Journal of Archaeological Science: Reports 64 (2025) 105152

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

# A quantitative approach to decoding pottery technology: Confocal microscopy applied to the traceological and textural analysis of surface treatment☆

Sara Díaz Bonilla [a,*], Niccolò Mazzucco [b]

[a] Universitat Autònoma de Barcelona, Departament de Prehistòria - Facultat de Filosofia i Lletres, Carrer de la Fortuna, 08193 Bellaterra, Cerdanyola del Vallès, Spain
[b] Università di Pisa, Dipartimento di Civiltà e Forme del Sapere, Via dei Mille 19, 56126 Pisa, Italy

ARTICLE INFO

*Keywords:*
Pottery technology
Experimental archaeology
Confocal microscopy
Surface texture analysis
Quantitative methods

ABSTRACT

Among the various phases of pottery production and use that can be examined through traceological analysis, surface treatment remains one of the least explored. Understanding certain phases of past production processes through material remains often necessitates the establishment of reference frameworks that facilitate the identification and characterization of the actions responsible for their formation. In this context, experimental archaeology provides a means to reconstruct the relationships between the archaeological record and past technological practices.

This study proposes an experimental program focused on the surface treatment of pottery and the tools employed in these processes, with a primary emphasis on the categories of tools utilized in the production of prehistoric handmade ceramics. The central hypothesis posits that distinct tools generate distinguishable surface traces. To systematically document and characterize the traces produced by various tool types—including pebbles, flint spatulas, pottery spatulas, shell spatulas, linen rags, grass, and leather—a comprehensive catalogue has been compiled. This catalogue integrates visual documentation with qualitative data on surface traces and overall appearance.

Additionally, confocal microscopy was tested as a means to quantitatively assess the visual differences observed between distinct surface treatments. The findings indicate that confocal microscopy is both a precise and accessible technique for measuring surface microtexture. The results underscore the methodological potential for traceological and textural analysis of ceramic surface treatments. The ability to differentiate between various surface treatment techniques offers new avenues for the study of prehistoric pottery, enhancing our understanding of ancient ceramic production practices.

## 1. Introduction

Pottery vessels shared functionality with those made from other perishable materials, such as baskets made from natural fibres and containers made from cucurbits, large seeds or tree bark. In contrast, pottery vessels survive in the archaeological record. Their relative abundance and optimal degree of preservation make it possible to obtain information on the methods and strategies of artefact production in the past, as the various steps in the process of manufacture, use and amortisation can be reconstructed.

In order to analyse the production techniques and use of pottery vessels, the application of traceological analysis methods is essential (Semenov, 1964). Although originally associated with the lithic and bone industries, in recent years it has been extended to the study of pottery manufacture (Pierret, 1995; Gelbert, 2005; Visseryas, 2007; Godon, 2010; Colas, 2005; Cascadden et al., 2020; García-Rosselló, 2006, 2010; García-Rosselló & Calvo, 2006, 2013; Martineau, 2001, 2006, 2010; Livingstone-Smith, 2007; Petrequin et al., 2009; Ard, 2014; Fazeli et al., 2010; Lepère, 2014; Forte, 2014, 2019; Gomart, 2014; Gomart & Burnez-Lanotte, 2016; Gomart et al., 2017; Roux, 2016, 2019; Cámara et al., 2021a, 2021b; Calvo, 2019; Gawron-Szymczyk et al, 2020; Ionescu & Hoeck, 2020; Thér, 2020) and use (Hally, 1983; López-

☆ This article is part of a special issue entitled: 'Tracing Social Dynamics' published in Journal of Archaeological Science: Reports.

* Corresponding author.
*E-mail addresses:* Sara.Diaz@uab.cat (S. Díaz Bonilla), Niccolo.Mazzucco@unipi.it (N. Mazzucco).

https://doi.org/10.1016/j.jasrep.2025.105152
Received 31 March 2024; Received in revised form 16 February 2025; Accepted 10 April 2025
Available online 28 April 2025

Varela et al., 2002; Vieugué, 2014a, 2014b, 2015; Forte, 2018; Barjeot et al., 2020; Debels, 2024; Drieu et at. 2020; Taranto et al., 2023).

Among the various phases of pottery production and use that can be approached through traceological analysis, surface treatment remains one of the least explored. Surface treatment of a pottery vessel involves a specific form of intervention on the raw material. It is the set of technical operations during which the internal and external walls of the pot are regularised and treated in order to increase impermeability, thermal conductivity and wear resistance. In addition, there is a visual and aesthetic improvement (Timsit, 1997). This type of treatment is usually carried out before firing, either by hand or using tools. However, some specific treatments using organic or inorganic substances can be carried out after firing to improve the mechanical and aesthetic properties of the pottery. These are the so-called "post-firing treatments" (Gosselain, 2002, 2010; Roux, 2016, 2019). On archaeological artefacts, surface treatment is documented by the identification of traces – of various types and with multiple attributes – and by the appearance of the surface. The variability of the traces depends on the state of drying consistency of the paste and its composition, the time spent working the surface and the tools used (Martineau, 2010). The potter's choice is determined by the functional or aesthetic purpose of the surface treatment. Thus, by reconstructing the final stages of the pottery-making process, it is possible to identify human activity in terms of technical choices, production methods and labour investment. The surface treatment tends to erase the traces left by the first stages of modelling, through mechanical action and the overlapping of working stages on the vessel. Other traces are still visible in the section of the sherd (García-Rosselló & Calvo, 2006, 2013; Roux, 2016, 2019).

Although some research has defined and characterised surface treatment (Shepard, 1956; Rye, 1981; Rice, 1987, 1999; Arnal, 1989; Skibo, 1992; Orton et al., 1993; Gibson and Woods, 1997), the processes of finishing pottery vessels are still considered a marginal stage in the pottery technology. The focus has been on the other stages, such as clay acquisition and processing, forming techniques and firing. Nevertheless, the last three decades have seen a proliferation of interesting methodological contributions calling for more detailed studies and advocating the development of specific research programmes to better understand the surface treatment stage. The potential for in-depth research has, in other words, started to be recognised (Schiffer, 1990; Binder et al, 1994; Schiffer et al, 1994; Skibo et al, 1997; Timsit, 1997; Martineau, 2006, 2010; García-Rosselló & Calvo, 2006, 2013; Forte, 2014, 2019; Lepère, 2014; Forte & Lemorini, 2017; Ionescu et al. 2015, 2019; Roux, 2016; Calvo, 2019; Díaz-Bonilla, 2019; Cascadden et al. 2020; Gawron-Szymczyk et al. 2020; Ionescu and Hoeck, 2020; Previti & Lemorini, 2024). The results of the experimental programmes of traceological recreation, when compared with archaeological material, enable us to explore questions related to the labour time invested in the execution of each manufacturing phase, the evolution of *savoir-faire* socially, the processes of know-how, etc. This paper aims to approach surface treatment through a quantitative methodology by applying confocal microscopy and metrology to the characterization and classification of pottery surface wear. The application of quantitative methods to the study of wear patterns has developed enormously over the last few decades, and a wide range of techniques has been applied to an increasingly diverse array of raw materials (e.g., flaked stone and ground stone tools made of flint, quartz, and other rocks, as well as bone, teeth, shell, etc.) (Martisius et al. 2018; Macdonald et al. 2019, 2025; Ibáñez et al. 2019; Pedergnana et al. 2020; Jiménez-Manchón et al. 2024; Zupancich et al. 2025).

Pottery surfaces have also been characterized using confocal microscopy, and an initial pilot study was published by Diaz-Bonilla et al. (2020) as part of a broader project that includes both qualitative and quantitative explorations of surface techniques (Diaz-Bonilla 2022). In this study, the method previously tested is expanded by increasing the number of samples and variables included in the analysis. A broader range of treatment methods is examined, and two types of clay raw materials are tested.

The main objective of this research is not only to confirm the applicability and reliability of confocal microscopy for characterizing pottery surface treatment techniques but also to explore whether this method allows for the accurate identification of perishable tools, which are rarely recognized in the archaeological record due to their organic nature.

### 1.1. Main goals

This paper analyses part of the experimental programme carried out (Díaz Bonilla, 2022; 2023) using quantitative analysis methods.

The traces obtained experimentally will be studied using confocal microscopy, a method that allows data of a quantitative nature to be extracted. These data will be statistically analysed. Our hypothesis is that the traces can be grouped according to their typology and character, depending on the conditions under which they were created. Traces can be classified of quantitative observations, but their visual variability can be also expressed in terms of variation of textural parameters by using quantitative methods. This has been recently tested in different works (Ibañez et al. 2019, 2021; Ibañez & Mazzucco, 2021; Mazzucco et al. 2022). In this way, the treatment of quantitative data from texture exploration will allow us to confirm the proposed groups, giving quantitative solidity to this proposal. The originality of this research is to provide quantitative alternative methods that will help to support the qualitative categorisation of the traces.

The use of quantitative methods for the study of handmade pottery production processes has been proposed in previous work, in a very preliminary way (Díaz-Bonilla et al. 2020). This has already yielded positive preliminary results in correlating certain traces unambiguously with different types of tools. In the case of the present work, we aim to go further by considering a more extended and complete part of the experimental programme for quantitative analysis.

In any case, the use of quantitative methods for the analysis of technological traces of pottery production will allow us (1) to classify the traces according to their production conditions, (2) to establish groups of traceological and textural similarity, (3) to give solidity to the classification by carrying out statistical tests, (4) to correct the subjectivity introduced by the analyst during the macroscopic/qualitative analysis and (5) to promote the empirical classification of technological production processes left on pottery surfaces.

## 2. Materials and methods

### 2.1. Materials: The experimental reference collection

As a basis for the research, an experimental programme was developed with the aim of reproducing the manufacturing traces on the pottery surfaces, considering the variables involved in the technological production process of the vessels.

Through the analysis of the experimental samples, the evolution of the regularisation and finishing stages of the vessel, better known as the surface treatment (traces and appearance of the surfaces), has been characterised. The surfaces of the experimental samples show traceological and textural characteristics that are the result of the combination of variables selected and controlled in the experimental programme.

The reference collection has been designed to be general and to represent a wide range of surface treatments. When designing the experimental programme, we take certain variables that exist in reality as given or external: the aim is to study how their variation affects the behaviour of the other aspects. We therefore recreate as many types of surface traces and aspects as possible, taking into account a wide range of variables, selected from previous research by García-Rosselló, 2010; García-Rosselló & Calvo, 2013; Martineau, 2010; Lepère, 2014. These variables are of two types: those that constitute the experiment or the independent variables (type of clay, drying time or consistency of the

**Table 1**
Samples selected from the experimental programme to be examined by confocal microscopy. M is the abbreviation for sample (muestra).

| Sample code | Type of pottery tool | Type of clay | Clay consistency | Labour investment |
|---|---|---|---|---|
| M1.0 / M2.0 | Untreated | Industrial (M1group) / Natural (M2 group) | Green-leather consistency | Medium (5′) |
| M1.56 / M2.56 | Pebble | | | |
| M1.57 / M2.57 | Flint spatula | | | |
| M1.58 / M2.58 | Metapodial spatula | | | |
| M1.59 / M2.59 | Grass | | | |
| M1.60 / M2.60 | Antler | | | |
| M1.61 / M2.61 | Pottery spatula or *Estèque* | | | |
| M1.62 / M2.62 | Wooden spatula | | | |
| M1.63 / M2.63 | Shell spatula | | | |
| M1.64 / M2.64 | Linen rag | | | |
| M1.65 / M2.65 | Leather rag | | | |
| M1.66 / M2.66 | Wool | | | |

clay, time or labour investment and type of tool) and those that allow the experiment to be analysed (type of trace – type of section, edge and limit of the trace – depth, dimension, distribution and orientation of the traces).

Two types of clay have been selected, differing in nature and physical properties. The first is an industrial clay sold in commercial outlets specialising in pottery. Its particularity is that it is obtained packaged and ready to use, which guarantees its optimal conservation; specifically, the product reference is PA84BIS15 Bisbal Red wet paste. 15 kg per package. The technical specifications are plastic dough with 18–21 % moisture content; drying shrinkage 6–6.5 %; loss on firing 4.9–5.4 %; optimum firing temperature 1000°-1080 °C; water absorption 12–16 %; firing shrinkage 1–1.2 %. The choice of this unique clay was motivated by the need to reproduce the traces and aspects of surfaces on a base where there would be no interference from a large grain temper. However, its purity means that it is not equivalent to archaeological pottery, where the clay is rich in organic or inorganic temper, often very abundant and large in size. For this reason, it was necessary to include in the experimental programme other types of clay, more in line with the way in which archaeological pottery is made. A clay from a calcareous geological environment in the south of the Iberian Peninsula was selected.

Eleven tools have been selected, which can be divided into two groups: perishable (Grass, wooden spatula, linen rag, leather and wool) and non-perishable tools (pebble, flint spatula, metapodial spatula, antler, pottery spatula or *estèque* and shell spatula).

In relation to the consistency of the ceramic clay, four drying stages have been experimented with: wet, leather-green, leather-hard and dry consistency.

Finally, three different intensities of labour investment have been considered: low (2 min per sample), medium (5 min) and high investment (10 min).

In order to plan the experiment accurately, only one of the variables was modified in each experimental sample, leaving the others stable. The variables considered in the experimental programme are the following: 1) type of clay, 2) type of pottery tools, 3) clay consistency and 4) labour investment.

In the present programme, 264 experimental samples have been

**Table 2**
Samples selected for testing from the experimental programme. For each one, the production conditions and the results of the qualitative analysis of its characteristics are observe. As indicated, for all samples the consistency of the paste is green-leather, and the investment of labour is medium. Concerning the abbreviations in the table. Sp. is spatul.

| SAMPLE | TOOLS | VISIBILITY | TYPE_TRACES | MARGIN_TRACE | LIMIT_TRACES | SECTION_TRACES | DEPTH | DIMENSION | DISTRIBUTION | ORIENTATION | APPEARANCE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **M1.56** | Pebble | HIGH | GROOVE | PROMINENT | MARKED | U_FLAT | DEEP | WIDE | OVERLAPPED | HORIZONTAL | SATIN |
| **M1.57** | Flint | HIGH | FLUTED LINE | PROMINENT | MARKED | U_STRIATED | DEEP | NARROW | CROSSED | HORIZONTAL | SATIN |
| **M1.58** | Metapode sp | MEDIUM | POLISHED AREAS | NO MARGIN | NO LIMIT | NO SECTION | NO DEPTH | NO DIMENSION | COVERING | NO ORIENTATION | SHINY |
| **M1.59** | Grass | MEDIUM | STRIATIONS | FLAT | DIFUSSED | STRIAT_FINE | SUPERF. | NARROW | GROUPED & PARALLEL. | HORIZONTAL | MATT |
| **M1.60** | Antler | MEDIUM | GROOVE | FLAT | DIFUSSED | U_STRIATED | SUPERF. | WIDE | OVERLAPPED | HORIZONTAL | SATIN |
| **M1.61** | Pottery sp. | HIGH | STRIATIONS | PROM. | MARKED | STRIAT_COARSE | DEEP | NARROW | GROUPED & PARALLEL. | HORIZONTAL | SATIN |
| **M1.62** | Wooden sp. | MEDIUM | GROOVE | FLAT | DIFUSSED | U_STRIATED | SUPERF. | WIDE | OVERLAPPED | HORIZONTAL | SATIN |
| **M1.63** | Shell sp. | MEDIUM | GROOVE | PROMINENT | MARKED | U_STRIATED | DEEP | NARROW | OVERLAPPED | HORIZONTAL | SHINY |
| **M1.64** | Linen rag | MEDIUM | STRIATIONS | FLAT | DIFUSSED | STRIAT_FINE | SUPERF. | NARROW | GROUPED & PARALLEL. | HORIZONTAL | SATIN |
| **M1.65** | Leather | LOW | NO TRACES | NO MARGIN | NO LIMIT | NO SECTION | NO DEPTH | DIFUSSED | NO DISTRIB. | NO ORIENT. | SATIN |
| **M1.66** | Wool | LOW | STRIATIONS | FLAT | DIFUSSED | STRIAT_FINE | SUPERF. | NARROW | GROUPED & PARALLEL. | HORIZONTAL | SATIN |
| **M2.56** | Pebble | MEDIUM | GROOVE | PROMINENT | DIFUSSED | U_FLAT | SUPERF. | NARROW | OVERLAPPED | HORIZONTAL | MATT |
| **M2.57** | Flint | MEDIUM | FLUTED LINE | PROMINENT | DIFUSSED | U_FLAT | SUPERF. | NARROW | OVERLAPPED | HORIZONTAL | MATT |
| **M2.58** | Metapode sp. | LOW | NO TRACES | NO MARGIN | NO LIMIT | NO SECTION | NO DEPTH | NO DIMENSION | NO DISTRIBUTION | NO ORIENT. | MATT |
| **M2.59** | Grass | HIGH | STRIATIONS | FLAT | DIFUSSED | STRIAT_FINE | SUPERF. | NARROW | CROSSED | HORIZONTAL | MATT |
| **M2.60** | Antler | LOW | GROOVE | FLAT | DIFUSSED | U_STRIATED | SUPERF. | NARROW | OVERLAPPED | HORIZONTAL | MATT |
| **M2.61** | Pottery sp. | MEDIUM | STRIATIONS | PROMINENT | MARKED | STRIAT_COARSE | DEEP | NARROW | GROUPED & PARALLEL. | HORIZONTAL | MATT |
| **M2.62** | Wooden sp. | LOW | GROOVE | FLAT | DIFUSSED | U_STRIATED | SUPERF. | WIDE | OVERLAPPED | HORIZONTAL | MATT |
| **M2.63** | Shell sp. | LOW | GROOVE | FLAT | DIFUSSED | U_FLAT | SUPERF. | NARROW | OVERLAPPED | HORIZONTAL | MATT |
| **M2.64** | Linen rag | MEDIUM | STRIATIONS | FLAT | DIFUSSED | STRIAT_FINE | SUPERF. | NARROW | GROUPED & PARALLEL. | HORIZONTAL | MATT |
| **M2.65** | Leather | MEDIUM | NO TRACES | NO MARGIN | NO LIMIT | NO SECTION | NO DEPTH | NO DIMENSION | NO DISTRIBUTION | NO ORIENTATION | SATIN |
| **M2.66** | Wool | LOW | NO TRACES | NO MARGIN | NO LIMIT | NO SECTION | NO DEPTH | NO DIMENSION | NO DISTRIBUTION | NO ORIENTATION | SATIN |

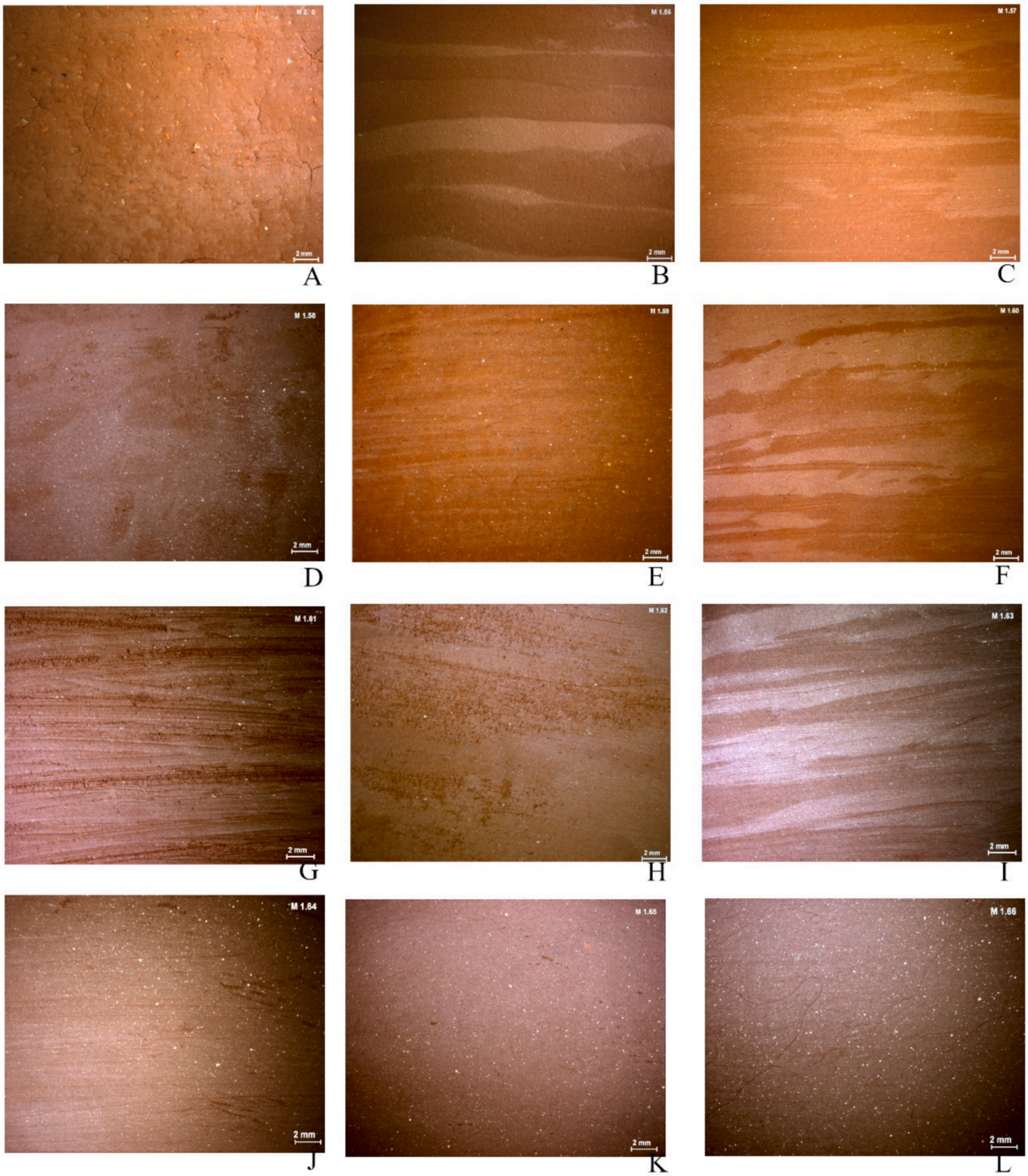


**Fig. 1.** *Macroscopic photographs taken with a Leica IC 3D MZ16FA binocular loupe at 6.30x magnification of the surface of each test sample of industrial clay included in the test.* A: M 2.0 / B: M 2.56 / C: M 2.57 / D: M 2.58 / E: M 2.59 / F: M 2.60 / G: M 2.61 / H: M 2.62 / I: M 2.63 / J: M 2.64 / K: M 2.65 / L: M 2.66.

generated. Of these, 132 are for industrial clay and 132 for natural clay (Tables 1 and 2). For the specific quantitative analysis, the samples are selected as detailed in the following section.

#### 2.1.1. *Selection of samples*

To perform the statistical test, 24 samples from the experimental programme were analysed. These samples are the result of the combination of the following variables:

a) Industrial and natural clay
b) Green-leather consistency
c) Medium labour investment (5′ for sample)
d) All types of tools (pebble, flint spatula, metapodial spatula, shell spatula, antler, pottery spatula or e*stèque, w*ooden spatula, linen rag, grass, wool and leather)

This set of conditions is considered highly representative for archaeological applications. Green-leather consistency is regarded as the most likely state in which pottery was worked, as the material is resistant yet still malleable at this stage. Medium labour investment (5

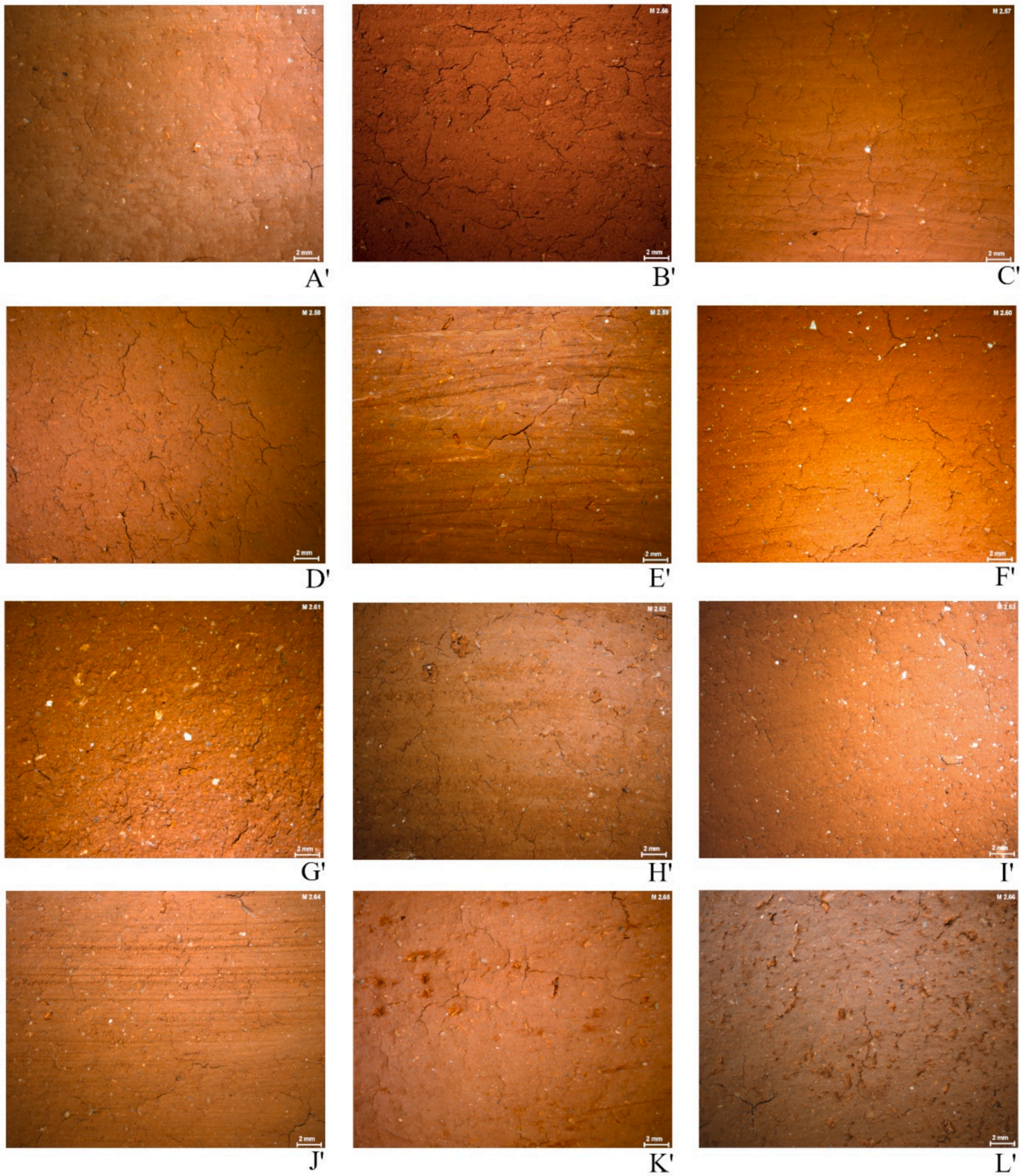


**Fig. 2.** *Macroscopic photographs taken with a Leica IC 3D MZ16FA binocular loupe at 6.30x magnification of the surface of each test sample of natural clay included in the test.* A': M 2.0 / B': M 2.56 / C': M 2.57 / D': M 2.58 / E': M 2.59 / F': M 2.60 / G': M 2.61 / H': M 2.62 / I': M 2.63 / J': M 2.64 / K': M 2.65 / L': M 2.

min for sample) is assumed to be an average working time, sufficient to produce the desired surface characteristics. All types of tools and both industrial and natural clays were included in the analysis to capture a comprehensive range of potential wear patterns.

### 2.2. Methods: Textural analysis through confocal microscopy

The first application of confocal microscopy to explore pottery surface treatment has been recently published in Díaz Bonilla et al. 2020. Building on the methodology presented in this first pilot study, a standard workflow for data acquisition has been applied, drawing also on previous studies by Ibáñez et al. (2019, 2021), Ibáñez & Mazzucco (2021), and Mazzucco et al. (2022). A Sensofar Plu Neox blue light scanning confocal microscope equipped with a 10X (0.30NA) objective was used. In previous tests, the 10X magnification gave better discrimination results than the 20X and 50X magnifications (Díaz Bonilla 2022). The spatial sampling used was set to 0.69 μm, with an optical resolution of 0.47 μm and a z-step interval of 1 μm. The field of view (FOV) for these measurements was 2.2 mm. For each plate, 40 areas of 650 × 500 μm were measured to fully cover the internal textural variability. Each

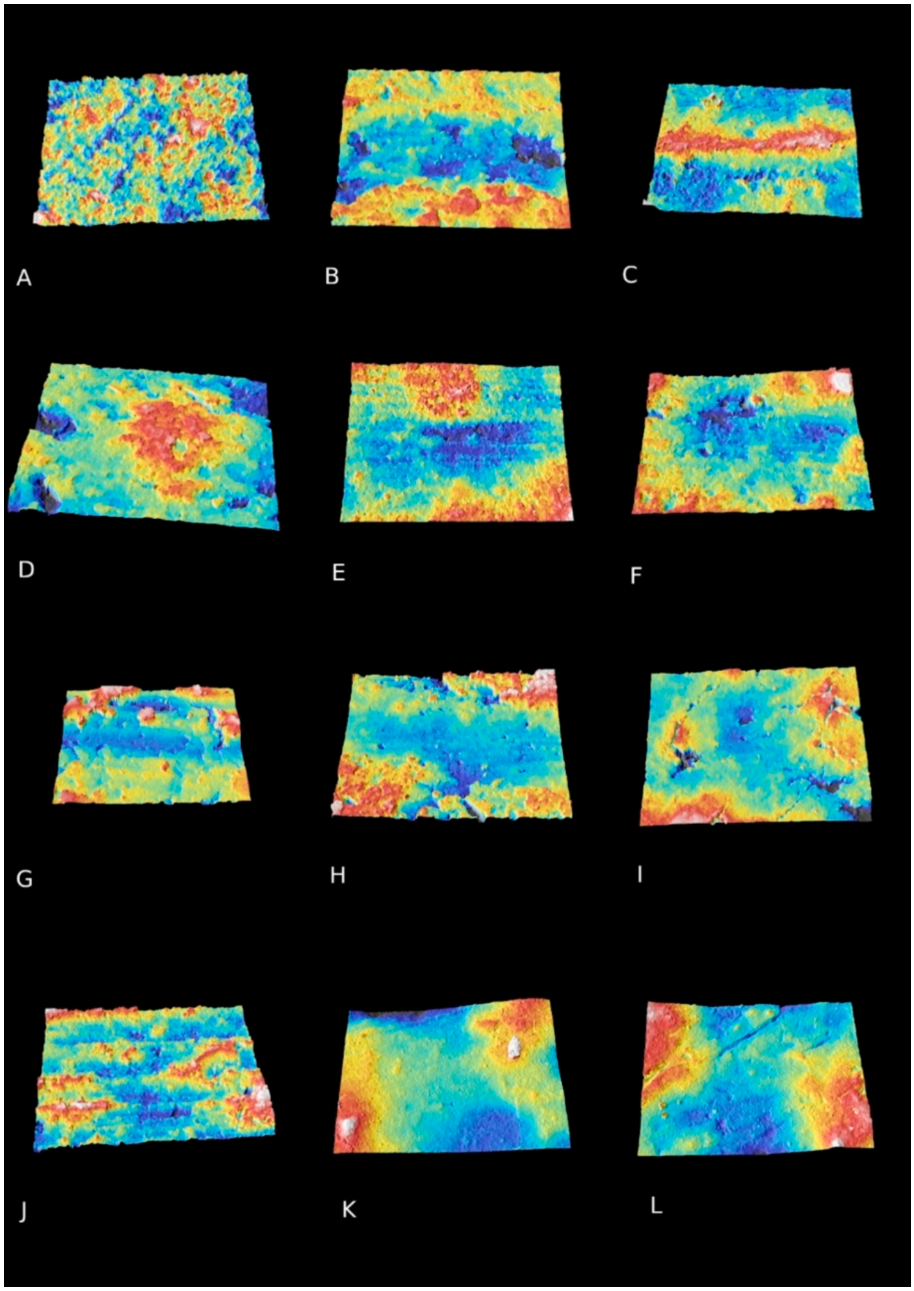


**Fig. 3.** 3D images of the surface of each test sample with natural clay included in the test. A: M 2.0 / B: M 2.56 / C: M 2.57 / D: M 2.58 / E: M 2.59 / F: M 2.60 / G: M 2.61 / H: M 2.62 / I: M 2.63 / J: M 2.64 / K: M 2.65 / L: M 2.66.

area was then processed using SensoMAP Standard v.8 from Digital Surf. The scanned areas were processed using a levelling operator with a least-squares (LS) plane method and a shape removal operator. Spatial filtering is then applied to isolate the roughness components of the surfaces using a Gaussian filter with a 0.08 mm cut-off.

A total of 40 texture parameters included in the ISO 25178 standard and three parameters measuring the furrows contained in each surface were extracted. The surfaces were classified according to the type of tool used for their treatment (Fig. 1), which represents our FACTOR1: (1.00 'untreated' 2.00 'pebble' 3.00 'flint sp. 4.00 'bone' 5.00 'grass' 6.00 'antler' 7.00 'pottery') 8.00 wood 9.00 'shell 10,00 'linen' 11,00 'leather' 12,00 'wool').

Once data has been acquired, filtered, and processed, a statistical flow for its analysis has been applied. The entire statistical procedure used to clean, process and analyse the surface data is described in the TRAC3D repository, already used in previous papers (Clemente-Conte et al. 2024; Mazzucco et al. 2024). The repository is available in open access. All the tables generated are attached as supplementary materials (S1-13). The original dataset (RAWDATA.csv) is cleaned and checked for integrity by removing duplicates and columns containing missing values (NA). The variance of the 43 texture parameters is then calculated to eliminate predictors with zero or near-zero variance. At this point, two procedures are carried out to select the most significant predictors (S1-2): removal of predictors with a low p-value (>0.005) and removal of highly correlated predictors (>0.8) (Table 3). A final set of 12 predictors was selected (Table 1) (S3-4). An outlier removal procedure using the interquartile range (IQR) method (Tukey, 1977) was then initiated and applied to the selected textural parameters. As a result, 57 rows containing outliers are removed from the original data set (S5).

Once the data set has been cleaned, a limited set of significant parameters is selected and a Linear Discriminant Analysis (LDA) is performed using the lda function, where FACTOR1 is used as the dependent

**Table 3**
Texture parameters used in the analysis and selected based on the statistical procedure.

| Acronym | Description |
|---|---|
| Sku | Kurtosis of surface heights. Sku measures the peakedness or flatness of the surface height distribution. A positive value indicates a peaked distribution with a sharp peak and heavy tails, while a negative value suggests a flatter distribution with lighter tails. |
| Sal | Auto-correlation length. Sal parameter is indicative of the dominant spatial wavelength of surface features. It describes how quickly surface features lose their similarity or correlation as you move across the surface. |
| Sda | Mean dale area. Sda represents the average area of the dale-like or valley-like features. It quantifies the typical size or extent of depressions or valleys observed across the surface texture. Larger values of Sda indicate larger and more extensive dale features, while smaller values suggest smaller and less prominent dale structures. |
| Sha | Surface height amplitude. Sha measures the difference in height between the highest peak and the lowest valley within the measurement field. It provides information about the height variations across the surface. |
| Smr2 | Valley material portion. Smr2 it is the percentage of the surface area that lies below a specified height, usually the height corresponding to the deepest valleys on the surface. |
| Sfd | Developed interfacial area ratio. Sfd measures the ratio of the developed surface area to the nominal surface area. It provides information about the surface roughness and complexity. |
| Sbi | Surface bearing index. Sbi represents the ability of the surface to support lubricant. It indicates the proportion of surface texture elements that can potentially support lubricant. |
| Sci | Surface core fluid retention index. Sci measures the ability of the surface texture to retain fluid in its core structure. It provides information about the surface's porosity and fluid retention properties. |
| Svi | Surface valley fluid retention index. Svi measures the ability of surface valleys or depressions to retain fluid. It indicates the proportion of surface texture elements that can retain fluid in valleys or depressions. |
| Mean depth of furrows | This parameter measures the mean depth of furrows or grooves on the surface. It provides information about the depth of surface features. |
| Maximum depth of furrows | Furrows Maximum Deep represents the maximum depth of furrows or grooves observed on the surface. It indicates the deepest depressions or valleys present on the surface. |
| Mean density of furrows | This parameter measures the mean density or spacing of furrows or grooves across the surface. It provides information about the frequency and distribution of surface features. |

variable and all other parameters are independent variables. The first test was carried out on natural clay samples only (Fig. 1). The LDA model is used to predict the class labels for each observation in the training data set (S6). Therefore, cross-tables are created to compare the actual FACTOR1 values with the predicted values (S7). A second LDA model is made using the same texture parameters but grouping data in a reduced set of categories (so grouping tool categories) based on the previous model. Finally, the procedure is repeated for samples made on industrial clay.

## 3. Results

### *3.1. Quantitative analysis*

As outcome of the statistical procedure, the global percentage of cases correctly classified across the 12 classes is 60.7 %. Looking at the scatter plot (Fig. 4), three main clusters can be identified. The pottery spatula class appears to be stretched along the LD1 axis, indicating that this discriminant is effective in separating it from other classes. The wool and leather classes appear to be separated along the LD1 axis. They appear as distinct clusters away from the centre of the plot, indicating that LD1 is effective in distinguishing them. The larger cluster containing the remaining classes shows a mixture of points, although there are sub-clusters within this group.

Looking at the contribution of the texture parameters to the first two dimensions (S8), we can see that:

– LD1 separates 'pottery spatula' from other classes: as illustrated in Fig. 4, LD1 explains 53.4 % of the variance and effectively separates the pottery spatula class from the rest of the classes. The most influential variables for LD1 are Svi (26.56), Sbi (2.25), and Sci (−1.92), all of which are associated with the surface's roughness and texture. The negative coefficients for variables such as Sci and mean depth of furrows (−0.97) indicate that surfaces manipulated with a pottery spatula tend to have smoother textures and shallower furrows, which reduces the surface's capacity to retain fluid and decreases overall roughness.

– 'Wool' and 'leather' classes correlation with LD1: 'wool' and 'leather' are positively correlated with LD1. The most influential variables are Svi (26.56) and Sbi (2.25), which both have positive values. This indicates that higher values of these variables are associated with a positive LD1 score. This aligns with the expectation that these surfaces are characterized by rougher textures, distinguishing them from smoother surfaces like those manipulated with a pottery spatula.

– LD2′s role in discriminating classes: LD2, explaining 26 % of the variance, further distinguishes the wool and leather classes from others. The most influential variables for LD2 are Svi (104.66), Sbi (14.76), and Sfd (5.03). The high positive coefficients for Svi and Sbi indicate that surfaces with elevated LD2 values have increased roughness and peak density. However, LD2 does not effectively separate wool and leather from each other, as shown by their similar LD2 values. This suggests that while these classes are distinct in terms of surface roughness, LD2 does not capture enough differences between them.

At this point, in order to strengthen the classification and to integrate the classification based on macroscopic criteria, we have grouped the original 12 categories into 6 groups (S9):

- Group1: Untreated samples. This group is associated with the absence of marks on the surface caused by the application of the treatment.
- Group 2: Samples treated with hard, rounded, tools. This group is associated with tools that produce grooves. It includes the pebble, the metapodial spatula and the ovicaprid antler, wood, and shell. It is a group that is highly consistent with macroscopic observation.
- Group 3: Samples treated with hard, but angular tools. It contains the flint spatula. This tool generates fluted traces, with a compact surface texture and a predominantly satin appearance.
- Group 4: Samples treated with a pottery spatula. As saw in the previous test, experimental samples worked with a pottery spatula form a well-defined group in itself. At the macroscopic level, the defining trace of this group is the coarse striation.
- Group 5: Samples treated with soft, flexible, and rough tools of plant origin. This includes flax and grass.
- Group 6: Samples treated with soft, flexible, and rough tools of animal origin. This includes leather and wool, that also formed a well-defined group.

Running a LDA model using the same texture parameters, we obtained an improved classification, with 74.1 % of cases correctly classified (S10-11). As shown in the scatter plot (Fig. 5), Groups 4 (Pottery Spatula) and 5 (Soft, Flexible, and Rough Tools of Plant Origin) are well-separated along the discriminant axes, forming clearly distinct clusters. They show the higher degree of correctness, between 90.2 % and 91.8 %, while the other groups, which were also more densely distributed in the scatter plot, show a degree of good classification between 55.9 % and 73.3 % (Table 4, Figs. 5-6). An overview of the values of each texture parameter for each analysed group is provided in Fig. 6.

A further test was carried out by classifying samples of industrial clay using the same textural parameters and grouping criteria. This was done

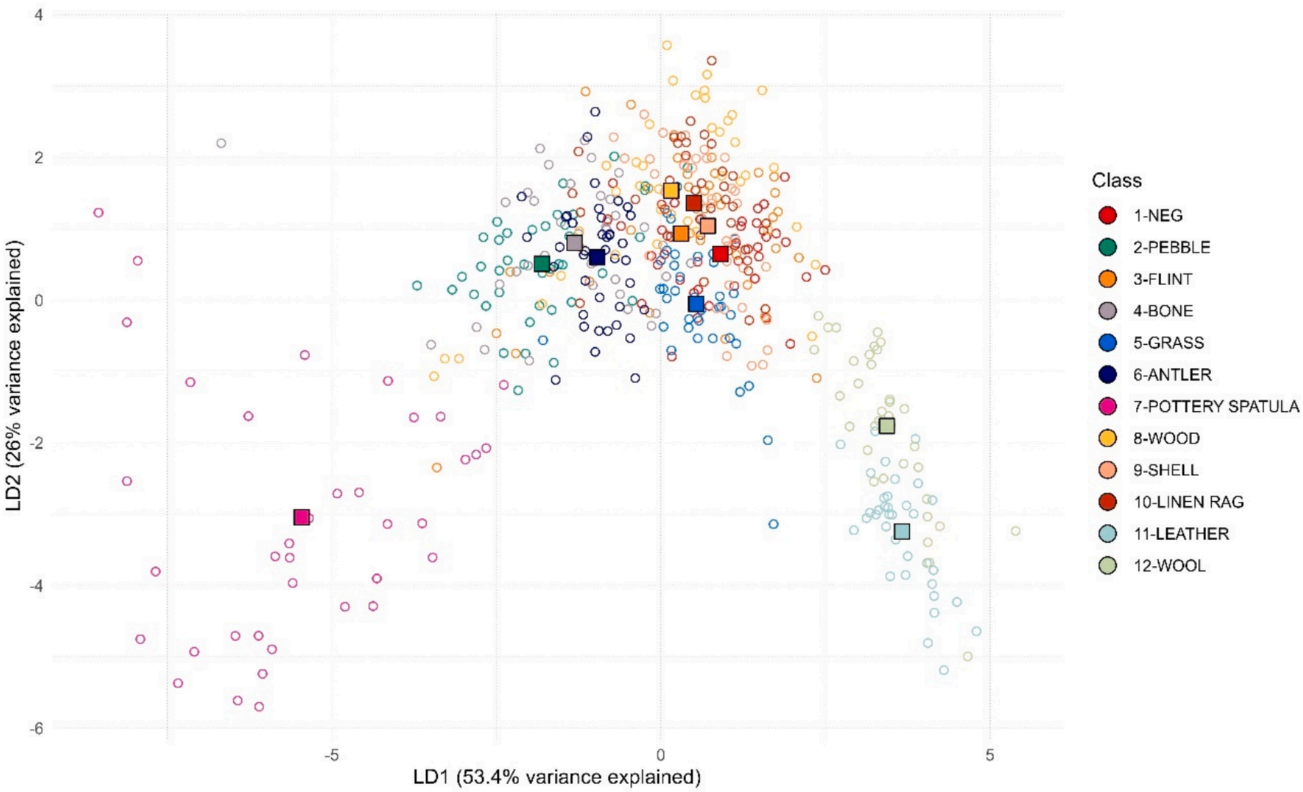


**Fig. 4.** Scatter plot of the LDA model based on 12 groups. The plot illustrates the separation of twelve groups according to the first two linear discriminants (LD1 and LD2) from the Linear Discriminant Analysis (LDA). The X-axis (LD1) accounts for 53.4% of the variance, and the Y-axis (LD2) accounts for 26% of the variance.

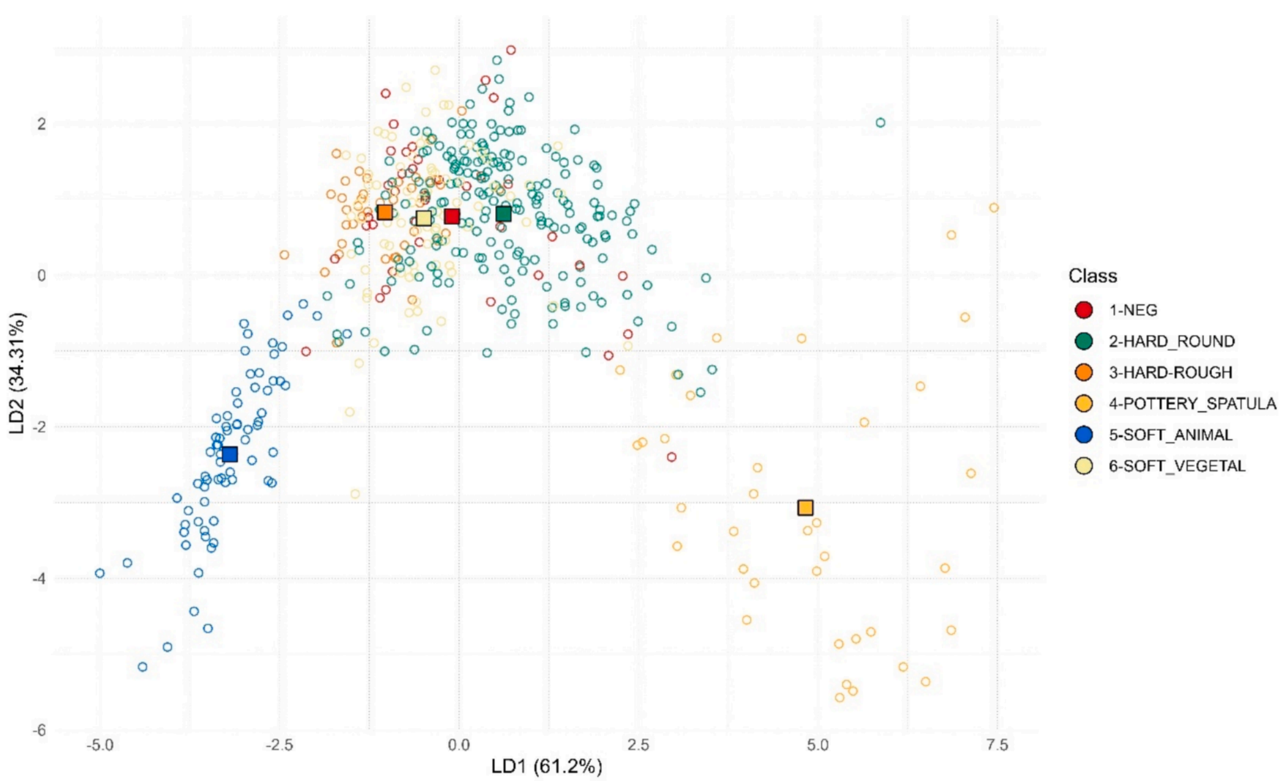


**Fig. 5.** Scatter plot of the LDA model based on 6 groups from plates made of natural clay. The plot shows the separation of six groups (1-NEG, 2-HARD ROUND, 3-HARD-ROUGH, 4-POTTERY SPATULA, 5-SOFT ANIMAL, 6-SOFT VEGETAL) according to the first two linear discriminants (LD1 and LD2) derived from the Linear Discriminant Analysis (LDA). The X-axis (LD1) explains 61.2% of the variance, and the Y-axis (LD2) explains 34.3% of the variance.

**Table 4**
Classification of samples from Group 1 to Group 6 from plates made of natural clay using Linear Discriminant Analysis (LDA). The bold numbers in the table represent the number of samples correctly classified into each group. The 'Sum' column and row represent the total number of samples for each group and the total percentage of correct classifications, respectively.

| | GROUP1 | GROUP2 | GROUP3 | GROUP4 | GROUP5 | GROUP6 | Sum |
|---|---|---|---|---|---|---|---|
| 1-NEG | **12** | 20 | 1 | 1 | 1 | 4 | 39 |
| | **57.1 %** | 8.3 % | 3.4 % | 2.4 % | 1.4 % | 6.8 % | |
| 2-HARD | 6 | **176** | 2 | 3 | 2 | 9 | 198 |
| ROUND | 28.6 % | **73.3 %** | 6.9 % | 7.3 % | 2.7 % | 15.3 % | |
| 3-HARD ROUGH | 0 | 8 | **18** | 0 | 1 | 13 | 40 |
| | 0.0 % | 3.3 % | **62.1 %** | 0.0 % | 1.4 % | 22.0 % | |
| 4-POTTERY | 0 | 1 | 0 | **37** | 0 | 0 | 38 |
| SPATULA | 0.0 % | 0.4 % | 0.0 % | **90.2 %** | 0.0 % | 0.0 % | |
| 5-SOFT ANIMAL | 2 | 1 | 0 | 0 | **67** | 0 | 70 |
| | 9.5 % | 0.4 % | 0.0 % | 0.0 % | **91.8 %** | 0.0 % | |
| 6-SOFT | 1 | 34 | 8 | 0 | 2 | **33** | 78 |
| VEGETAL | 4.8 % | 14.2 % | 27.6 % | 0.0 % | 2.7 % | **55.9 %** | |
| Sum | 21 | 240 | 29 | 41 | 73 | 59 | 463 |

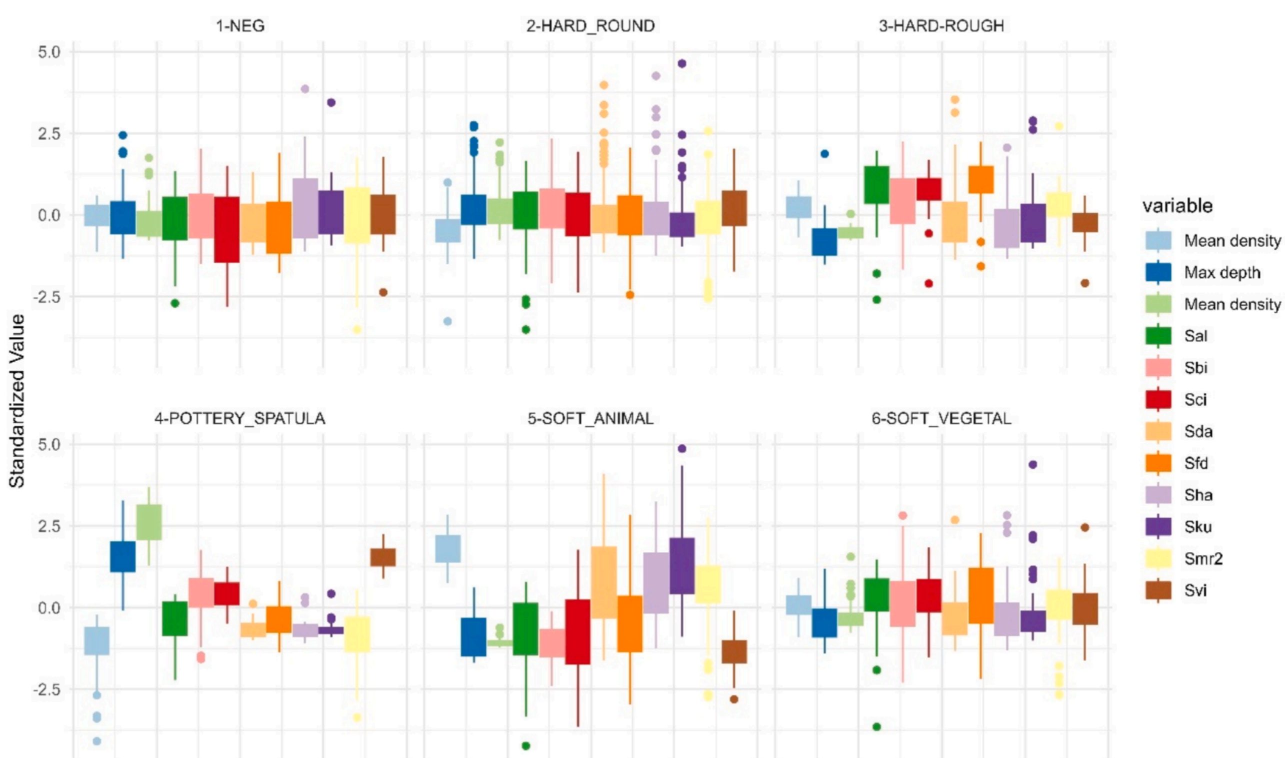


**Fig. 6.** Boxplot of the textural parameters used for discriminating the 6 groups. Each subplot represents a different group (1-NEG, 2-HARD ROUND, 3-HARD-ROUGH, 4-POTTERY SPATULA, 5-SOFT ANIMAL, 6-SOFT VEGETAL). The X-axis separates the texture parameters (e.g., Sku, Sal, Svi), while the Y-axis shows the standardized values of these parameters. The box plots illustrate the distribution (median, quartiles, and range) of each texture parameter within each group.

to evaluate how much the type of clay used affects the classification. The result is a LDA model with 79.6 % of cases correctly classified (Table 5) (S12). The two models are quite similar, except for the untreated samples (group 1), which are much better defined and represent a clearly distinguishable cluster in the industrial clay samples, also in this case, the groups that show a higher degree of correctness are group 4, group 5 and group 2 (Fig. 7). This could be explained by the fact that the industrial clay is poor in tempering agents and rich in fine particles. As a result, the traces are more defined than in natural clay, which is rich in temper and coarse particles.

Looking at the variable importance (S13) and the scores of each group on the scatter plot (Fig. 7), we can point out the following aspects:

– LD1 (82.37 % variance explained): Svi (65.19) and Sbi (2.89) have the highest positive contributions to LD1. Higher values of Svi (valley fluid retention index) and Sbi (bearing index) are typically associated with surfaces that have more pronounced valleys and peaks, respectively. This suggests that surfaces with higher LD1 scores are characterized by rougher textures with more complex surface features. Mean depth of furrows (−10.23) and Sfd (−1.68) (density of peaks) have strong negative contributions to LD1, indicating that lower values of these parameters correlate with higher LD1 scores. This means that smoother surfaces, with shallower furrows and lower peak density, will have lower LD1 values.

– LD2 (10.18 % variance explained): Sfd (−13.68) and Sci (−12.48) have the highest negative contributions to LD2. These variables, representing the density of peaks and core fluid retention index, respectively, suggest that surfaces with lower LD2 scores have lower peak density and core fluid retention capacity. This aligns with the interpretation of smoother surfaces or those with less complex patterns. Sbi (7.73) and Svi (−0.60) have positive contributions to LD2, indicating that surfaces with

**Table 5**
Classification of samples from Group 1 to Group 6 from samples made of industrial clay.

| | GROUP 1 | GROUP 2 | GROUP 3 | GROUP 4 | GROUP 5 | GROUP 6 |
|---|---|---|---|---|---|---|
| GROUP 1 | **36**<br>***100.0 %*** | 0<br>*0.0 %* | 0<br>*0.0 %* | 0<br>*0.0 %* | 0<br>*0.0 %* | 0<br>*0.05* |
| GROUP 2 | 0<br>*0.0 %* | **160**<br>***88.9 %*** | 10<br>*5.6 %* | 0<br>*0.0 %* | 5<br>*2.8 %* | 5<br>*2.8 %* |
| GROUP3 | 0<br>*0.0 %* | 22<br>*55.0 %* | **17**<br>***42.5 %*** | 0<br>*0.0 %* | 1<br>*2.5 %* | 0<br>*0.0 %* |
| GROUP 4 | 1<br>*5.9 %* | 0<br>*0.0 %* | 0<br>*0.0 %* | **14**<br>***82.4 %*** | 2<br>*11.8 %* | 0<br>*0.0 %* |
| GROUP 5 | 0<br>*0.0 %* | 11<br>*14.7 %* | 0<br>*0.0 %* | 1<br>*1.3 %* | **63**<br>***84.0 %*** | 0<br>*0.0 %* |
| GROUP 6 | 0<br>*0.0 %* | 28<br>*37.8 %* | 0<br>*0.0 %* | 0<br>*0.0 %* | 0<br>*0.0 %* | **46**<br>***62.2 %*** |

higher LD2 scores tend to have a higher bearing index (peak density) but lower valley fluid retention, pointing toward more complex surface structures with a mix of high and low areas.

We can now interpret the positioning of the different groups in relation to LD1 and LD2:

– Group 1 (Untreated Samples): This group, positioned with low LD1 and LD2 scores, corresponds to surfaces that are relatively smooth, with simple patterns and minimal variation. The lower scores on both LD1 and LD2 suggest low roughness (low Svi and Sbi) and fewer pronounced surface features, as indicated by the parameter contributions.

– Group 4 (Pottery Spatula): This group shows high LD2 scores and lower LD1 scores, suggesting surfaces with higher levels of complexity, roughness, and depth. The positive contributions of parameters like Sbi and Mean depth of furrows and the negative contribution of Sfd imply that these surfaces have more complex patterns with significant variations in roughness and depth.

– Remaining Groups (2, 3, 5, 6): These groups show moderate values for LD1 and LD2, indicating intermediate levels of surface complexity and roughness. For example, Group 2 (Hard, Rounded Tools) tends to have slightly higher LD1 scores, indicating rougher surfaces (higher Svi), while Group 6 (Soft, Flexible Tools of Animal Origin) has higher LD2 scores, pointing toward a mix of smoother and complex textures.

These data provide a very different scenario from that obtained with natural clay samples, suggesting that the presence of inclusions has a significant effect on the textural parameters. This is well exemplified by the case of pottery spatula. If we compare its positioning on LD1 and LD2 respectively using industrial and natural clay samples suggests different surface characteristics. In natural clay (Fig. 3), higher LD1 and lower LD2 suggest smoother and less rough surfaces, respectively. In industrial clay (Fig. 5), higher LD2 and lower LD1 suggest rougher and less smooth surfaces, respectively. Therefore, the type and quantity of inclusions present in the clay should be carefully evaluated when applying this methodology to archaeological samples.

## 4. Discussion

In this work, we studied the traces and textural appearance of 24 experimental samples using an unusual approach based on textural and quantitative measurements. The results of these tests were compared with the macroscopic classification of the same samples in order to identify similarities and differences in classification and to confirm the suitability and complementarity of the two methods.

In the results, the statistical treatment of the quantitative data leads to the creation of six groups of traces and surface texture. These results are compared with those obtained in the PhD dissertation (Díaz-Bonilla, 2022; 2023). A first group, 1-NEG, concentrates all the quantitative surface measurements where no surface traces or significant surface modifications (either by scraping or cutting the clay material or by polishing

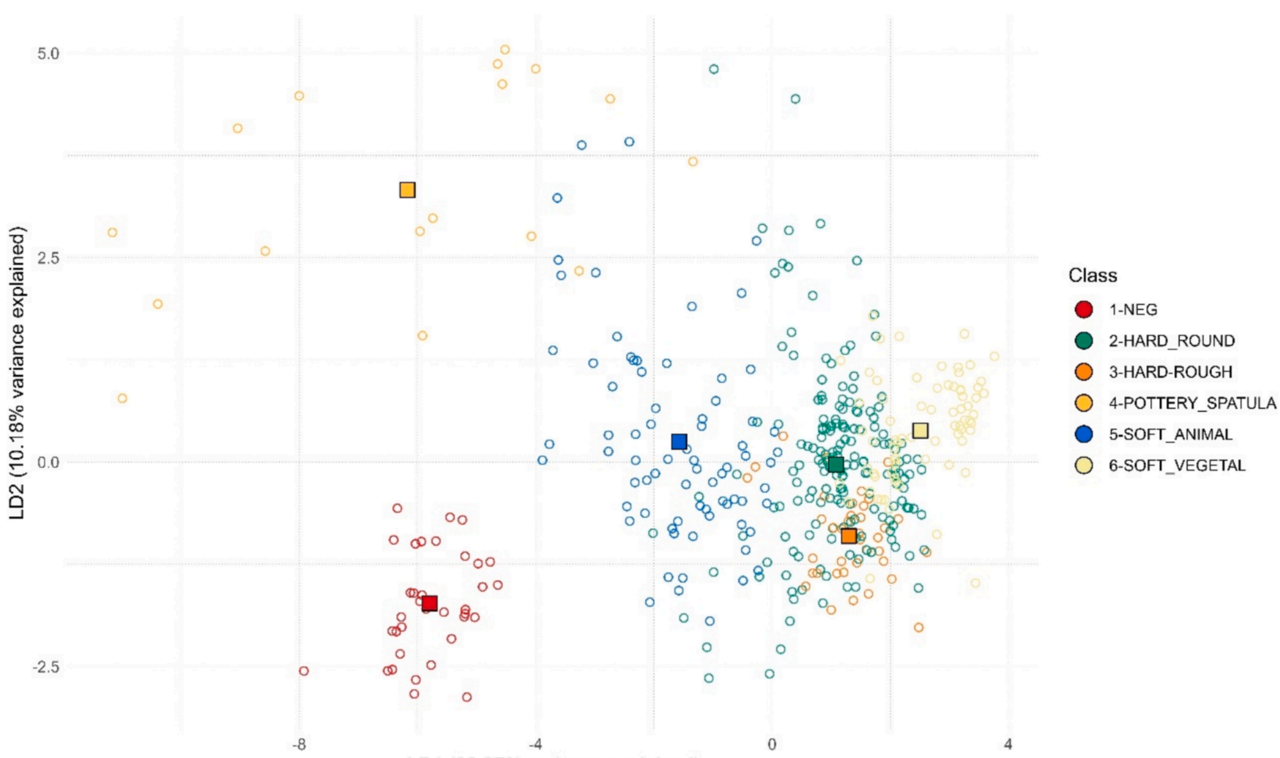


**Fig. 7.** Scatter plot of the LDA model based on 6 groups from samples made of industrial clay. The plot shows the separation of six groups (1-NEG, 2-HARD ROUND, 3-HARD-ROUGH, 4-POTTERY SPATULA, 5-SOFT ANIMAL, 6-SOFT VEGETAL) according to the first two linear discriminants (LD1 and LD2) derived from the Linear Discriminant Analysis (LDA). The X-axis (LD1) explains 82.4% of the variance, and the Y-axis (LD2) explains 10.2% of the variance.

the clay material) are detected. These samples can therefore be classified as 'no identifiable trace' at the archaeological level. This coincides perfectly with the grouping of these data into Group 1-NEG.

The quantitative data classification generates a second group, named 2- HARD ROUNDED TOOLS, which mainly includes the "groove" trace, from experimental samples treated with pebble, wooden spatula, shell and antler. This group, in turn, is in complete agreement with the proposal made in the dissertation, in which the group "hard, rounded and smooth-textured tools" is created, grouping together the same tools. In addition to the grooves mentioned above, this type of tool can also produce fluted lines and polished areas when the clay is at an advanced stage of drying (leather-hard consistency or dry consistency). However, in the consistency selected in the experimental programme to carry out the test ("green leather consistency"), the groove is the predominant stigma.

A third group classifies the samples whose surface shows fluted traces, with a compact and satin texture. In Fig. 3, these data are condensed into a well-defined group, represented by the orange colour, which has been named 3- HARD ANGULAR TOOLS. This group also shows a high degree of coincidence with those proposed in the PhD dissertation, specifically with a group called "hard and angular tools with smooth textures", which exclusively includes a type of angular spatula, made of flint, with numerous edges that produce well-defined, marked and deep traces, such as fluted traces.

The fourth group, 4- POTTERY SPATULA is like the previous one, but with only one traceological case, and is recognisable in the graph in Fig. 2 because of its wide dispersion of data. The coarse striation is the trace that produces such a marked dispersion of the data and has already been described in the macroscopic analysis as "hard and angular tools with a rough texture". There is complete agreement between the classification of the macroscopic analysis and this quantitative data set. The coarse striations are clearly produced by a hard, angular, and coarse tool, in this case the pottery spatula. This fact is perfectly reflected in the statistical tests carried out on the confocal microscopy data. Despite the dispersion of the data, it is a group that is clearly isolated from the rest of the data population, which is certainly clustered.

An important innovation in the statistical treatment of the data was the possibility of distinguishing between two groups of traces produced by perishable tools. In the macroscopic classification, the group "soft and flexible tools with rough texture" was classified, consisting of those traces (mostly fine striations and matt and satin surface appearances) produced by linen rag, grass, wool and leather. Fewer traces were produced by antler and wood, when the surfaces were dry, and it was not possible to trace too deeply. However, the canonical discriminant analysis shows that two groups can be distinguished: the first group consists of the traces produced by linen rags and grass, called 5- SOFT, FLEXIBLE, AND ROUGH TOOLS OF PLANT ORIGIN. The second group within the perishable tools is composed of the traces generated by leather and wool. It has been assigned as 6- SOFT, FLEXIBLE, AND ROUGH TOOLS OF ANIMAL ORIGIN. These traces are fine striations, but the main difference with respect to the other group is due to the satin and certainly polished appearance produced, as these are tools that compress the clay particles, creating gloss and shine on the surfaces.

As a result, statistical tests on the quantitative data show that a high percentage of the groups coincide with the groups obtained from the macroscopic analysis of the experimental samples. It is even possible to distinguish subgroups within a given population of data (the distinction between perishable tools of plant and animal origin). The rather high percentage of classification in both tests, considering natural clay (74.1 %) and industrial clay (79.6 %), supports this classification.

Therefore, the quantitative classification was effective in forming groups based on the differences between the traces, textures and aspects of the experimental pottery surfaces. Similarly, the data will allow us to identify and objectively classify the production circumstances of the archaeological handmade pottery vessels and sherds.

A word of caution should also be noted regarding the influence of the type and composition of the clay used in the recognition procedure for pottery surface treatments. Tests conducted suggest that the presence of inclusions within the clay can significantly impact the textural patterns of both untreated and treated surfaces. When using industrial clay, the matrix on which surface traces are produced is finer and does not contain coarse inclusions, thus making traces more distinguishable. The presence of inclusions considerably alters the values of surface parameters by introducing coarse elements into the clay matrix. This underscores the importance of creating an experimental reference collection that is well-adapted to the archaeological materials intended for analysis, in terms of the type of clay and inclusions used for the experimental reproduction, order to obtain reliable results.

These results show the potential of quantitative and textural approaches to distinguish different groups of traces and superficial appearance in based on variation of pottery tools, eliminating the subjectivity of other techniques.

## 5. Conclusions

The paper focuses on the quantitative study of the traces and texture of surfaces from the reference collection of pottery derived from the experimental programme. It aims to improve the understanding of manufacturing processes. To this end, a portion of samples were analysed by confocal microscopy in order to assess: 1) its usefulness in this type of analysis and 2) the robustness of the macroscopic analysis of the traces.

The following conclusions can be derived:

1. Confocal microscopy is a useful tool for characterising the treatment of pottery surfaces by means of numerical data matrices of microrelief and texture that can be processed statistically. It is an accessible, non-invasive and non-destructive method for pottery sherds.
2. It is possible to classify the different traces according to their production conditions (type of tools, clay consistency, labour investment and clay composition).
3. This made it possible to group tool types on the basis of the traces left on the surfaces, the morphology and nature (perishable and non-perishable) of the tools, and the conditions under which the samples were made.
4. The comparison between macroscopic (qualitative data) and textural (quantitative data) analysis validates the introduction of this approach to pottery technological analysis. The combination of both analytical methods offers significant analytical possibilities.

Finally, this work is an exploration of quantitative methods in the analysis of pottery technology, with initial positive results. In the immediate future, however, it will be necessary to increase and diversify the measurements of the reference collection and to supplement them with data from other experimental programmes.


## CRediT authorship contribution statement

**Sara Díaz Bonilla:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Niccolò Mazzucco:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgments

We are sincerely grateful to Juan José Ibañez Estévez, IMF-CSIC, for his contributions to the guidance and to the methodological development of this study. We also thank the IMF-CSIC for the loan of the microscopy equipment.

This study is part of a defended PhD thesis, published in open access and funded by the AGAUR of the Generalitat de Catalunya and the European Social Fund programme "Support to universities, research centres and hospital foundations for the recruitment of new researchers" (2017FI_B_00330). The results of this article are part of the R+D+i project "The first agropastoral communities of the southern slopes of the Central Pyrenees (5600-4500 calANE): economy and landscape" PID2020- 115205GB-I00 and A diversified economy? Occupation and exploitation of the middle and high Pyrenean mountains during the Early Neolithic. PID2023-148764OB-I00, both funded by the Ministry of Science and Innovation of the Spanish Government. This study is also part of the project 'Pratiche artigiane tra Mediterraneo ed Oriente. Studi interdisciplinari dalla Preistoria al Medioevo' (PRA_2022_17), funded by the University of Pisa.

## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105152.

## Data availability

I have shared the link with the data

## References

Ard, V. (2014). Produire et échanger au Néolithique : Traditions céramiques entre Loire et Gironde à l'IVe millénaire. Documents Préhistoriques, 33. Paris, Éditions du Comité des travaux historiques et scientifiques.

Arnal, G. (1989). Céramique et céramologie du Néolithique de la France Méditerranéenne. Mémoire N° V Du Centre de Recherche Archéologique Du Haut-Languedoc.

Bajeot, J., Caricola, I., Medeghini, L., Vinciguerra, V., Forte, V., 2020. An integrated approach based on archaeometry, use-wear analysis and experimental archaeology to investigate the function of a specific type of basin diffused in the Predynastic sites of lower Egypt (4th mill. BC). Quat. Int. 555, 135–149. https://doi.org/10.1016/j.jas.2018.07.001.

Binder, D., Gassin, B., & Sénépart, I. (1994). Eléments pour la caractérisation des productions céramiques néolithiques dans le sud de la France. L'exemple de Giribaldi. Terre cuite et société. La céramique, document technique, économique, culturel, XIVe Rencontres Internationales d'Archéologie et d'Histoire d'Antibes, Juan- les-Pins, APDCA, 255-267.

Calvo, S. (2019). Aproximación y caracterización de la de la tecnología de fabricación de los recipientes cerámicos en las Minas Prehistóricas de Gavà. PhD disseration. Universitat Autònoma de Barcelona.

Cámara, J., Clop, X., García-Rosselló, J., Pons, E., & Saña, M. (2021a). Identifying forming techniques and ways of doing from a diachronic perspective: the example of pottery production of La Dou (Northeast Iberian Peninsula) during the Middle Neolithic I and Late Bronze Age. Apport Des Approaches Technologiques de La Céramique à l'anthropologie et à l'archéologie Des Sociétés Pré et Protohistoriques (Proceedings of the XVIII UIPSS World Congress. 4-9 June 2018), April, 19–35.

Cámara, J., Clop, X., García-Rosselló, J., Camalich, M. D., & Martín-Socas, D. (2021b). Manufacturing traces and pot-forming processes during the Early Neolithic at Cueva de El Toro (Málaga, Spain, 5280–4780 BCE). Journal of Archaeological Science: Reports, 37 (November 2020), 102936. Doi: 10.1016/j.jasrep.2021.102936.

Cascadden, Z., Lyons, D., Paris, E., 2020. On the surface: an ethnoarchaeological study of marginalised pottery production and the social context of pottery surface treatments in Tigray Regional State, northern highland Ethiopia. Azania 55 (1), 69–96. https://doi.org/10.1080/0067270X.2020.1721842.

Clemente-Conte, I., Mazzucco, N., Santos, J.R., Socas, D.M., Massieu, M.C., 2024. A traceological and quantitative assessment of the function of the bone bi-pointed tools from the Late Neolithic of the Cueva del Toro (Antequera, Malaga). J. Archaeol. Sci. Rep. 56, 104559. https://doi.org/10.1016/j.jasrep.2024.104559.

Colas, C. (2005). Exemple de reconstitutions des chaînes opératoires des poteries du Néolithiques moyen II dans la moitié nord de la France. In Livingstone-Smith, A., Bosquet, D., Martineau, R. (eds). Pottery manufacturing processes: reconstitution and interpretation. Proceedings of XIV UISPP Congress, Liège, 2-8 September 2001. Oxford, BAR International Series 1349,139- 146.

Debels, P., Drieu, L., Chiquet, P., Studer, J., et al., 2024. Investigating grandmothers' cooking: A multidisciplinary approach to foodways on an archaeological dump in Lower Casamance. Senegal. Plos One 19 (5), 1–21.

Díaz-Bonilla, S., Benavides Ribes, A., Clemente Conte, I., Clop Garcia, F.J., Gassiot Ballbe, E., 2023. Le traitement de surface et les outils de travail dans la production des poteries préhistoriques : Le cas expérimental du galet en pierre. Société Préhistorique Française. Hiatus, Lacunes et Absences: Identifier et Interpréter Les Vides Archéologiques: Actes Du 29e Congrès Préhistorique De France.

Díaz-Bonilla, S., Mazzucco, N., Gassiot Ballbè, E., Clop García, X., Clemente Conte, I., Benavides Ribes, A., 2020. Approaching surface treatment in prehistoric pottery: Exploring variability in tool traces on pottery surfaces through experimentation. Quat. Int. 569–570, 135–149. https://doi.org/10.1016/j.quaint.2020.06.027.

Díaz-Bonilla, S., 2019. Experimentación aplicada a la cerámica prehistórica hecha a mano. Treballs D'arqueologia 23, 203–222.

Díaz-Bbonilla, S. (2022). El tratamiento de superficie de la cerámica hecha a mano: análisis traceológico a través de la experimentación arqueológica. PhD disseration. Universitat Autònoma de Barcelona.

Drieu, L., Lepère, C., Regert, M., 2020. The Missing Step of Pottery chaîne opératoire: Considering Post-firing Treatments on Ceramic Vessels Using Macro- and Microscopic Observation and Molecular Analysis. J. Archaeol. Method Theory 27 (2), 302–326. https://doi.org/10.1007/s10816-019-09428-8.

Fazeli, H., Vidale, M., Bianchetti, P., Guida, G., Coningham, R., 2010. The evolution of ceramic manufacturingtechnology during the Late Neolithic and TransitionalChalcolithic periods at Tepe Pardis Iran. Archäologische Mitteilungen Aus Iran Und Turan 42, 87–111.

Forte, V., 2014. Investigating pottery technological patterns through microwear analysis: the calcolithic village of Maccarese-Fiumicin. In: Marreiros, J., Bicho, N., Gibaja, J.F. (Eds.), International Conference on Use-Wear Analysis, 619-629. Cambridge Scholars Publishing, Newcastle (Gran Bretaña).

Forte, V., 2019. Skilled people or specialists? Knowledge and expertise in copper age vessels from Central Italy. J. Anthropol. Archaeol. 55, 101072. https://doi.org/10.1016/j.jaa.2019.101072.

Forte, V., Lemorini, C., 2017. Traceological analyses applied to textile implements: an assessment of the method through the case study of the 1st millennium bc ceramic tools in central Italy. Origini: Preistoria e Protostoria Delle Civiltà Antiche 40, 165–182.

Forte, V., Nunziante, S., Medeghini, L., 2018. Cooking traces on Copper Age pottery from central Italy: An integrated approach comprising use wear analysis, spectroscopic analysis and experimental archaeology. J. Archaeol. Sci. Rep. 18, 121–138.

García-Rosselló, J., 2006. La Etnoarqueología Como Experimentación: Ensayo Del Concepto De Cadena Operativa Tecnológica Aplicado a La Etnoarqueología. Universidad de Cantabria, Cantabria.

García-Rosselló, J. (2010). Análisis traceológico de la cerámica: modelado y espacio social durante el Postalayotico (V-I a.C.) en la península de Santa Ponça (Calviá, Mallorca). PhD thesis. Palma de Mallorca: Universitat de les Illes Balears.

García-Rosselló, J., Calvo, M., 2006. Análisis de las evidencias macroscópicas de cocción en la cerámica prehistórica: una propuesta para su estudio. Mayurqa 31, 83–112.

García-Rosselló, J., & Calvo, M. (2013). Making Pots: el modelado de la cerámica a mano y su potencial interpretativo. BAR International Series. Archaeopress, Oxford.

Gawron-Szymczyk, A., Łaciak, D., Baron, J., 2020. To smooth or not to smooth? A traceological and experimental approach to surface processing of bronze and iron age ceramics. Sprawozdania Archeologiczne 72 (2), 67–86. https://doi.org/10.23858/SA/72.2020.2.2275.

Gelbert, A. (2005). Reconaissance des techniques et des ḿethodes de façonnage par l'analyse des macrotraces:´etude ethnoarcheologique dans la vallee du Sénégal. In Livingstone Smith, A., Bosquet, D., Martineau, R. (Eds.), Pottery Manufacturing Processes: Reconstitution and Interpretation. BAR International Series, 1349. Archaeopress, Oxford, 67–78.

Godon, M., 2010. De l'empreinte à l'outil, de la trace à la fonction : exemples d'outils de potier dans le Néolithique céramique centre-anatolien (7000-5500 BC cal.). Bulletin De La Société Préhistorique Française 107, 4, 691–707. https://doi.org/10.3406/bspf.2010.13973.

Gomart, L. (2014). Traditions techniques et production céramique au Néolithique ancien. Étude de huit sites rubanés du nord-est de la France et de Belgique. Sidestone Press. Leiden.

Gomart, L., Burnez-Lanotte, L., 2016. Technique de façonnage, production céramique et identité de potiers : une approche technologique de la céramique de style non rubané du site du Staberg à Rosmeer (Limbourg, Belgique). Bulletin De La Société Préhistorique Française 109 (2), 231–250. https://doi.org/10.3406/bspf.2012.14105.

Gomart, L., Weiner, A., Gabriele, M., Durrenmath, G., Sorin, S., Angeli, L., Colombo, M., Fabbri, C., Maggi, R., Panelli, C., Pisani, D., Radi, G., Tozzi, C., & Binder, D. (2017). Spiralled patchwork in pottery manufacture and the introduction of farming to Southern Europe. Antiquity, 91, 360, 1501–1514. 10.15184/aqy.2017.187.

Gosselain, O. (2002). Poteries du Cameroun méridional. Styles techniques et rapports à l'identité (CNRS Edition). CRA - Monographies.

Gosselain, O., 2010. Ethnographie comparée des trousses à outils de potiers au sud du Niger. Bulletin De La Société Préhistorique Française 107 (4), 667–689. https://doi.org/10.3406/bspf.2010.13972.

Hally, D., 1983. Use Alteration of Pottery Vessel Surfaces: An Important Source of Evidence for the Identification of Vessel Function. North American Archaeologist 4 (1), 3–26. https://doi.org/10.2190/ak54-rne2-9ngy-ahqx.

Ibáñez, J.J., Lazuen, T., González-Urquijo, J., 2019. Identifying experimental tool use through confocal microscopy. J. Archaeol. Method Theory 26 (3), 1176–1215.

Ibáñez, J., Anderson, P., Arranz-Otaegui, A., González-Urquijo, J., Jörgensen-Lindahl, A., Mazzucco, N., Pichon, F., Richter, T., 2021. Sickle gloss texture analysis elucidates

long-term change in plant harvesting during the transition to agriculture. J. Archaeol. Sci. 136, 105502. https://doi.org/10.1016/j.jas.2021.105502.
Ibáñez, J., Mazzucco, N., 2021. Quantitative use-wear analysis of stone tools: Measuring how the intensity of use affects the identification of the worked material. PLoS One 16, 9. https://doi.org/10.1371/journal.pone.0257266.
Ionescu, C., Hoeck, V., 2020. Ceramic technology. How to investigate surface finishing. Archaeol. Anthropol. Sci. 12, 9. https://doi.org/10.1007/s12520-020-01144-9.
Ionescu, C., Fischer, C., Hoeck, V., Lüttge, A., 2019. Discrimination of Ceramic Surface Finishing by Vertical Scanning Interferometry. Archaeometry 61 (1), 31–42. https://doi.org/10.1111/arcm.12410.
Ionescu, C., Hoeck, V., Crandell, O., Šaric, K., 2015. Burnishing versus smoothing in ceramic surface finishing: a SEM study. Archaeometry 57 (1), 18–26. https://doi.org/10.1111/arcm.12089.
Jiménez-Manchón, S., Gourichon, L., Martínez, L.M., Estebaranz-Sánchez, F., Arbogast, R.M., Evin, A., Ibáñez, J.J., 2024. Comparative analysis of confocal microscopy objective magnifications on dental microwear texture Analysis. Implications for dietary reconstruction in caprines. J. Archaeol. Sci. Rep. 58, 104716. https://doi.org/10.1016/j.jasrep.2024.104716.
Lepère, C., 2014. Experimental and traceological approach for a technical interpretation of ceramic polished surfaces. J. Archaeol. Sci. 46 (1), 144–155. https://doi.org/10.1016/j.jas.2014.03.010.
Livingstone-Smith, A (2007). Chaîne opératoire de la poterie. Références ethnographiques, analyses et reconstitution. Publications digitales, Musée royal de l'Afrique Centrale. 202 p.
López Varela, S.L., Van Gijn, A., Jacobs, L., 2002. Demystifying pottery production in the maya lowlands: detection of traces of use-wear on pottery sherds through microscopic analysis and experimental replication. J. Archaeol. Sci. 29, 1133–1147.
Macdonald, D.A., Xie, L., Gallo, T., 2019. Here's the dirt: First applications of confocal microscopy for quantifying microwear on experimental ground stone earth working tools. J. Archaeol. Sci. Rep. 26, 101861. https://doi.org/10.1016/j.jasrep.2019.05.026.
Macdonald, D.A., Martisius, N., Stemp, J., Brown, C., Guthrie, L., Gleason, M., 2025. Quantification of microwear on experimental shell tools: First results using focus variation microscopy, surface roughness, and multiscale geometric analyses. J. Archaeol. Sci. Rep. 62. https://doi.org/10.1016/j.jasrep.2025.104986.
Martineau, R. (2001). La fabrication des poteries du groupe Clairvaux ancien (Jura, France), entre 3025 et 2980 avant J.-C. Expérimentations et analyses du façonnage et des traitements de surface. In Bourgignon, L., Ortega, I., Frere-Sautot, M. C. (eds.). Préhistoire et approche expérimentale, 173-185. Montangac, Mergoil Éditions.
Martineau, R. (2006). Identification expérimentale des techniques de façonnage des poteries archéologiques. Artisanats, sociétés et civilisations : hommage à Jean-Paul Thévenot : actes du colloque organisé par l'UMR 5594, Dijon et le Centre de Recherche et d'Etude du Patrimoine (CEREP), Sens, 2-3 avril 2003, 251-258. Dijon.
Martineau, R., 2010. Brunissage, polissage et degrés de séchage : un référentiel expérimental. Les Nouvelles De L'archéologie 119, 13–19.
Martisius, N.L., Sidéra, I., Grote, M.N., Steele, T.E., McPherron, S.P., Schulz-Kornas, E., 2018. Time wears on: Assessing how bone wears using 3D surface texture analysis. PLoS One 13 (11), e0206078.
Mazzucco, N., Mineo, M., Arobba, D., et al., 2022. Multiproxy study of 7500-year-old wooden sickles from the Lakeshore Village of La Marmotta. Italy. Sci Rep 12, 14976. https://doi.org/10.1038/s41598-022-18597-8.
Mazzucco, N., Ibáñez, J.J., Anderson, P., Kotsakis, K., Kita, A., Adaktylou, F., Gibaja, J.F., 2024. Use-wear evidence for the use of threshing sledges in Neolithic Greece. J. Archaeol. Sci. Rep. 56, 104579. https://doi.org/10.1016/j.jasrep.2024.104579.
Pedergnana, A., Ollé, A., Evans, A.A., 2020. A new combined approach using confocal and scanning electron microscopy to image surface modifications on quartzite. J. Archaeol. Sci. Rep. 30, 102237. https://doi.org/10.1016/j.jasrep.2020.102237.
Petrequin, P., Martineau, R., Nowicki, P., Gauthier, E., Schaal, C., 2009. La poterie Hoguette de Choisey (Jura), les Champins. Observations techniques et insertion régionale. Bulletin De La Société Préhistorique Française 106, 3, 491–515.
Pierret, A. (1995). Analyse technologique des céramiques archéologiques : développements méthodologiques pour l'identification des techniques de façonnage. Un exemple d'application : le matériel du village des Arènes à Levroux (Indre). Thèse de doctorat de l'Université de Paris I-Sorbonne.
Previti, G., Lemorini, C., 2024. People and artefacts. Craft production of 'testelli' in the medieval town of Cencelle (VT, Italy): An experimental and traceological approach. J. Archaeol. Sci. Rep.
Rice, P., 1987. Pottery analysis: A Sourcebook. The University of Chicago Press, p. 559.
Rice, P., 1999. On the origins of pottery. J. Archaeol. Method Theory 6 (1), 1–54.
Roux, V. (2016). Des céramiques et des hommes. Décoder les assemblages archéologiques. Presses universitaires de Paris Ouest, Nanterre, 415 p.
Roux, V. (2019). Ceramics and Society. A technological approach to archaeological assemblages. Springer International Publishing. https://doi. org/10.1007/978-3-030-03973-8.
Rye, O. (1981). Pottery technology. Manuals of Archaeology, 4, Washington. Taraxacum Inc.
Schiffer, M.B., 1990. The influence of surface treatment on heating effectiveness of ceramic vessels. J. Archaeol. Sci. 17 (4), 373–381. https://doi.org/10.1016/0305-4403(90)90002-M.
Schiffer, M., Skibo, J., Boelke, T., Neupert, M., Aronson, M., 1994. New perspectives on experimental archaeology: surface treatments and thermal response of the clay cooking pot. Am. Antiq. 59, 197–217.
Semenov, S. A. (1964). Prehistoric Technology. An experimental study of the oldest tools and artefacts from traces of manufacture and wear. Cory, Adams & Mackay. London.
Shepard, A., 1956. Ceramics for the Archaeologist. Carnegie Institute of Washington, Washington.
Skibo, J., 1992. Ethnoarchaeoology, experimental archaeology and inference building in ceramic research. Archaeologia Polona 30, 27–38. https://doi.org/10.1007/978-1-4899-1179-7_2.
Skibo, J.M., Butts, T.C., Schiffer, M.B., 1997. Ceramic surface treatment and abrasion resistance: an experimental study. J. Archaeol. Sci. 24, 311–317.
Taranto, S., Portillo, M., Gómez, A., Molist, M., La Mière, M., Lemorini, C., 2023. Investigating the function of late-Neolithic 'husking trays' from Syrian Jazira through integrated use-alteration and phytolith analyses. J. Archaeol. Sci. Rep. 47. https://doi.org/10.1016/j.jasrep.2022.103694.
Thér, R., 2020. Ceramic technology. How to reconstruct and describe pottery-forming practices. Archaeol. Anthropol. Sci. 12, 8. https://doi.org/10.1007/s12520-020-01131.
Timsit, D. (1997). De la trace à l'action technique : essai d'identification des traitments de surface sur les céramiques modelées. Estudis arqueológics i arqueomètrics. 5è Curs d'Arqueologia d'Andorra, 1997. 4t Congrés Europeu sobre Ceràmica Antiga, 319-330. Andorra la Vella: Govern d'Andorra.
Tukey, J.W., 1977. Exploratory Data Analysis. Addison-Wesley Pub, Co., p. 668p
Vieugué, J., 2014a. Use-wear analysis of prehistoric pottery: Methodological contributions from the study of the earliest ceramic vessels in Bulgaria (6100-5500BC). J. Archaeol. Sci. 41, 622–630. https://doi.org/10.1016/j.jas.2013.09.004.
Vieugué, J. (2014b). Fonction des contenants et des outils en céramique. Les premières productions de Bulgaire (VIè millènaire av. J.-C.), CNRS éditions, Paris, 197 p.
Vieugué, J., 2015. What were the recycled potsherds used for? Use-wear analysis of Early Neolithic ceramic tools from Bulgaria (6100–5600 cal. BC). J. Archaeol. Sci. 58, 89–102. https://doi.org/10.1016/j.jas.2015.03.016.
Visseyrias, A., 2007. Les formes de la tradition : techniques et savoir-faire céramique à la fin de l'âge du Bronze, entre Rhin et Rhône. Bulletin De La Société Préhistorique Française 104 (3), 604–609.
Zupancich, A., Cristiani, E., Di Fazio, M., et al., 2025. Beyond the Surface: Exploring Ancient Plant Food Processing through Confocal Microscopy and 3D Texture Analysis on Ground Stone Tools. J. Archaeol. Method Theory 32, 30. https://doi.org/10.1007/s10816-025-09697-6.