



# Pulse of the Past: a ground stone tools perspective on the significance of legumes at the Pre Pottery Neolithic site of Kharaysin (Jordan)

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## Abstract

Ground stone tools are considered prime evidence for exploring significant aspects of prehistoric societies, particularly concerning plant food processing. For this reason, studying their use can reveal relevant clues concerning the modes of exploitation of specific plants and highlight local and shared culinary practices. This paper presents the first functional study of the ground stone tools from the Pre Pottery Neolithic site of Kharaysin in Jordan. Excavation at the site yielded significant information on the habits and lifestyle of the early Neolithic communities inhabiting the site between the end of the 10th millennium and the middle of the 8th millennium BC. Among this wealth of evidence, of particular interest is the relevant role suggested by the archaeobotanical record, played by legumes at Kharaysin. We further investigate this aspect through the functional analysis of ground stone tools, carried out through the combination of use-wear, residues and 3D surface texture analyses. We identified three use-wear patterns associated with the working of legumes and cereal grains, which provided detailed information on the gestures performed and the species of worked plant. The qualitative and quantitative use-wear data have been coupled with the analysis of plant micro remains identified on the analysed tools, further strengthening our functional interpretations. The results from our study further support the importance that legumes have had at Kharaysin, also shedding more light on the relevance of these plant foods in the diet and daily life of the first Neolithic farming communities in Southwest Asia.

**Keywords** Ground stone tools · Pre Pottery Neolithic · Use-wear · Plants · Legumes · SW Asia

## Introduction

The transition to agriculture happened ca. 10.000 years BP in the Neolithic and represented one of the main turning points in human history (Braidwood 1960; Willcox 2004, 2024; Weiss et al. 2006; Fuller et al. 2012; Ibáñez et al.

2018; Gopher et al. 2021; Fuller and Lucas 2025). Among the pivotal changes that are attested during the Neolithic is the domestication of plants, which dramatically changed the millennia-long liaison between plants and humans. Plant domestication studies have identified a “package” of founding crops, including three cereal grains, four legumes

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and flax, which were likely domesticated at the same time between the mid-9th and 7th millennium BC (Zohary and Hopf 1973; Weiss and Zohary 2011; Zohary et al. 2012). However, this assumption has been challenged, and current debate is ongoing regarding the inclusion of plant species not originally considered (Arranz-Otaegui and Roe 2023; Fuks et al. 2024). Among legumes, the species identified as being part of the “original” Neolithic package include pea (*Pisum elatium*; *P. sativum*), lentil (*Lens orientalis*; *L. culinaris*), chickpea (*Cicer reticulatum*; *C. arietinum*), bitter vetch (*Vicia ervilia*), faba bean (*Vicia faba*), rambling vetch (*Vicia peregrina*) along with other members of the Fabaceae family (e.g. *Lathyrus* spp.) (Arranz-Otaegui and Roe 2023).

In the Levant, the significance of legumes in prehistory is testified by their finding in numerous archaeological contexts dating back to the Palaeolithic as in the case of the Middle Palaeolithic site of Kebara Cave in Israel (Lev et al. 2005). Furthermore, the importance of legumes in the Pre Pottery Neolithic (henceforth PPN) is testified by their finding in the archaeobotanical assemblages, where they often outnumber cereals in numerous archaeological sites (Arranz-Otaegui et al. 2016; Caracuta et al. 2017).

In Southeast Anatolia, lentils dominate the archaeobotanical record in the PPNA and PPNB levels at G sir H y k, suggesting the systematic harvesting of wild legumes, potentially associated with cultural preferences related to plant exploitation (Kabukcu et al. 2021; Kabukcu 2023). Furthermore, large amounts of legume remains have been identified in the archaeobotanical assemblage of  ay n  and Nevali  ori (Van Zeist and De Roller 1991; Pasternak 1998). In Northern Syria, a significant amount of lentils has been found at the PPNA site of Jerf el-Ahmar. Specifically, a concentration of *Lens orientalis* seeds was found in room 2 of Building 10, which has been defined as a food processing/cooking area (Willcox 2002). Numerous remains of lentils have also been found at the Khiamian site of Tell Qaramel (Willcox et al. 2008). At the site of Dja’de el Mughara, dated to the Early PPNB, a large quantity of legumes, in particular lentils, along with several other species (e.g. *Cicer* sp.), have been identified in the archaeobotanical record (Pichon 2017; Douch  and Willcox 2018; Pichon et al. 2021). In the Southern Levant, remains of faba bean have been found at the Natufian site of el-Wad Terrace (Belli et al. 2023) while, the recovery at the PPN site of Yiftah’el of nearly 1.4 million lentil seeds and more than 2000 charred faba bean seeds have been interpreted as evidence of storage (Garfinkel et al. 1987). Also at the Early PPNB sites numerous legume seeds have been found. Lentil, faba bean, and bitter vetch have been identified at Tell Qarassa North (South Syria) (Arranz-Otaegui et al. 2016) while at Ahihud faba bean, bitter vetch, narbon vetch, pea, and vetchling were found in pits and domestic contexts (Caracuta et al. 2015, 2017).

Furthermore, seeds of faba bean and lentils were recovered from the domestic building at Neshar Ramla Quarry and Nahal Zippori, dated respectively to the Early PPNB and the PPNB (Caracuta et al. 2015, 2017).

Despite the examples mentioned above, the domestication process and the exploitation dynamics (i.e. processing and consumption manners) of legumes remain poorly understood and are yet a matter of discussion. Nonetheless, they can provide invaluable evidence on plant food technology, the dietary and culinary habits, and the plant knowledge of the first farming communities. Indeed, several species of legumes must be processed before consumption, as they are toxic, as in the case of *Vicia* spp. and *Lathyrus* spp. (Pe a-Chocarro and Zapata Pe a 1999; Valamoti et al. 2021). Along with boiling and charring, the most common techniques adopted to reduce the toxicity of legumes and make them more digestible are grinding, pounding and winnowing (Valamoti et al. 2011, 2021). In this matter, significant clues can be gathered from the tools with which legume remains have been found in association with and that were most likely involved in their processing. In most cases, these correspond to ground stone implements, including grinding slabs, pestles, mortars, and handstones, often found in the same contexts as the seeds. Ground stone tools are indeed considered strictly related to significant socioeconomic changes, specifically concerning the evolution of ancient food practices (Hamon et al. 2021; Hamon 2022).

However, detailed functional studies based on the analysis of use-wear traces on ground stone tools found at early Neolithic contexts are still limited. Recently, the functional analysis of the limestone ground stone implements from the PPNA site of Hasankeyf H y k demonstrated that these tools were used to process a wide range of vegetables, including legumes and cereals (Ishida et al. 2025). Similarly, the use-wear study of the ground stone tools assemblage at G bleki Tepe allowed to stress the importance, during the PPNB at the site, not only of cereals and legumes, but of a wide array of fruits and spices processed following specific gestures and steps (Dietrich and Haibt 2020; Dietrich et al. 2020; Dietrich 2021). A further example comes from the functional study by Dubreuil and Goring-Morris on the ground stone tools from the PPNB sites of Kafar HaHoresh and Beisamun (Dubreuil and Goring-Morris 2021). Here, the analysis of use-wear permitted to reconstruct the tools’ use and demonstrated their involvement in plant food processing activities, which were carried out by employing different grinding systems. In particular, at Kafar HaHoresh, ground stone tools were mainly used to process legumes, performing a one-handed circular or back-and-forth gesture, while conversely at Beisamun, cereals were the most worked plant, processed through a two-handed handstone

and quern grinding system (Dubreuil and Goring-Morris 2021). These examples demonstrate the importance of ground stone tools for understanding ancient plant processing strategies and food preparation habits during the early Neolithic in Southwest Asia.

This paper presents the functional study of ground stone tools from the PPN site of Kharaysin in Jordan. We investigate the use of these tools at the site, applying a novel workflow based on the combination of optical and confocal microscopy (Zupancich et al. 2025). Specifically, we reconstruct the function of ground stone tools in processing plant foods through use-wear and residue analysis, allowing us to accurately determine the gestures and types of worked plants. Integrating these results with 3D surface texture analysis, we achieve further detail in our functional interpretation, defining the worked plant at the proposed species level. We identified diverse use-wear patterns related to the working of legumes and cereals, along with starch granule morphotypes associated with plants from the Fabaceae and Poaceae families. By combining the ensemble of qualitative and quantitative data, we provide a high-resolution perspective on plant foods processing strategies ongoing at the site, demonstrating the significant involvement of ground stone tools in processing legumes, emphasizing the relevance of these latter in the diet and daily life of the first farmers of Kharaysin in the Late PPNA and the Middle and Late PPNB between beginning of the 9th millennium BC and the beginning of the 7th millennium BC.

## The Pre Pottery Neolithic site of Kharaysin

The site of Kharaysin is located across the slope of a natural terraces system in the Zarqa Province, in the vicinity of the Zarqa River, ca. 40 km from Amman (Fig. 1) (Ibáñez et al. 2020, 2024, 2025a). First discovered in 1984 within the framework of the Jerash region survey project carried out by the Hanbury-Tenison team, Kharaysin was described as a Pre Pottery Neolithic B context (Edwards and Thorpe 1986; Ibáñez et al. 2025a). Since 2014, extensive excavations have been carried out by a Spanish team under the direction of J-J Ibáñez and J. Muñiz, revealing the complex stratigraphic sequence of the site and allowing to identify seven areas (A, B, C, D, E, F and G) (Fig. 2a) (Ibáñez et al. 2025a). The first occupation at the site dates to the Late PPNA, while the latest one lasts until the Late PPNB/PPNC covering a timespan going from 9.000 to 6.800 years cal BC (Moník et al. 2018; Ibáñez et al. 2025a). The analysis of the architectural features at Kharaysin allowed for the definition of its evolution and development throughout its different occupation phases (Fig. 2b, c) (Ibáñez et al. 2025a). The site's earliest occupation (Late PPNA) is characterised by

small circular sunken dwellings placed in the natural clay layers and terraces (Ibáñez et al. 2025a).

Semi-subterranean structures with earth-packed or lime-plastered floors are instead associated with the site's Transitional PPNA/B phase. The buildings, while sometimes preserving the rounded corners and bent walls seen in the older structures, are larger (up to 30m<sup>2</sup>), exhibit straight walls and corners and are characterised by domestic features placed in the main rooms (Moník et al. 2018; Ibáñez et al. 2025a). During the Early PPNB, pseudo-rectangular structures are present, adjoining one another. Plastered floors, fireplaces, postholes and burials characterise these latter.

Finally, large square buildings reaching 50m<sup>2</sup> are found in the Middle PPNB occupational levels at Kharaysin. The structures all show lime-plastered floors and were arranged in parallel rows perpendicular to the slope (Ibáñez et al. 2025a).

Changes in material culture are observed across the different occupation phases as well. Unidirectional blades and small arrowheads were found during the Late PPNA, and mixed unidirectional and bidirectional technology and arrowheads with double notches were found in the site's Transitional PPNA/B levels. In contrast, large standardised blades, Jericho and Amuq points, and sickle elements, along with ground stone tools, are typical of the Early and Middle PPNB occupation of Kharaysin (Ibáñez et al. 2018; Borrell et al. 2022). Furthermore, over 80 flint figurines have been unearthed at the site and associated with funerary practices (Ibáñez et al. 2020).

Concerning the faunal assemblage, wild animals, including birds, foxes, gazelles, and bezoars, were hunted during the site's earliest occupation. A shift in animal exploitation strategies is evident during the Early PPNB, where small game decreases. In contrast, a significant increase in the proportion of goats is recorded in the faunal assemblage. Goats become the dominant species during the Middle PPNB at Kharaysin, possibly evidencing their domestication and management, while cattle, gazelles, boars, and small game are present but in lower proportions (Jimenez-Manchon et al. 2023; Jiménez-Manchón et al. 2024).

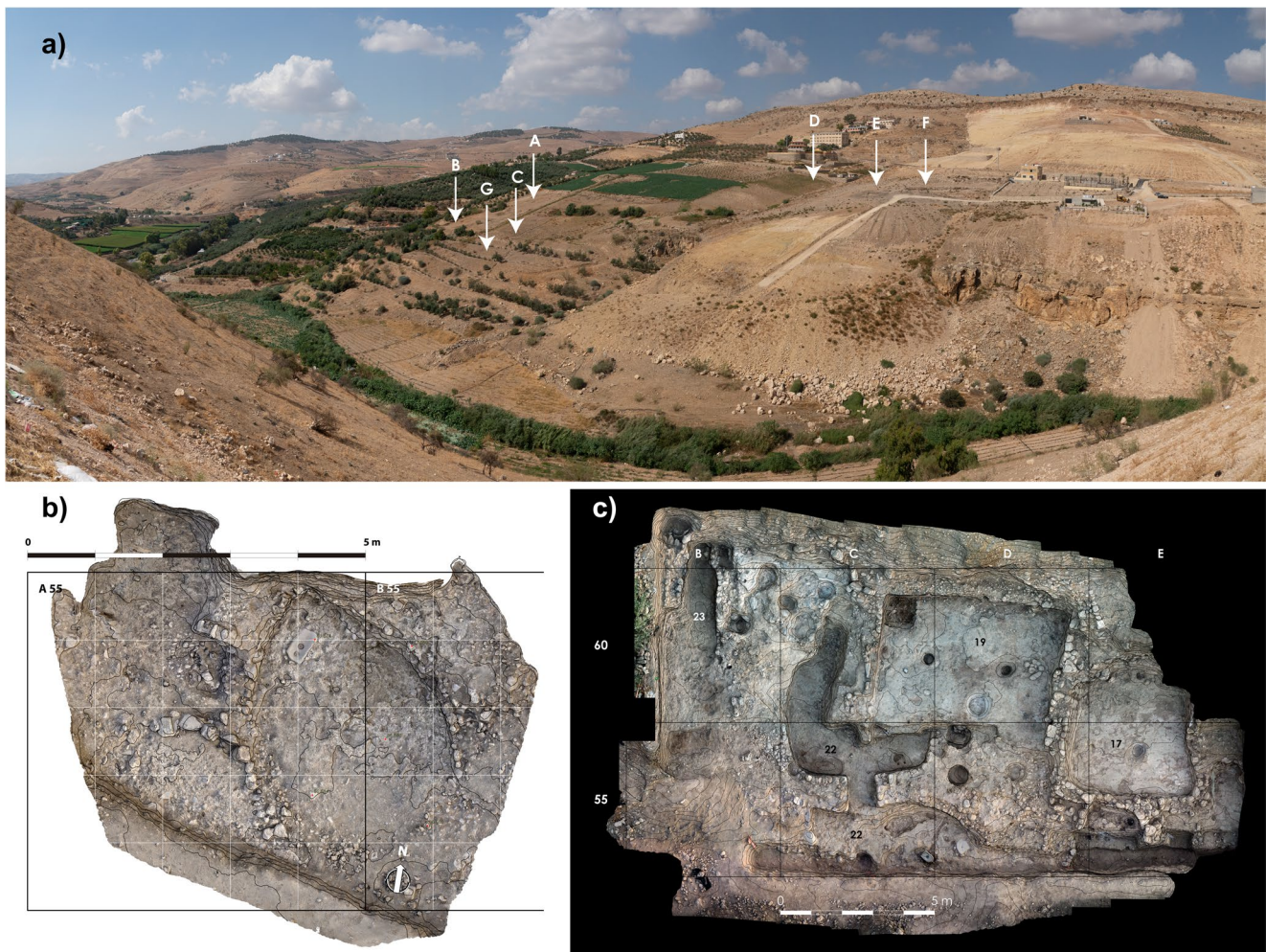
The archaeobotanical record at Kharaysin shows a high diversity in the range of plant taxa, including cereals, and fruits, but legumes are the prevalent plant category at the site (Douché et al. 2025). To date, most of the archaeobotanical evidence comes from the site's Early and Middle PPNB occupational levels. Unfortunately, few botanical remains have been recovered from the earliest, Late PPNA occupation. A comparison between phases shows that fruits and wild taxa dominate the archaeobotanical assemblage of the Late PPNA and the Transitional PPNA/PPNB period. Conversely, during the Early PPNB, the botanical assemblage appears to be dominated by possible crops, specifically



**Fig. 1** Map showing the location of Kharaysin

legumes, whereas cereals appear limited (Fig. 2a). Among legumes, *Vicia narbonensis* (narbon vetch), *V. faba* (faba bean) and *Lens* spp. (lentil) are dominant. *Pisum* spp. (pea), *Lathyrus sativus* (grass pea), *Cicer arietinum* (chickpea), and *Vicia ervilia* (bitter vetch) are also found, but in lower occurrences. Among the few identified cereals, *Triticum monococcum* (einkorn wheat) and *Hordeum vulgare* (barley)

are attested, with the latter being the most represented (Douché et al. 2025). Fig (*Ficus carica*), grape (*Vitis vinifera*), nuts like pistachio and almond (*Pistacia* spp., *Prunus/Amygdalus*), and possible oak (*Quercus*-type) are present among the fruit remains recovered at Kharaysin. Wild plant remains are limited but comprise *Buglossoides tenuiflora* (gromwell), wild grasses, Chenopodiaceae, mallow (*Malva*



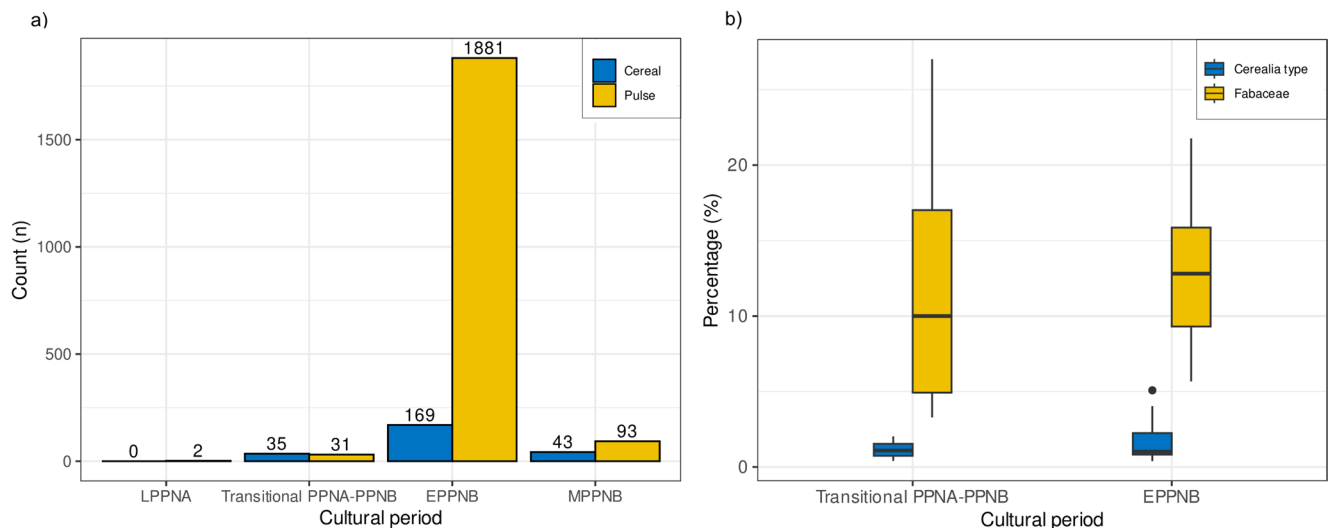
**Fig. 2** (a) Overview of Kharaysin and location of the excavated areas; (b) oval dwelling (Structure 25) dated to the Late PPNA from Area B; (c) squared structures from Area B dated to the Early PPNB

spp.), small legumes (e.g. *Astragalus* sp.), remains of *Panicoidae* and of *Brassicaceae* (Douché et al. 2025).

The pollen data obtained from the Transitional PPNA/B and Early PPNB phases reveals an open vegetation landscape near the archaeological site, with pistachio (*Pistacia*) and Tabor oak (*Quercus ithaburensis*-type) constituting the dominant arboreal elements (Mateos-Cabero et al. 2026). The tree component is completed with regionally distributed Mediterranean woodland taxa, namely Aleppo pine (*Pinus halepensis*), juniper/cypress (*Cupressaceae*), Palestine oak (*Quercus calliprinos*), or wild rose (*Rosa*-type). Buckthorn (*Rhamnus*), white weeping broom (*Retama*-type), and joint pine (*Ephedra fragilis*-type) were identified, probably confined to the nearby karstic outcrops. Given the site's proximity to the Wadi Kharaysin riverbank, the gallery forest likely included riparian elements such as poplar (*Populus*), willow (*Salix*), ash (*Fraxinus angustifolia*-type), tamarisk (*Tamarix*), and oleander (*Nerium oleander*). Regarding the herbaceous layer, steppe taxa are particularly prevalent,

with members of the chicory subfamily (*Cichorioideae*) and seepweeds/seablites (*Suaeda*-type) being the most abundant taxa, followed by grasses (*Poaceae* <35  $\mu$ m), as well as some geophytes, namely alliums (*Allium*-type), or asparagus (*Asparagaceae*). Notably, members of the *Asteraceae* family, particularly thistles (e.g., *Carduus*-type, *Carthamus*-type, *Centaurea nigra*-type, or *C. solstitialis*-type, among others), exhibit considerable taxonomic diversity and are typically associated with open land grazing-resistant vegetation. Nitrophilous and ruderal taxa (e.g., *Heliotropium*, *Papaver*-type, *Malva*-type, *Polygonum*, *Rumex*, and *Urtica*-type) are well-represented in both the Transitional PPNA/B and Early PPNB phases, suggesting the existence of cultivated or disturbed habitats surrounding the site (Mateos-Cabero et al. 2026).

Particularly, *Fabaceae* pollen reaches notable scores in both the Transitional PPNA/B (3.3–27%) and Early PPNB phases (5.7–21.8%) without showing significant variation in the obtained frequencies (Fig. 3b). Clumps of up to ten



**Fig. 3** Composition of the archaeobotanical assemblage of Kharaysin. **(a)** Barplot of the occurrence of carpological remains found at the site across its different phases. **(b)** Boxplot of the percentage of pollen remains identified in the Transitional PPNA/B period and the Early PPNB periods

monospecific grains have been identified, which could be related to systematic plant collection and processing activities from nearby orchards, since monospecific clumps are typically associated with pollen-rich anthers and deliberate handling of floral material (Miras et al. 2018; Eastwood et al. 2018). In the case of Cerealia-type, the obtained pollen frequencies (0.4–2.4% in Transitional PPNA/B vs. 0.4–5.1% in Early PPNB) are notably lower than Fabaceae, although they are continuously reported in both phases (Fig. 3b). Low Cerealia-type values, however, are explained by the large pollen size (>40 µm) and the bad pollen dispersal ability (Fyfe 2006), and therefore, even low but consistent occurrences suggest cereal cultivation in the immediate vicinity of the site.

## Materials and methods

A total of 85 artefacts compose the ground stone tool assemblage associated with the Late PPNA – Transitional PPNA/B and Early PPNB cultural periods of Kharaysin. Among these, 34 tools were selected, including both passive (e.g. ground stones and mortars) as well as active elements (handstones and pestles) made of basalt and limestone (Fig. 4). The selection was based on the state of preservation of the artefacts (i.e. absence of severe post depositional alterations), allowing for their functional study. The tools have been classified following Wright’s typological classification (Wright 1992). The functional study of the tools consisted of the combination of both qualitative (Optical Light Microscopy - OLM) and quantitative techniques (Confocal Microscopy - CM). The tools’ working surface(s) were observed at low and high magnifications under reflected

light optical microscopes to identify surface modifications and micro traces associated with the use of the tools. The qualitative use-wear study was coupled with the quantitative analysis of the used surface(s) performed through confocal light microscopy and 3D surface texture analysis. Furthermore, the functional study included the analysis of preserved plant micro residues (i.e. starch granules, phytoliths and vegetal tissues) extracted from the used surface(s) and observed under a transmitted light microscope.

## Use-wear analysis

A first selection of the tool was performed at the storage facility, where tools exhibiting surface modifications (surface flattening, pitting, abrasion, etc.), potentially associated with use, were selected for further analysis. Tools bearing severe post-depositional modifications such as a high degree of fragmentation, surface concretion and surface spalling were excluded, together with implements not showing any potential use-related modifications. The tools selected for further analysis first underwent residue sampling (see Sect. 3.2). Following the extraction of residues, the tools were washed by hand with deionised water and, once dried, high-resolution silicon casts of the used surfaces were moulded using Provil Novo Light Fast (Pichon et al. 2026; Banks and Kay 2003). Silicon casts were then observed at higher magnification to analyse microwear and 3D surface texture (see Sect. 3.3).

Macroscopic surface modifications consisting of surface flattening, pitting, abrasions and macro striations were observed at the naked eye and low magnifications at the storage facility. Following published protocols, the localisation, distribution and development of use-related



**Fig. 4** Example of ground stone tools from Kharaysin. **(a)** Ground stone with double cuphole made of basalt; **(b)** stone vessel/mortar made of limestone; **(c)** round handstone made of basalt, and **(d)** pestle made of basalt

modification were recorded across the surface. Microwear analysis took place at the IMF-CSIC laboratory in Barcelona (Spain) and the DANTE – Diet and ANcient TEchnology laboratory in Rome (Italy). The analysis was performed using an Olympus BX51 metallographic microscope and a ZEISS AxioScope A1 metallographic microscope under reflected light, at magnification ranging between 200x and 400x. Microwear, including micro polishes, micro striations, and micro abrasion visible on the sampled surface, were described according to published standards and nomenclature (Delgado-Raack and Risch 2008; Adams et al. 2009; Hamon and Plisson 2009; Adams 2014a, b; Cristiani and Zupancich 2021; Delgado-Raack et al. 2022; Dubreuil et al. 2023) along with microwear affecting the crystal grains embedded in the stone matrix. These latter included the micro polish, abrasions and striations of the grains' surfaces and edges (Adams et al. 2009; Hamon and Plisson 2009; Cristiani and Zupancich 2021; Delgado-Raack et al. 2022; Dubreuil et al. 2023). To ensure a strong and reliable interpretation of the traces identified on the archaeological ground stone tools, a comparison was made with the an extensive use-wear reference collection, which included macro and microwear generated by the processing of different plants species (cereal grains, legumes and grass grains) performed using modern ground stone replicas made of limestone and basalt (see Zupancich et al. 2025 and Supplementary Fig. 3). Microphotographs of the identified traces were taken using a ZEISS AxioCam305 colour camera controlled using the ZEISS ZEN Core (v3.8) software.

### Microremain analysis

Each of the analysed tools was sampled primarily for starch granules. At this stage we focused on starch granules only as other plant microremains (i.e. phytoliths) will be analysed in a further step of the study focusing on working areas and environments at the site. Following published standards (Torrence and Barton 2006; Fullagar 2016; Cristiani et al. 2021), several drops of deionised water were placed on the tool's used surface(s) using a micro pipette. Before pipetting out the water, the plastic tip of the micropipette was used to aid the displacement of residual matter from the tool's surface. The water was pipetted and stored in a sterile micro centrifuge tube. Residue analysis was performed at the DANTE Laboratory at Sapienza University of Rome, Italy. Following published standards, plant micro remains, namely starch granules, were extracted from the samples using heavy liquid flotation. Specifically, Sodium Polytungstate (SPT) was used at a specific gravity of 1.8 g/cm<sup>3</sup> (Liu et al. 2014; Santiago-Marrero and Pagán-Jiménez 2023). Once extracted, starch granules were analysed using a ZEISS Imager M2 transmitted light optical microscope equipped with 10x oculars and 20x, 40x and 63x objectives and cross-polarised light. Microphotographs were taken using a ZEISS AxioCam305 color camera controlled using the ZEISS ZEN Core (v3.8). DANTE Laboratory is a facility under strict environmental control and the archaeological extraction and analysis were carried out on specific days, separate from experimental work, and after sanitising all surfaces to avoid modern contamination. Before each analysis,

benches were washed with soap and ethanol, covered with film, and starch-free nitrile gloves were worn at all times. Moreover, control samples from cleaned benches and dust traps were collected to monitor lab contamination. This protocol is routinely applied at the DANTE Laboratory, even when no archaeological analyses are performed, to track seasonal variation in contamination. In the specific case, no debris comparable to archaeological remains was observed in the controls, and only a few non-diagnostic starch granules were found in laboratory dust. The interpretation of the identified starch granules was aided by the extensive reference collection housed at the laboratory, which comprises samples of plant species from the study area.

Starch identification was carried out following established morphometric and typological criteria (Torrence and Barton 2006; Yang and Perry 2013; Gismondi et al. 2019; Chakraborty et al. 2020; Cristiani et al. 2021; Louderback et al. 2022). Diagnostic traits considered included grain size, overall shape, hilum position and fissure type, presence of lamellae, surface facets, and extinction cross morphology. For consistency and comparability, we also relied on the work of Ahituv and Henry (2022), which proved particularly useful in establishing a common descriptive vocabulary. A reference collection of more than 300 plant species from the Mediterranean, including the Levant, was used for the identification of archaeological starch granules (Supplementary Fig. 4 and Supplementary Table 8).

### 3D surface texture analysis

Following the OLM analysis, a sample of the studied ground stone tools was selected for confocal microscopy and 3D surface texture analyses. The selection criteria are based on the degree of development and preservation of the micropolish observed at high magnifications across the tool's used area(s). Thus, tools exhibiting used surface areas allowing for sampling a minimum of two  $100 \times 100 \mu\text{m}$  polished sub-areas from a  $562.9 \times 562.9 \mu\text{m}$  area were selected.

3D images of the used areas were taken using a ZEISS Smartproof 5 confocal light microscope equipped with a 20X objective (C-Epiplan Aplanachromat) with a 0.7 NA and a working distance of 1.3 mm. 3D images were acquired in fast mode using ZEN Core (v.3.8). The number of 3D pictures for each tool varied from a minimum of 4 to a maximum of 10. The acquired images were processed using the metrological software MountainsMap (v.9) from Digital Surf. From each 3D image ( $562.9 \times 562.9 \mu\text{m}$ ),  $100 \times 100 \mu\text{m}$  sub-areas of micro polish were extracted. Each sub-area was processed as follows: *i*) extraction of the topographic layer; *ii*) image mirroring in z; *iii*) image levelling (L-S plane); *iv*) use of a metrological S-filter (cut-off  $2 \mu\text{m}$ ); *v*) removal of the form

(polynomial degree of 10); *vi*) Spatial filter (arithmetic mean  $9 \times 9 \mu\text{m}$ ); *vii*) surface was thresholded (0.05% – 99.5%) and finally *viii*) non-measured points were filled. Once processed, for each 3D image, ISO 25178 surface parameters were extracted and texture direction, furrow analysis and scale-sensitive fractal analyses were performed. Following published workflows applied to knapped stone tools (Ibáñez and Mazzucco 2021; Ibáñez et al. 2025b; Pichon et al. 2025a; 2025b) and ground stone tools (Zupancich et al. 2025), quadratic discriminant analysis (QDA) based on Bayes' theorem is applied to classify the archaeological tools. The QDA models used to classify the tools from Kharysin are built by selecting 3D surface parameters adopting a stepwise classification based on Wilks  $\lambda$  (Supplementary Tables 1 and 2). The accuracy of the models has been tested experimentally to classify 3D surfaces from basalt and limestone ground stone replicas used to process legumes and cereals (Supplementary Tables 1–6). To ensure a reliable classification of the archaeological specimens, when assigning the group, both the maximum posterior probability and the margin are considered from the model output. The maximum probability informs us of the degree of confidence of the model in its group prediction, while the margin refers to the difference between the first two probabilities selected by the model. Therefore, a threshold of  $>70\%$  on the maximum posterior probability (Ibáñez-Estévez et al. 2021) and  $>30\%$  on the margin is set to assign a tool to a specific worked plant. When the above condition is not met, the tool is considered unclassified. 3D surface data was processed using R (v. 4.4.3). The raw data and code are available in ZENODO (<https://doi.org/10.5281/zenodo.17632498>).

## Results

Among the analysed ground stone tools, 23 specimens exhibit diagnostic traces of use (Table 1), namely artefacts with well-developed macro- and micro-wear showing clear morphological features that allow their description and interpretation (Table 1). Conversely, 11 tools within the analysed assemblage are characterised by macro- and micro-wear, lacking well-developed morphological characteristics, and are therefore not diagnostic.

Most of the tools are made of basalt (n. 17) while six specimens are made of limestone. Concerning the typology of the artefacts, the analysed assemblage is dominated by active tools, namely pestles and handstones. Passive tools are less in number and include ground stones, mortar/stone vessels and a specific type of grinding slab with single or double cupholes (Fig. 4a). Within each artefact type, the range of morphologies varies.

**Table 1** Tools showing diagnostic use-wear traces. OLM=optical light microscope; CM=confocal microscope; - = unclassified

Tool id	Area	Tool type	Raw material	State	Gesture	Functional interpretation - OLM	Functional interpretation - OLM and CM
74293	A	Ground stone	Limestone	Preserved	Longitudinal	Grinding legumes	Grinding pea
74292	A	Stone vessel	Limestone	Fragmented	Perpendicular	Pounding plant material	-
72502	A	Pestle	Basalt	Preserved	Perpendicular and circular motions	Grinding and light pounding of legumes	Grinding and light pounding of faba bean
74296	A	Handstone	Basalt	Preserved	Longitudinal	Grinding cereal grains	Grinding barley
55	A	Grinding slab with double cupholes	Basalt	Preserved	Perpendicular and short longitudinal	Pounding and grinding legumes	Pounding and grinding lentil
75107	A/B	Pestle	Basalt	Preserved	Perpendicular	Pounding vegetal material (probably legumes)	-
75111	A/B	Pestle	Basalt	Preserved	Short longitudinal	Punctual grinding of vegetal material	-
75110	A/B	Handstone	Basalt	Preserved	Longitudinal bidirectional	Grinding legumes	-
75351	A/B	Handstone	Limestone	Preserved	Longitudinal bidirectional	Grinding legumes	Grinding pea
75349	A/B	Handstone	Limestone	Preserved	Longitudinal	Grinding vegetal material (probably grains)	-
75113	A/B	Handstone	Limestone	Preserved	Longitudinal	Grinding grains	Grinding einkorn wheat
65	B	Grinding slab with double cupholes	Basalt	Preserved	Perpendicular and circular	Pounding and grinding legumes	Pounding and grinding chickpea
70765	B	Pestle	Basalt	Preserved	Perpendicular and circular	Pounding and light grinding grains	Pounding and light grinding barley
56410	B	Handstone	Basalt	Preserved	Longitudinal	Grinding vegetal material	-
55	B	Ground stone	Basalt	Fractured	Longitudinal	Grinding grains	Grinding barley
70596	B	Handstone	Basalt	Preserved	Longitudinal	Grinding legumes	Grinding chickpea
921	C	Handstone	Basalt	Preserved	Longitudinal	Grinding legumes	Grinding grass pea
905	C	Ground stone	Basalt	Preserved	Longitudinal	Grinding legumes	Grinding faba bean
46864	D	Handstone	Basalt	Preserved	Longitudinal	Grinding vegetal material	-
61508	D	Pestle	Basalt	Preserved	Perpendicular and short longitudinal	Pounding and grinding legumes	Pounding and grinding grass pea
55	D	Grinding slab with double cupholes	Limestone	Preserved	<b>Cupholes:</b> Perpendicular and circular; <b>Flat area:</b> Longitudinal	Pounding and grinding vegetal material	<b>Cupholes:</b> Pounding oat; <b>Flat area:</b> Grinding faba bean
31810	I	Stone vessel	Limestone	Preserved	Perpendicular	Pounding grains	Pounding goat grass
46775	I	Pestle	Basalt	Preserved	Perpendicular and circular	Pounding legumes	-
2310	FCTX	Grinding slab with a single cuphole	Basalt	Preserved	Perpendicular and circular	Pounding legumes	Pounding grass pea

**Grinding tools** The morphologies of the passive elements identified among the studied assemblage from Kharaysin span from medium-sized rectangular or round shapes, characterised by flat or slightly concave working surfaces. A further type of grinding tool is represented by medium-large grinding slabs, rectangular or circular, with a flat working surface and single or double cupholes (Fig. 4a).

**Mortars/Stone vessels** Few (n 3) stone vessels are part of the analysed assemblage. Following Wright's (1992) classification, these can be described as round or slightly

elongated globular bowls with convex walls and rounded bases (Fig. 4b).

**Handstones and pestles** At least four types of handstones have been identified within the analysed assemblage. Following Wright's (1992) classification, these latter range from bifacial discoidal, bifacial lens, bifacial ovate and unifacial loaf (Fig. 4c, d). The working surfaces of the studied handstones are usually either flat or flat and convex (Wright 1992). The typologies of pestles instead range from unipolar cylindrical and unipolar conical ones

(Fig. 3d). In these cases, the working surfaces are flat or rounded (Wright 1992).

### Use-wear analysis

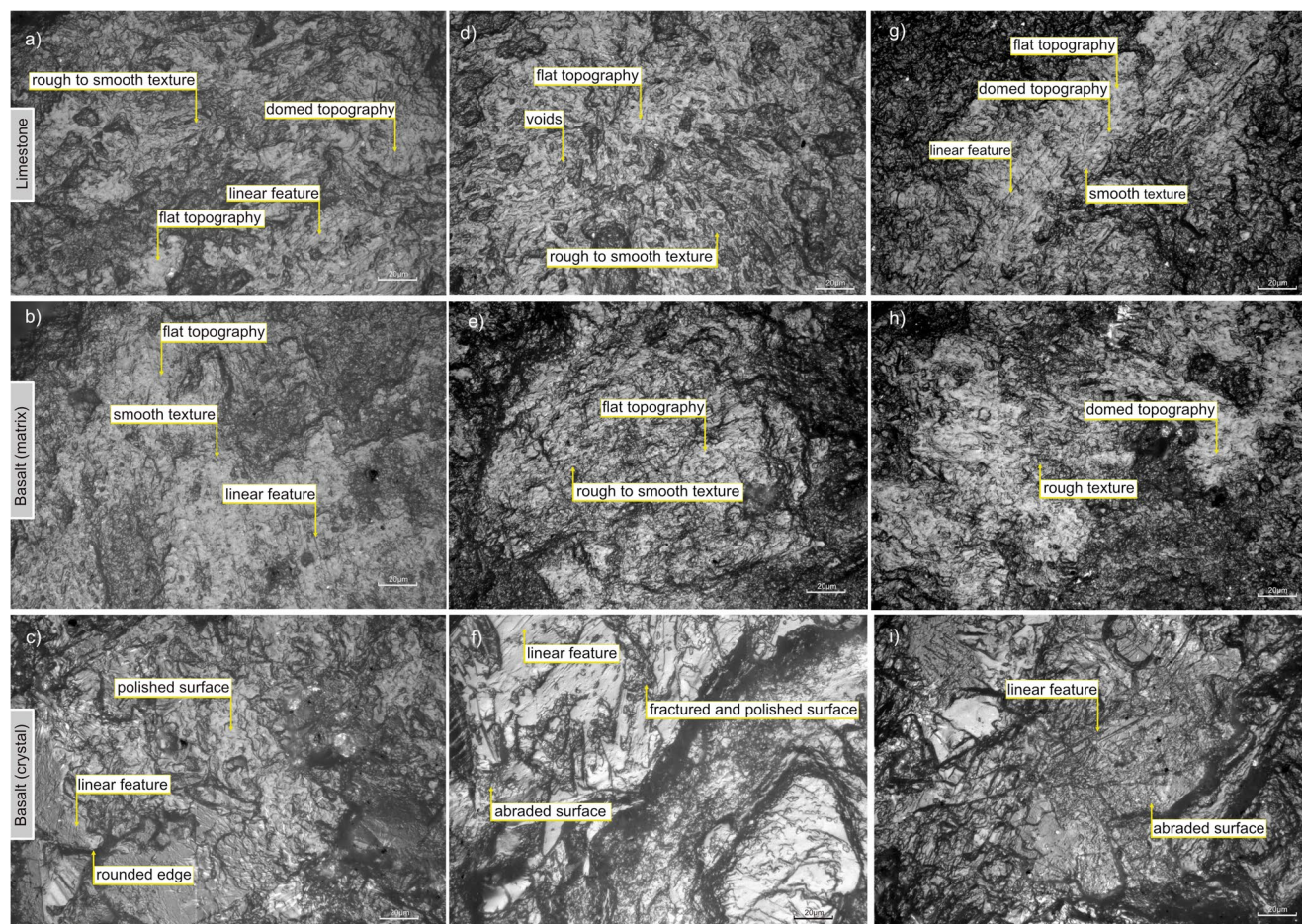
Through the analysis of the tools under low and high magnifications, three main surface modification patterns have been identified, one associated with both the processing of legumes and grains, one related nearly exclusively to the processing of legumes and third associated mostly to the processing of grains (Figs. 5 and 9). At low magnifications, a first pattern consists of flattened (i.e. plateau) areas identified across the working surface of the tool and ranging in size from medium ( $\leq 20$  mm across) to large ( $> 50$  mm across). These areas, occurring isolated or connected between each other, correspond to part of the surface showing an overall homogenous, mostly flat topography. These areas are characterised by a levelled and highly homogeneous macro topography on tools made of limestone, whereas on tools made of basalt, these areas exhibit a

slightly lower homogeneity. Specifically, the macro topography is more undulate and crystal grains are contiguous and amalgamate. Also, sporadic voids due to crystal grain detachment are observed. The crystal grains show levelled surfaces and highly rounded edges. Vacuoles appear shallow and have heavily rounded edges when present across the used surfaces.

When observed under high magnifications, medium to large ( $> 100$   $\mu\text{m}$  across) polished areas are observed across the used surface on both limestone and basalt tools (Fig. 5a-c).

Limestone: Micro polish shows a clear longitudinal orientation, the distribution of the polish is loose, and its density is connected. The micro polish affects the micro surface's high and low topographic heights. Micro polish texture is smooth while its topography is domed with occasional flat areas. Linear features are not observed.

Basalt: Micro polish exhibits a longitudinal orientation, and its distribution and density are covered closed. The micro polish develops on low and high topographies; its



**Fig. 5** Use-wear patterns identified on the ground stone tools from Kharaysin. **a-c)** Pattern associated with pounding grinding legumes and grains; **d-f)** pattern associated with pounding legumes; **g-i)** pattern associated with the grinding of grains

texture and topography are smooth and domed. Occasional short and shallow linear features with polished bottoms are observed. Crystals are affected by surface polishing associated with a heavy rounding of the edges and the presence of linear features with matte bottom.

Through the comparison with the available experimental use-wear reference collection, it is possible to associate the observed use-wear pattern with the processing of legumes and grains worked through a combination of perpendicular and short longitudinal gestures referred to an initial pounding followed by grinding.

The second observed pattern consists of a diffused pitting of the working surface, often associated with small (<5 mm across) scattered levelled areas. On tools made of limestone, the pits are irregular in shape and are often associated with surface crushing. On tools made of basalt, these areas are characterised by a heterogeneous macro topography. Pits are irregular, elongate in shape, and crystal grains are distinct and exhibit a moderate to heavy abrasion and fracturing of their surfaces, which sometimes appear completely crushed. Under high magnifications, medium (= < 100 µm across) polished areas are identified (Fig. 5d-f).

Limestone: Micro polish does not show a clear orientation, its density and distribution range from loose separated to loose connected, and it develops over the micro surface's high and low topographic heights. Micro polish texture is generally rough, tending to smooth, with occasional smoother areas. At the same time, the topography is domed overall with voids (i.e., micro surface areas not affected by polishing). Linear features are rarely observed.

Basalt: Micro polish exhibits an undefined orientation, as in limestone, its density and distribution across the matrix range from loose separated to loose connected. Both the high and low topographic heights are affected by polishing. Micro polish texture is rough tending to smooth, while its topography is domed and flat. Crystal grains appear highly modified. The crystal surfaces are fractured, abraded and lightly polished while their edges are fractured. Linear features with a matte bottom are observed on the crystals' surfaces.

These surface modification and microwear patterns have been observed experimentally on tool replicas used to work legumes, where a combination of perpendicular and circular movements is employed and resulted highly efficient to first pulverise and then finely grind the seeds.

A third pattern has been observed in a few of the analysed tools and consists of medium to large levelled areas (> 100 µm across) visible at low magnifications. On tools made of limestone, these areas show a significant flattening of the surfaces, resulting in a highly homogeneous

topography. On basalt tools, these areas are characterised by levelled and amalgamate crystal grains. At high magnifications, large, polished areas are identified across the used surface (Fig. 5g-i).

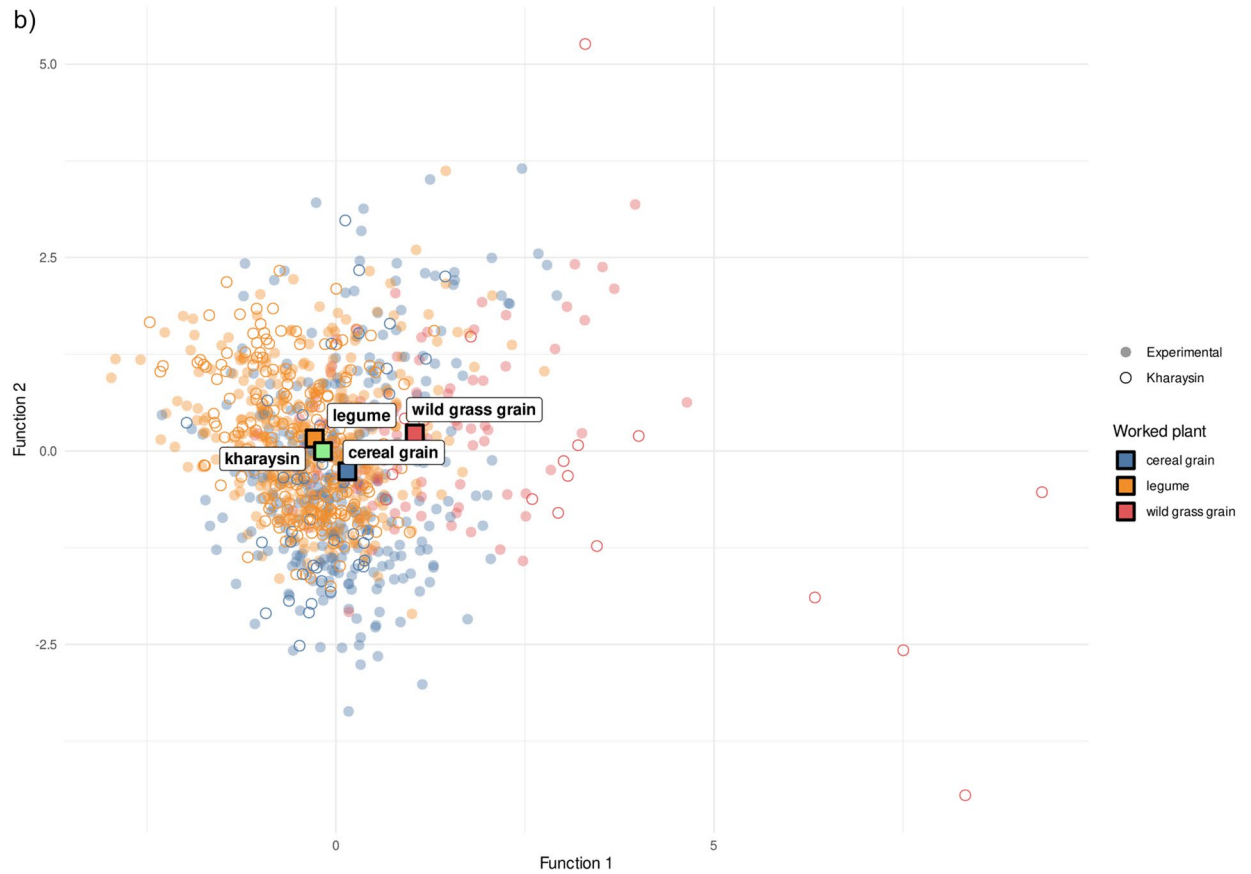
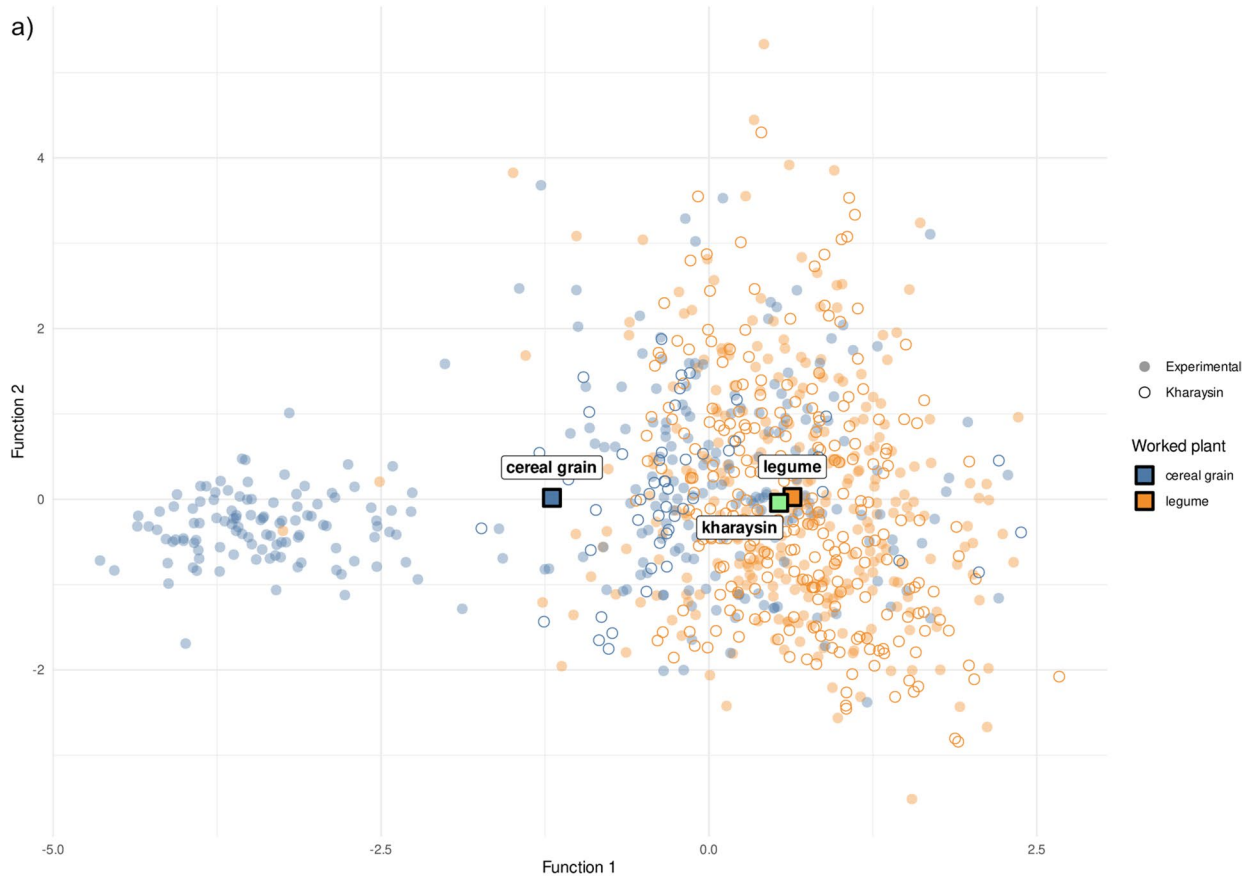
Limestone: On limestone tools, the micro polish exhibits a loose distribution and a connected density, mainly affecting the high topographic heights with a limited incidence on the lower ones. Micro polish texture is smooth, and its topography is domed with flatter areas. Furthermore, short and shallow unidirectional striations with a matte bottom are visible across the polished surface.

Basalt: Micro polish developing across the matrix resembles the same density, distribution and incidence observed in limestone. The difference lies in the texture, which results in a transition from rough to smooth and in the absence of linear features. Micro polish topography is domed. Crystal grain surfaces are heavily abraded and polished. Large and deep linear striations are also visible on the crystals' surfaces. The edges of the grains show moderate to light rounding and abrasion.

Throughout the experiments, these use-wear patterns were observed on limestone and basalt ground stone tool replicas used to process grains (e.g. barley and oat) through longitudinal gestures.

### 3D Surface texture analysis

Of the 23 tools bearing diagnostic use-wear, 18 showed well-developed micro polishes and were selected to be analysed through confocal microscopy and 3D surface texture analysis. Based on the multi-level approach developed in our previous experimental work (Zupancich et al. 2025), the observed micro polishes were first classified between cereal grains, wild grass grains and legumes (Fig. 6; Table 2). Here, on 11 out of 18 implements, the 3D surfaces were classified as micro polishes generated by legume processing, whereas on five artefacts, the 3D surfaces have been classified as cereals (Table 2). Interestingly, on one of the analysed grinding slabs with cup-holes, two different micro polishes were identified and classified as originating from cereal processing inside the cuphole, while the one located across the flat surface was associated to legume working. The confidence threshold was not reached for three artefacts among the analysed ground stone tools; thus, the tool was defined as unclassified (Table 2). As a further step of analysis, the tools were classified by processed plant species. Concerning legumes, surfaces were classified as micro polishes associated with the working of grass pea ( $n=3/27.27\%$ ), faba bean ( $n=3/27.27\%$ ), chickpea ( $n=2/18.18\%$ ), pea ( $n=2/18.18\%$ ), and lentil ( $n=1/9.09\%$ ) (Table 3).



**Fig. 6** QDA classification of the 3D surfaces between cereals and legumes. **(a)** Basalt ground stone tools; **(b)** limestone ground stone tools. The squares refer to the centroid of each group. Filled points refer to the 3D surfaces of the archaeological samples, while the empty circles refer to the 3D surfaces of the experimental replicas

Among the tools grouped as being involved in the working of cereal grains, the 3D surfaces of the micro polishes identified were classified as related to barley processing ( $n=3$ , 60%), einkorn wheat ( $n=1$ , 20%), and oat ( $n=1$ , 20%) (Table 3). Finally, the micro polishes identified on one limestone stone vessel/mortar (I-31810) were classified as originating from the processing of goat grass (Table 3).

From confocal microscopy and 3D surface texture analysis, it is found that most of the micro-polishes are classified as generated from processing several species of legumes. These results are well in accordance with the functional interpretation based on the qualitative analysis of use-wear and plant micro remains (see below), which they corroborate by reinforcing the view on the significant role of legumes, especially grass pea and faba bean, and their processing at Kharaysin.

### Plant microremain analysis

The tools bearing diagnostic use-wear were sampled for residue analysis and comprised different passive and active elements. Starch granules and plant micro residue have been

identified on 12 tools and include five morphotypes (Table 4). Microremains identified on tools not bearing diagnostic use-related traces are reported in Supplementary Table 9. Within the observed morphotypes, 67.7% of the identified granules are associated with plant species of the Fabaceae family, 32.2% with plants of the Poaceae family, including members of the Triticeae and Paniceae tribes (see Supplementary Fig. 4).

Morphotype 1 ( $n=30$ ) (Fig. 7a).

Ellipsoid granule, with a single distribution, characterised by a mesial longitudinal cleft fissure (MLCF). The fissure obscures the hilum, and lamellae are visible. The extinction cross has four short arms bearing the same length and spreading towards the apices of the granule and exhibits a “chi” shape. Granule size ranges between 25 and 40  $\mu\text{m}$ . One of the main morphological characteristic of this morphotype is the MLCF running across its surface. MLCF is typical of starch granules of plants from the Ciceraceae and Fabaceae tribes within the Fabaceae family, including *Cicer* spp., *Lens* spp., *Lathyrus* spp., *Pisum* spp. and *Vicia* spp. (Ahituv and Henry 2022) (Supplementary Fig. 4 and Supplementary Table 8).

Morphotype 2 ( $n=9$ ) (Fig. 7b).

Reniform granule with visible thick lamellae on the outer portion of the surface. A plateau is visible at the centre of the granule, where also surface wrinkles are observed. The hilum is slightly eccentric, however, mostly obscured by the surface depression, while the extinction cross has four arms

**Table 2** Results of 3D surface texture analysis. Grouping of the sampled 3D surfaces between legumes and cereals

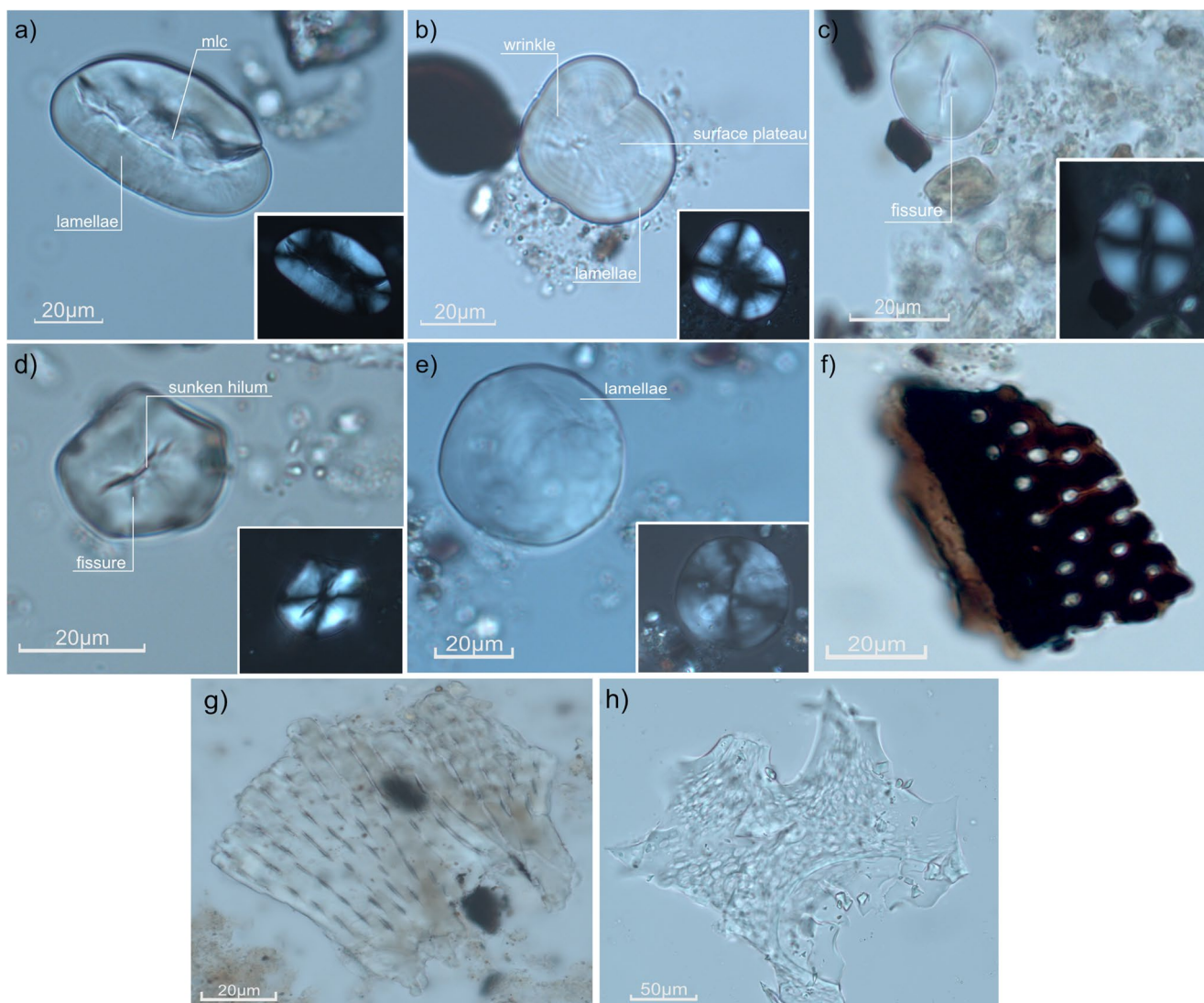
Tool ID	Area	Tool type	Analysed 3D surfaces (n)	Average Maximum Probability (%)	Average Margin (%)	Classification
<i>Basalt ground stone tools</i>						
2310	FCTX	Ground stone with a single cuphole	20	84.65	69.30	legume
55	A	Ground stone with double cuphole	24	80.21	60.42	legume
72502	A	Pestle	9	82.02	64.04	legume
74296	A	Handstone	38	81.83	63.66	cereal grain
75110	A/B	Handstone	28	67.96	35.93	unclassified
55	B	Ground stone	7	71.06	42.12	cereal grain
70596	B	Handstone	20	82.57	65.13	legume
70765	B	Pestle	10	73.56	47.12	cereal grain
65-Cuphole	B	Ground stone with double cuphole	24	79.58	59.16	legume
65-Flat surface	B	Ground stone with double cuphole	29	68.78	37.56	unclassified
905	C	Ground stone	14	73.54	47.09	legume
921	C	Handstone	50	84.78	69.56	legume
61508	D	Pestle	15	88.33	76.65	legume
46775	I	Pestle	10	69.02	38.04	unclassified
<i>Limestone ground stone tools</i>						
74293	A	Ground stone	21	80.96	68.67	legume
75113	A	Handstone	97	78.13	60.46	cereal grain
75351	A/B	Handstone	31	89.38	80.70	legume
55-Cuphole	D	Ground stone with double cuphole	53	93.34	86.71	cereal grain
55-Flat surface	D	Ground stone with double cuphole	50	92.42	85.16	legume
31810	I	Stone vessel	25	89.45	79.97	wild grass grain

**Table 3** Results of 3D surface texture analysis. Detailed classification of the 3D surfaces among plant species

Tool ID	Area	Tool type	Analysed 3D surfaces (n)	Average Maximum Probability (%)	Average Margin(%)	Classification
<i>Basalt ground stone tools</i>						
2310	FCTX	Ground stone with a single cuphole	20	92.58	86.71	grass pea
55	A	Ground stone with double cuphole	24	98.65	97.49	lentil
72502	A	Pestle	9	72.4	51.95	faba bean
74296	A	Handstone	38	88.72	77.45	barley
55	B	Ground stone	7	94.2	88.41	barley
70596	B	Handstone	20	91.94	84.04	chickpea
70765	B	Pestle	10	93.77	87.55	barley
65-Cuphole	B	Ground stone with double cuphole	24	91	84.5	chickpea
905	C	Ground stone	14	87.62	77.06	faba bean
921	C	Handstone	50	87.02	76.49	grass pea
61508	D	Pestle	15	99.2	98.46	grass pea
<i>Limestone ground stone tools</i>						
74293	A	Ground stone	21	65.74	44.1	pea
75113	A	Handstone	97	90.45	83.29	einkorn wheat
75351	A/B	Handstone	31	60.37	30.62	pea
55-Cuphole	D	Ground stone with double cuphole	53	97.19	94.43	oat
55-Flat surface	D	Ground stone with double cuphole	50	71.85	53.81	faba bean
31810	I	Stone vessel	25	89.45	79.97	goat grass

**Table 4** Ground stone tools from Kharaysin where diagnostic use-wear and plant micro residue have been identified

Tool id	Area	Tool type	Micro residues	Functional interpretation
65	B	Grinding slab with double cupholes	<b>Heavily damaged starch granules</b>	Pounding and grinding chickpea
55	D	Grinding slab with double cupholes	<b>Starch granule:</b> Fabaceae (morphotypes 1 and 2); Poaceae - Triticeae tribe (morphotype 5)	Pounding and grinding pea
905	C	Ground stone	<b>Starch granule:</b> Fabaceae (morphotypes 1 and 3); Poaceae - Triticeae tribe (morphotypes 5); Poaceae - Paniceae tribe (morphotype 4); <b>Amorphous vegetal tissues; Vegetal fibres</b>	Grinding faba bean
74296	A	Handstone	<b>Starch granule:</b> Fabaceae (morphotypes 1 and 2); <b>Carbonised wood; Amorphous vegetal tissues</b>	Grinding barley
75351	A/B	Handstone	<b>Vegetal tissues:</b> parenchyma	Grinding pea
75349	A/B	Handstone	<b>Starch granule:</b> Poaceae - Triticeae tribe (morphotype 5); <b>Amorphous vegetal tissue; Heavily damaged starch granules</b>	Grinding vegetal material (probably grains)
921	C	Handstone	<b>Starch granule:</b> Fabaceae (morphotypes 1 and 3); Poaceae - Triticeae tribe (morphotype 5); Poaceae - Paniceae tribe (morphotype 4); <b>Amorphous vegetal tissue; Vegetal fibres; Wood tracheids</b>	Grinding grass pea
72502	A	Pestle	<b>Starch granule:</b> Fabaceae (morphotypes 1 and 2)	Grinding and light pounding of faba bean
75107	A/B	Pestle	<b>Starch granule:</b> Fabaceae (morphotype 3)	Pounding vegetal material (probably legumes)
61508	D	Pestle	<b>Starch granule:</b> Fabaceae (morphotype 1 and 3); Poaceae - Triticeae tribe (morphotype 5)	Pounding and grinding grass pea
46775	I	Pestle	<b>Starch granule:</b> Fabaceae (morphotype 2)	Pounding legumes
31810	I	Stone vessel	<b>Starch granule:</b> Poaceae - Triticeae tribe (morphotype 5)	Pounding goat grass



**Fig. 7** Plant micro residues identified on the surfaces of the ground stone from Kharaysin. **a-e)** Starch granules. **f-h)** Wood and plant tissue. All pictures are taken at 630x

of the same length spreading towards the border of the granule. Granule size ranges between 45 and 35  $\mu\text{m}$ . In our reference collection the central surface plateau along with thick lamellae localised on the outer portion of the granule are commonly observed in *Lathyrus* spp., *Vicia* spp. and *Cicer* spp. (see Supplementary Fig. 4 Supplementary Table 8).

Morphotype 3 (n 26) (Fig. 7c).

Spherical granule with a faint MLCF at its centre. The fissure shape is longitudinal and limited to the central area of the granule. The hilum is centric. Lamellae are not visible. The extinction cross has four straight arms of the same length. Granule size ranges between 25 and 30  $\mu\text{m}$ . Morphological characteristics of this morphotype, specifically a faint MLCF and invisible lamellae are observed in plant members of the Fabaceae family, such as *Cicer* spp., *Lens* spp., *Lathyrus* spp. and *Pisum* spp. (Ahituv and Henry

2022). In the case of *Lens* spp. and *Cicer* spp. this type of granule is present along the larger oval ones (Supplementary Fig. 4 and Supplementary Table 8).

Morphotype 4 (n 17) (Fig. 7d).

Polygonal granule with an open or sunken hilum form, showing minute longitudinal fissures radiating from the centre. Lamellae are not visible, and the surface is smooth. The hilum is centric, and the extinction cross exhibits four arms of the same length, with one displaying a slight bend. The size of the granules ranges from 20 to 30  $\mu\text{m}$ . The morphometric characteristics observed in this morphotype are commonly associated with members of the Poaceae family, particularly with species belonging to the Paniceae tribe, such as *Setaria* spp. (Supplementary Fig. 4 and Supplementary Table 8).

Morphotype 5 (n 14) (Fig. 7e).

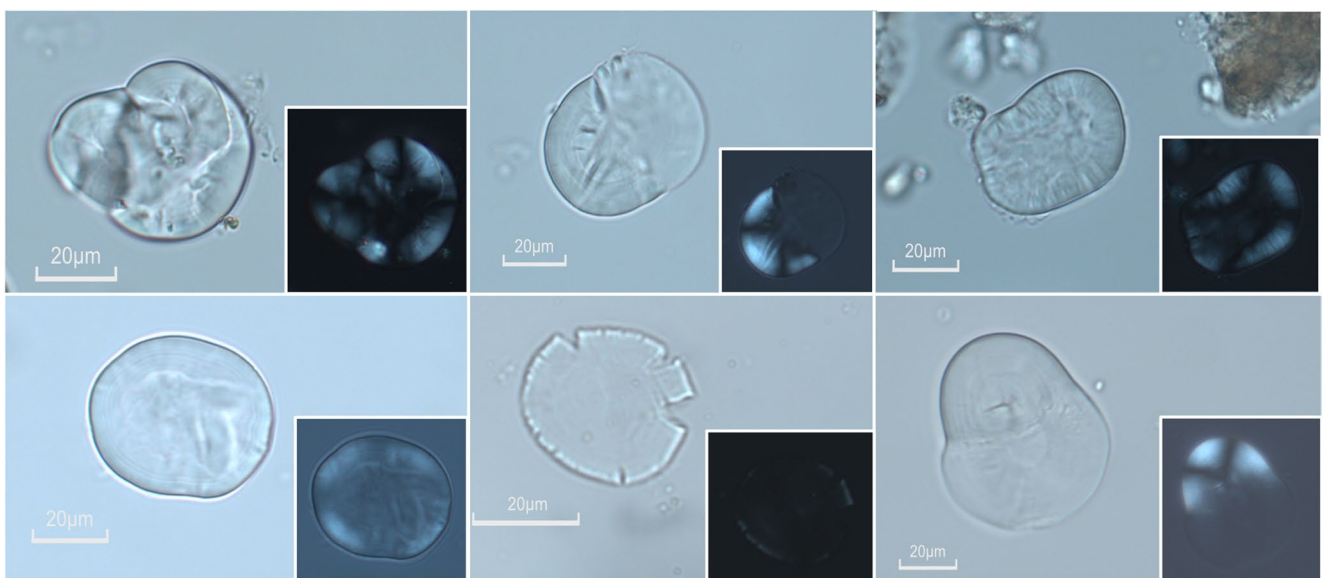
Spherical to sub-spherical granule with thick and clearly visible lamellae across the surface. The hilum is centric and shows a slight depression. The extinction cross displays four straight arms of equal length radiating towards the apices of the granule. Granule size ranges between 35 and 50  $\mu\text{m}$  and the surface may occasionally appear cratered (6e). Starch granules are usually single but have also been observed in bimodal distributions. This morphotype exhibits morphometric features commonly associated with plant members of the Poaceae family, particularly of species of the tribe Triticeae, such as *Triticum* spp. or *Hordeum* spp. (Ahituv and Henry 2022) (Supplementary Fig. 4 and Supplementary Table 8).

The analysis of starch granules from plant members of the Fabaceae family in our experimental reference collection, together with published data (e.g. Ahituv and Henry 2022; Henry 2020; Cristiani et al. 2021) demonstrates a significant variability of morphotypes within the same plant species, as well as overlaps in shape and size, which pose challenges for species-level identification of the specimens observed on the ground stone tools of Kharaysin. An example is provided by starch granules of *Lens* spp. and *Cicer* spp. which can appear as large ellipsoid with a clear MLCF (morphotype 1), or as small, spherical granules with narrow MLCF (morphotype 3). The same applies to morphotype 2, which shows characteristics (e.g. reniform shape and visible lamellae) commonly observed in several species of the Fabaceae family, such as *Lathyrus* spp. and *Vicia* spp. However, despite the recurrence of these morphological features, several specific traits allow us to narrow the interpretation to particular legume species. For instance, the significant thickness of the MLCF

observed in morphotype 1 granules, together with the presence of continuous lamellae in the granule, allows this morphotype to be associated with distinct species of *Lens*, *Lathyrus*, *Pisum*, and *Vicia* (Ahituv and Henry 2022) (Supplementary Fig. 4).

Many of the identified starch granules exhibit damage patterns possibly related to mechanical stress caused by plant processing (Babot 2003; Henry et al. 2009; Ma et al. 2019; García-Granero 2020). Among the types of damage observed, the most common are swelling, edge fracturing, and surface fissuring, often associated with the partial or complete loss of birefringence (Fig. 8). Finally, together with starch granules, plant tissues were often recovered from the used surfaces of the ground stone tools (Fig. 7f-g), including carbonised wood fragments (Fig. 7f) and various plant tissues (e.g. parenchyma) (Fig. 7g).

In most cases, the identified microresidues confirm the functional interpretation derived from the use-wear observed on the tools' working surface. However, in some instances, multiple starch morphotypes were identified on the same tool (Table 4). For example, the starch morphotypes found on pestles consistently correspond to plant species of the Fabaceae family, suggesting their specific use in legume processing. Conversely, morphotypes associated with cereal and legume species were identified on different types of ground stone tools at Kharaysin, including the grinding slabs with mortars, ground stones, stone vessels and handstones. This evidence further refines our understanding of the use of these tools at Kharaysin, highlighting their long and complex life-histories, which likely included multiple stages of use on different types of plant foods.



**Fig. 8** Damage patterns associated with processing observed on the starch granules retrieved from the ground stones of Kharaysin

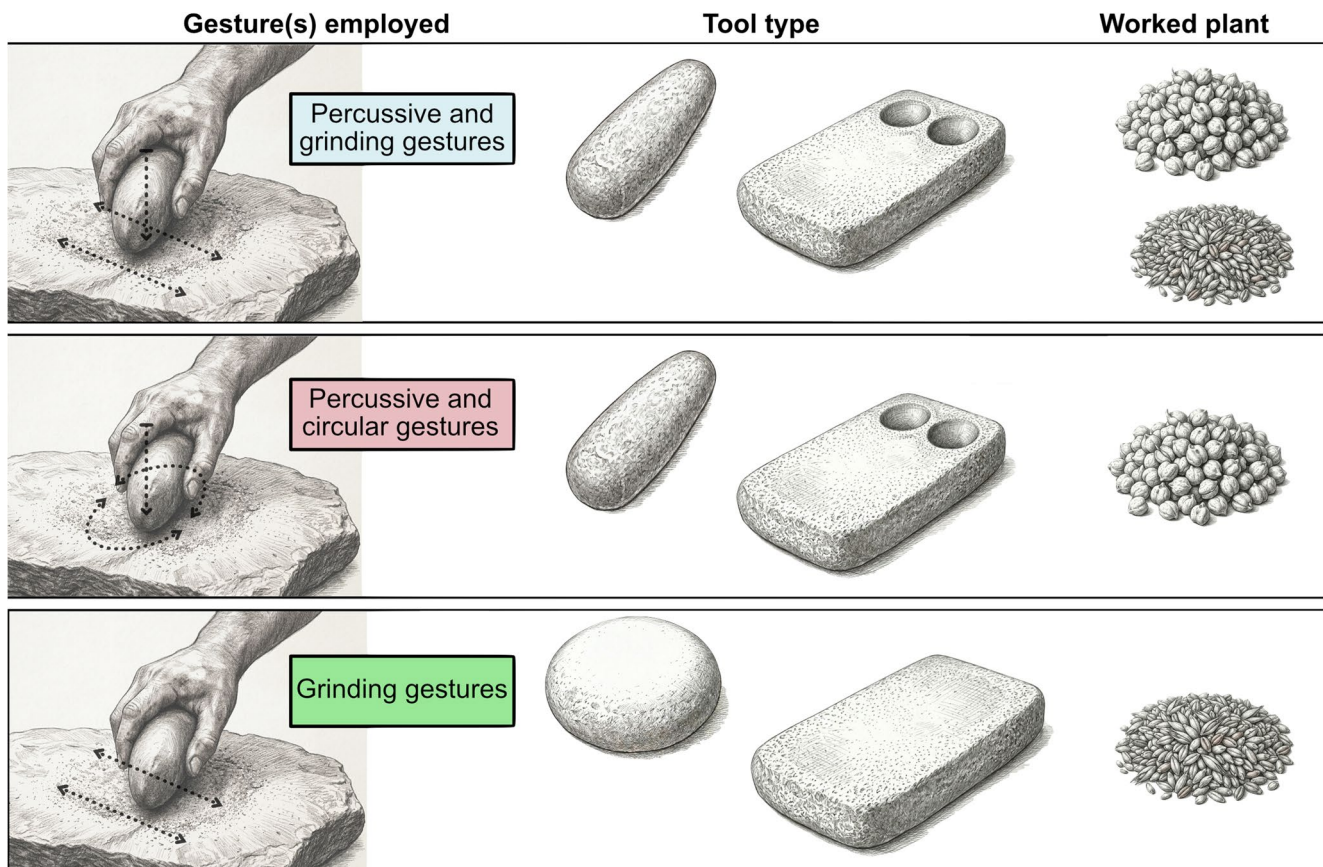
## Discussion

The domestication and exploitation of plants, including legumes and cereals, in Southwest Asia is one of the most debated topics in archaeology. Studies to date, primarily focused on macrobotanical remains, have identified specific morphological traits and changes in plants directly linked to domestication, and proposed models to explain the dynamics of this process during the early Neolithic. These results also highlight the diversity and complexity of the process during the Pre Pottery Neolithic, with evidence suggesting potential local trajectories in plant processing strategies as well as evidence related to a broader range of cultivated and wild taxa (Caracuta et al. 2015, 2017; Arranz-Otaegui et al. 2016; Kabukcu et al. 2021; Kabukcu 2023). In this regard, significant insights can be gathered from the analysis of plant food technologies, especially from ground stone tools often referred to as prime evidence for reconstructing ancient plant processing strategies by early farming communities (Dubreuil et al. 2023). In this paper, we presented evidence for the use of ground stone tools at Kharaysin (Jordan), demonstrating their significant role in tasks related to the processing of plant foods, and specifically of legumes. Our results are consistent with the

archaeobotanical record of the site, which also highlights the considerable role of legumes, and specifically lentils, in the dietary habits of the inhabitants of the site during the second half of the 9th millennium BCE (Douché et al. 2025).

By combining multiple analytical techniques, including optical microscopy for use-wear, starch grain analyses, confocal microscopy, and 3D surface texture analysis, we provide high-resolution functional data that allow both the identification of processed plants and the reconstruction of the gestures involved in their transformation. Both basalt and limestone implements were analysed, with the former dominating the studied assemblage. Such a difference in raw material occurrences does not seem to be related to functional or technological choices, as we did not evidence specific uses, gestures, or tool types associated with either basalt or limestone. Therefore, we believe that such a difference should be attributed to the proximity (less than 5 km) of the site of the basalt source.

Three use-wear patterns were observed among the analysed basalt and limestone tools at Kharaysin (Figs. 5 and 9). Comparison with modern experimental references allowed two of these patterns to be associated with legume processing. The first refers to a short-range grinding, consisting of



**Fig. 9** The three functional patterns identified through the analysis of the ground stone tools of Kharaysin, their associated gestures, tool types and worked plants

limited back-and-forth motions and the limited extension of the use-wear. In some cases, this grinding was accompanied by light pounding, likely carried out during the first stages to break down legumes and aid the following grinding. This combination of gestures, identified on pestles, ground stones and on the flat areas of ground stones with cupholes, has proven very effective in experimental legume grinding (Zupancich et al. 2025). The second pattern related specifically to the pounding of legumes, identified on pestles, and inside the cupholes of ground stones. Here, the wear indicates a combination of perpendicular and rotatory motions, which resulted in the fine pulverisation of the worked material. The third pattern, identified on handstones and grindstones is associated with the cereal grain processing. In this case, the extensive distribution of traces across the active surfaces of the tools refers broader back-and-forth motions compared to the ones carried out for legume grinding. In terms of occurrence, this latest functional pattern is limited within the analysed assemblage if compared with the previous ones. Finally, only in one instance on a stone vessel/mortar (I-31810) pounding gestures have been identified in combination to grain processing, specifically wild grass grains as suggested by the observed use-wear and residue. Given the similarities with our experimental reference, this evidence, can potentially be interpreted as the use of the tool for dehusking.

Although only a part of the Kharaysin ground stone assemblage has been studied so far, these findings underline the importance of legumes at the site. This hypothesis is also supported by the composition of the Kharaysin ground stone tool assemblage, in which pestles and stone vessels/mortars predominate. These tool types are commonly associated with activities combining pounding and grinding, two gestures widely employed and highly efficient in processing plant foods such as legumes (Dubreuil et al. 2023; Zupancich et al. 2025). Of particular interest is also the finding at Kharaysin of a specific type of ground stone tool, grinding slabs characterised by single or double cupholes (Fig. 3a), found in structures chronologically associated with the Late PPNA and the Transitional PPNA/B period at the site (Ibáñez et al. 2025a). At Kharaysin, these tools, apart from one (D-55) show use-wear and residue related to legume processing both in the cupholes and across the flat surface. Such implements have been defined as typical of the PPNA in Northern Levant but have also been found in the south at Gilgal, Netiv Hagdud, 'Iraq ed-Dubb, all contexts where legumes are well represented in the archaeobotanical record (Noy 1979; Bar-Yosef et al. 1991; Kuijt 2004; Kislev et al. 2010; Rosenberg and Gopher 2010; Colledge et al. 2018). Unfortunately, to date, functional data for these implements remain scant, preventing a direct functional comparison with those from Kharaysin. However, following the hypothesis

proposed by Rosenberg and Gopher (2010) concerning the grinding slabs with cupholes of Gilgal, and by Finlayson and colleagues for the cuphole mortars from the buildings at WF16 and Dhra', these implements can be reasonably defined as stationary elements placed inside domestic contexts (Finlayson et al. 2011).

The evidence from Kharaysin therefore demonstrates that plants were processed inside the buildings. Based on archaeobotanical data, this latter assumption is also consistent with the hypothesis that legumes were stored indoor (Douché et al. 2025). While use-wear clearly indicates the latest use of these tools for processing legumes, we cannot exclude they were also used to process a different range of plants, as suggested by Poaceae-associated starch granules identified on one sample (D55).

The substantial evidence for legume processing at Kharaysin further supports the hypothesis of their relevance in the diet and lifeways of the site's inhabitants during the Late PPNA and the Middle PPNB. Indeed, the amount of lentil seeds and the size of faba bean seeds (Douché et al. 2025) are evidence of the continuous exploitation of legumes during the Early and Middle PPNB at the site, which potentially reflects a certain degree of management of these plants at the site. This is particularly significant given the challenges posed by the cultivation of wild legumes (i.e. high rate of seed dormancy, indeterminate growth and pod dehiscence) (Abbo et al. 2009) and may reflect the agronomical knowledge of the inhabitants of the site. Moreover, our results demonstrate specific dietary practices and a ground stone technology focused on pounding and grinding tools, which are most strictly related to and probably developed upon processing these specific plant foods. The considerable effort invested in the exploitation of legumes can be justified by their high nutritional value, and specifically lentils, rich in protein, minerals and carbohydrates (Kerem et al. 2007). One of the aspects that remains unexplored and will undoubtedly require further investigation is the state of the processed plants. Indeed, while our results allow us to assess the gestures involved and, in some cases, identify the plant taxa, they cannot yet clarify whether legumes were pre-treated before being processed. The analysis of food remains at the site, along with future experimental trials will allow to gather further clues, informing whether legumes were roasted, soaked or boiled before grinding (Valamoti et al. 2011; Kabukcu et al. 2021). Specifically in the case of use-wear the pre-processing of the worked plant influences the characteristics of the resulting traces (Li et al. 2020; Chondrou 2020; Chondrou et al. 2021; Hamon 2022). Identifying such patterns at Kharaysin will enable us to define whether local or shared culinary practices existed between the Late PPNA and the PPNB, providing new insights on

the dynamics and characteristics of this transitional phase at the site. A final consideration concerns the methodology presented in this paper. After experimentally assessing the potential of confocal microscopy and 3D surface texture analysis to study use-wear on ground stone tools (Zupancich et al. 2025), we tested their application to archaeological implements and to basalt as a raw material. Our results show, first, the effectiveness of the method in analysing micro polishes on basalt. Secondly, we demonstrated its effectiveness on archaeological tools. Third, we show the advantages of integrating this technique with the qualitative analysis of use-wear and residue analysis under optical light microscopy allowing for accurate and high-resolution functional interpretations. When combined with other strands of evidence such as archaeobotanical and architectural data available from a given site, these results can significantly enhance our understanding not only on plant exploitation strategies and technology, but also on the lifeways and social structures of the first Neolithic farming communities in Southwest Asia.

## Conclusion

Ground stone tools represent prime evidence for exploring the characteristics and development of human-plant relations. Specifically, their techno-functional study can provide significant information about plant processing strategies and indirectly inform about the relevance of plants in the lifeways and the dietary practices of prehistoric communities. In this paper, we presented the results gathered from the functional study of ground stone tools at the PPN site of Kharaysin (Jordan). Our research, based on combining qualitative and quantitative methods in functional analysis, underlines the importance of legumes at the site. We identified three use-wear patterns, demonstrating that legumes were processed through different motions, including pounding and grinding gestures, while cereals were exclusively worked through grinding. Moreover, the analysis of a specific type of ground stone tool, characterised by a single or multiple cupholes, showed their exclusive use to work legumes, providing a glimpse into the use of similar implements found in other North Levantine contexts for which the functional studies are still lacking. Also, the application of confocal microscopy and 3D surface texture analysis permitted further interpretation by associating the identified micro polish with specific plant species, particularly grass pea and faba bean. These results find support and are consistent with the archaeobotanical record of Kharaysin, further underlining the importance that legumes played in the lifeways and dietary habits of its inhabitants between the Late PPNA and the Middle PPNB.

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**Data availability** The raw datasets and scripts generated and analysed in the current study are available in a Zenodo at the following link <https://doi.org/10.5281/zenodo.17632498>.

## Declarations

**Competing interests** The authors declare no competing interests.

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