence of occupational residues on the floors of domestic buildings (Braidwood et al., 1983; Matthews, 2012, 2020). This pattern has long constrained interpretations of household organisation and activity areas, as most assemblages derive from abandonment or post-abandonment deposits rather than *in situ* occupation layers (Clarke, 1973; LaMotta and Schiffer, 1999). Such patterns suggest that domestic interiors were subject to regular cleaning and maintenance, reflecting an increasing concern for hygiene and spatial organisation in contexts of growing sedentism. This concern may have become particularly important as communities became more permanently settled, population densities increased, and greater quantities of architectural materials and waste accumulated, becoming increasingly problematic in both volume and potential health hazards.

These practices coincided with an increasing investment in the domestic sphere as a locus of social and symbolic activity (Cauvin, 1994; Hodder and Cessford, 2004; Watkins, 2006). The maintenance of interior spaces may therefore have carried not only practical but also social and ideological significance. Consequently, open areas adjacent to buildings were frequently used for waste disposal, in some cases resulting in extensive midden deposits. However, these deposits represent complex formation processes rather than simple refuse accumulations, reflecting repeated episodes of deposition, reworking and surface maintenance, in which burning and waste management formed part of deliberate and routine practices (Shillito and Matthews, 2013).

Within this framework, fire use emerges as a key component of both

domestic practice and waste management, including the intentional burning of refuse for sanitation purposes. On the other hand, fire use within domestic contexts is also likely to have had implications for human health, as heat, smoke, and fine particulates constitute well-documented hazards affecting the respiratory system, eyes, and soft tissues (Bruce et al., 2000; Roberts, 2016; Smith and Pillarisetti, 2017). Evidence from Early Neolithic sites indicates that smoke accumulated within interior spaces, as demonstrated by soot deposits interstratified with wall plasters at sites such as Shimshara and Çatalhöyük (Matthews, 2005, 2016). Experimental studies on reconstructed early built environments further show that herbaceous fuels such as reeds and grasses can generate substantial smoke under poorly ventilated conditions, while combustion in enclosed environments can produce extremely high concentrations of fine particulate matter, particularly when dung is used, largely exceeding modern safety thresholds (Mustafaoğlu and Bar-Yosef, 2016; Shillito et al., 2022). In this context, fuel selection and fire management strategies at Tell Halula may have been shaped not only by availability and functional requirements but also by the need to mitigate smoke exposure. Practices such as trasnferring embers produced in exterior installations into interior spaces may have reduced smoke emissions while maintaining heat, while more smoke-producing fuels may have been preferentially used in outdoor fire pits where ventilation was less constrained.

Micromorphological analysis provides further insight into these processes. Examined deposits indicate that most combustion-related deposits represent secondary accumulations derived from cleaning and maintenance activities, rather than *in situ* burning events. These deposits largely consist of displaced and reworked materials associated with rake-out practices, as evidenced by heat-altered earthen aggregates and fragments of lime plaster, indicating that structural components of fire installations were occasionally removed during maintenance. The relative homogeneity of micro-residues within individual deposits currently limits the direct association of specific fuel types with particular activities. Nevertheless, the frequent presence of burnt bones and other domestic refuse suggests the multipurpose use of fire, likely extending beyond fuel combustion to include cooking and possibly craft-related activities. A notable exception is provided by deposits rich in silicified plant materials. In these units, the generally high degree of phytolith articulation, together with microlaminated structures and parallel orientation of inclusions, indicates limited disturbance, making sweeping and redeposition less likely. These deposits may therefore represent the partial burning of grasses and reeds, either *in situ* or very close to the sampled area, and, in some cases, reflect localised open-air combustion episodes. Such events may be linked to the burning of waste generated through the processing of plant remains from cooking or craft-related activities.

When considered alongside excavation data, including their spatial distribution and architectural investment, these lines of evidence suggest that different fire installations were used for distinct, though sometimes overlapping, purposes. Among the three identified combustion installations, fire pits appear to have been the most flexible and multifunctional. Their predominant occurrence in exterior areas surrounding domestic buildings, together with their morphological variability and the frequent presence of thermally altered stone pebbles, indicates their primary association with open-air domestic tasks, particularly food processing and cooking. Their outdoor location would also have been well-suited to activities involving larger flames and greater smoke production (i.e., herbaceous plants, animal dung), and possibly to the burning of domestic waste as part of routine sanitation and cleaning practices. By contrast, the more occasional presence of fire pits in porches and back rooms suggests more specific complementary functions. The presence of storage features and grill-plan structures in these same spaces indicates activities that were likely not performed in the main room. Ovens are more intensively used installations, most likely for daily food preparation and possibly for activities requiring sustained high temperatures, and are characterised by substantial labour investment, complex construction, high thermal efficiency, and repeated maintenance. Their standardised placement in a central position indicates further roles in heating, lighting, and social gathering. Lastly, hearths exhibit low-intensity combustion consistent with a brazier-like function, used for heating, lighting, or small-scale culinary practices. Their location near roof-support posts may have improved smoke ventilation or sheltered flames from draughts. At the same time, their location close to the burial area and painted floors suggest that their use may have extended into socially or symbolically significant practices.

Indeed, the standardisation and continuity observed in the design and spatial layout of ovens and hearths at Tell Halula, as well as in building morphology, are unlikely to be explained by functional requirements alone. Several scholars have argued that the repeated arrangement of fire installations in Neolithic houses reflects the emergence of institutionalised households and new forms of social organisation linked to increasing sedentism (Hodder, 1990; Cessford and Near, 2005; Baird et al., 2016; Anspach, 2018). Fire installations thus operated as key elements in structuring domestic life and social relations, with the hearth often acting as the symbolic focus of the house, around which everyday practices, memory and social identity were organised (Hodder and Cessford, 2004; Bloch, 2010; Hastorf, 2012; Fuchs-Khakhar, 2022).

At Tell Halula, repeated rebuilding of combustion features and floors reinforces their integration into domestic life cycles. Burials beneath floors and painted surfaces near hearths further highlight the symbolic character of main rooms. The standardisation of fire installations and, more broadly, building design may therefore reflect shared politico-ideological or symbolic practices, reinforcing group identity and social cohesion in a context of increasing household autonomy (Byrd, 2002; Kuijt et al., 2011). Ultimately, fire use at Tell Halula extended beyond functional requirements, becoming embedded in the social reproduction of domestic and community identities.

6. Conclusions

This study has explored how the transition to more permanent and densely occupied settlements during the Pre-Pottery Neolithic reshaped the organisation, technology, and social significance of fire. By integrating architectural evidence with high-resolution micromorphological analysis, it has been possible to move beyond functional interpretations and situate fire use within broader processes of economic intensification and social transformation.

The results demonstrate that increasing sedentism was accompanied by the diversification and standardisation of combustion installations, including ovens, hearths and fire pits at Tell Halula, each associated with distinct but sometimes overlapping roles. These installations show clear evidence of technological investment, expressed in the use of more durable materials such as lime plaster and thermally resistant sediments, as well as in increasingly complex construction and maintenance sequences. Their recurrent placement in structured locations within domestic architecture, particularly in the main room, indicates that fire installations were not only designed for efficiency but also embedded within spatial conventions that were maintained through time. Repeated rebuilding episodes further underscore their integration into the life cycle of the house, reinforcing architectural continuity and the persistence of domestic practices across generations.

Fuel selection strategies further reflect the interplay between environmental availability and social practice. The identification of a wide range of fuel types, including wood, herbaceous plants, and animal dung, demonstrates a diversified and flexible approach to fuel procurement. This variability likely responded not only to resource accessibility and seasonal availability, but also to the functional requirements and operational demands of different fire installations and activities, alongside broader environmental, economic, and health considerations. Additionally, the predominance of single-fuel depositional events may suggest a structured and selective approach to fuel use, rather than indiscriminate use.

Beyond their functional role, fire installations also had important social implications. The increasing integration of combustion features within domestic architecture reflects a broader shift towards the household as the primary unit of production and social life. The spatial centrality, standardisation, and long-term continuity of ovens and hearths point to their importance in structuring daily practices and social interaction. Their association with features such as burials and decorated floors further suggests that fire installations were embedded within symbolically charged contexts, contributing to the construction of memory, identity, and social relations within the household. In line with broader regional patterns, these developments reflect a shift towards the institutionalisation of the household as a key social unit, within which fire-related activities became increasingly structured around the household and less communal in character.

Overall, the study highlights how fire use at Tell Halula cannot be understood solely in technological or economic terms. Instead, it formed part of an integrated system linking resource use, architectural organisation, domestic practices, and social meanings. These findings demonstrate the value of combining micromorphological and excavation data analyses to reconstruct past fire practices and fuel use. More broadly, they provide new perspectives on the role of fire in mediating the relationship between people, built environments, and emerging forms of social life in the earliest farming societies.

CRediT authorship contribution statement

Joaquim Sisa-López de Pablo: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Anna Bach Gómez:** Writing – review & editing, Resources, Project administration, Data curation. **Miquel Molist:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2026.106085.

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