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Method

A method to assess inter- and intra-vessel shape variation in pottery using outline-based geometric morphometrics

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Important aspects of craft organisation, such as standardisation and artisanal skill, are encoded into the final shape of ceramic vessels. Here, the authors present a quantitative method for assessing inter-/intra-vessel morphological variation using metrics and geometric morphometrics obtained from 3D models and open-source software. Within the wider framework presented, novel analyses that assess rotational symmetry and intra-vessel variation by virtual slicing have the potential to reveal idiosyncratic motor habits of individual potters within communities of practice. Application of this approach is demonstrated through a comparison of vessels from three pre-Hispanic Colombian ware traditions, revealing meaningful patterns in vessel variability.

Keywords: South America, pre-Hispanic period, geometric morphometrics, artefact variability, ceramic technology

Introduction

Variability in the shape of ceramic vessels is a valuable source of information about craft organisation, knowledge transmission and artisanal skill. Such variation can be explored in two key dimensions: inter- and intra-vessel, each providing information on complementary aspects of craft production. Assessments of inter-vessel variability—measuring consistency in size and/or shape between vessels, within and between assemblages—are

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more commonly undertaken, relaying data regarding the degree of specialisation and control in production and the number of craftspeople involved.

Pottery vessels typically have curved shapes and linear measurements have limited sensitivity to such shape variations. Research on inter-vessel variability has therefore increasingly turned to outline-based geometric morphometric methods (GMM), which can capture subtle differences in shape through the use of a Cartesian co-ordinate system for shape quantification (Wang & Marwick 2020). This method has been applied to examine inter-vessel variation and standardisation between wares (Topi *et al.* 2018; Klesner *et al.* 2025), across periods (Wang & Marwick 2020; Loftus 2022) and sites (Roux & Harush 2022) and between different makers (Roux & Karasik 2018; Gandon *et al.* 2018).

Intra-vessel variability—the consistency in size and/or shape of features such as wall thickness or rotational symmetry within individual vessels—is less commonly explored. Yet, such data hold great potential for identifying the skill and personal style of individual potters, beneath the broader categorisation of 'workshops' or production sites, and hence for the reverse-engineering of craft organisation and knowledge transmission (Crown 2007; Martinón-Torres & Uribe-Villegas 2015; Harush *et al.* 2019, 2020; Baysal & Yelözer 2023). Integration of 3D models within GMM studies of ceramics allows for more accurate quantification of vessel shape (Winemiller *et al.* 2018) and more robust assessment of variability. Recent 3D GMM studies have identified individual style and skill in experimental and ethnographic pottery (Harush *et al.* 2019, 2020), visualised intra-vessel variability on archaeological ceramics (Loftus & Seguchi 2022) and piloted methods to quantify intra-vessel variation to identify primary forming methods (Thér & Wilczek 2022; Caloi & Bernardini 2024).

Here, we present a quantitative method to assess inter- and intra-vessel morphological variation in archaeological ceramics from 3D models, working toward the comparison of skill and craft organisation in the archaeological record. We use a case study as a proof-of-concept and demonstrate how variation in vessels made within the same production system can inform us about the skills and habits of the makers of different wares, adding a new level of resolution to the study of ceramic variability.

Case study: the Serranía nariñense (Colombia)

In the Serranía nariñense, three decorative wares, Capulí, Piartal and Tuza, differentiated by their distinct decorative styles, were produced in the pre-Hispanic period (*c.* fourth–sixteenth centuries AD). While these wares are recovered and discussed frequently, their predominant recovery context (from burials) and the lack of prior technical studies limit inferences about technologies of manufacture, craft organisation and the diachronic evolution of each ware. Prior research (Klesner *et al.* 2025) reconstructed the *chaînes opératoires* of these wares based on morphological, compositional and technological analysis (see Figure 1), and clarified technological and diachronic relationships but provided less insight into the craft organisation and skill of their makers.

Thirty vessels, each broadly defined as a bowl with a pedestal foot, were selected for analysis (Table 1 & Table S1). The vessels were hand-built, most showing evidence of

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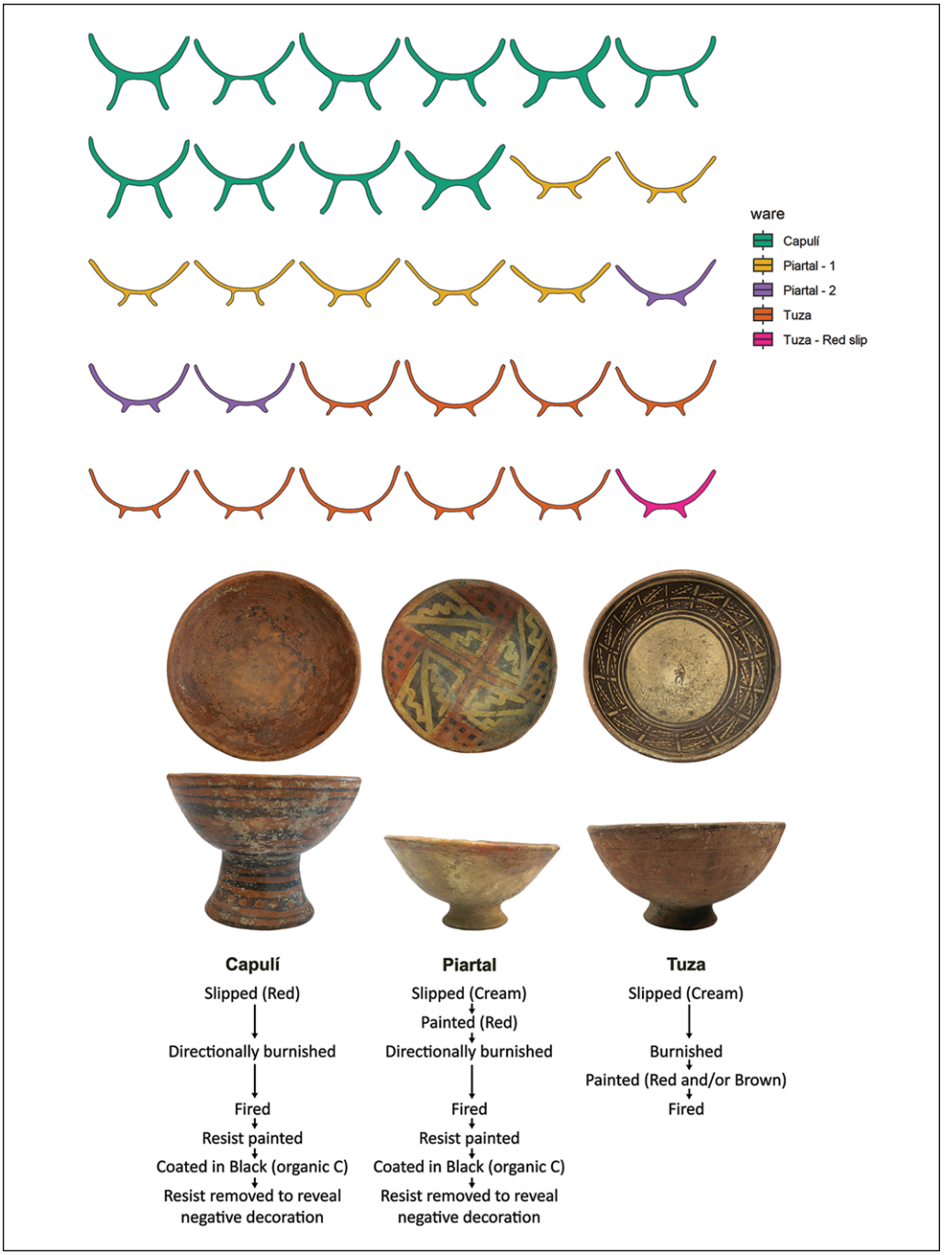


Figure 1. Above) cross-sections of the analysed ceramics, grouped by ware (sizes normalised); below) example wares (from left to right: CA230334; CA230416; CA230354) showcasing decorative features and simplified decorative chaînes opératoires *(figure by authors).*

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Table 1. Summary of the samples included in this study.

Collection/Site	Provenance?	Site	Capulí	Piartal-1	Piartal-2	Tuza	Tuza - Red slip	Total
Museo del Oro	No	Many	2	2	1	5		10
El Porvenir, Iles	Yes	Site 137	8					8
Catambuco, Pasto	Yes	San Damián				2	1	3
		Site 8			1			1
Obonuco, Pasto	Yes	CIAO21			5			5
Hacienda San Antonio de Bomboná	No	Many		1		2		3
Total			10	3	7	9	1	30

coil construction, with the bowls and pedestals made separately and later joined. Each ware is represented by 10 vessels, with Piartal and Tuza wares each further divided into subtypes (Klesner *et al.* 2025), that demonstrate the range of morphological features observed in the larger corpus, with a preference for well-preserved vessels.

Methods

An Artec Space Spider handheld structured light scanner was used to collect morphological data, capturing 3D metrics at a resolution of up to 0.1mm and a point accuracy of up to 0.05mm using blue-light technology. Scans were merged and processed in Artec Studio 16 (Artec 3D) to generate 3D models, from which all subsequent data were derived (Figure 2).

The 3D models were oriented and 36 cross-sections (every 5°) were extracted using the open-source software GigaMesh (v.5.15.2). Cross-sections containing less than 99% of the complete vessel were excluded to prevent the introduction of morphological variation resulting from use-life or burial (see online supplementary material (OSM) section S2). Most vessels retained 36 cross-sections, with a minimum of 31 meeting the >99% threshold. Cross-sections were processed in Inkscape (v.1.2.2), then converted into tanged points with tpsDIG264 (v.2.32) and loaded into the MOMOCS package (v.1.4.1) (Bonhomme *et al.* 2014) in R for further quantitative analyses, including Elliptical Fourier analysis (EFA) outline extraction, principal component analysis (PCA) for ordination and dimension reduction, and multivariate analysis of variance for group-based significance testing. All GMM visualisations and graphs were prepared in R (v.4.3.1) (R Core Team 2023) using RStudio (v.2023.06.1.524) (Posit Team 2023). OpenAI's ChatGPT 5.1 was used for generating or debugging parts of the code.

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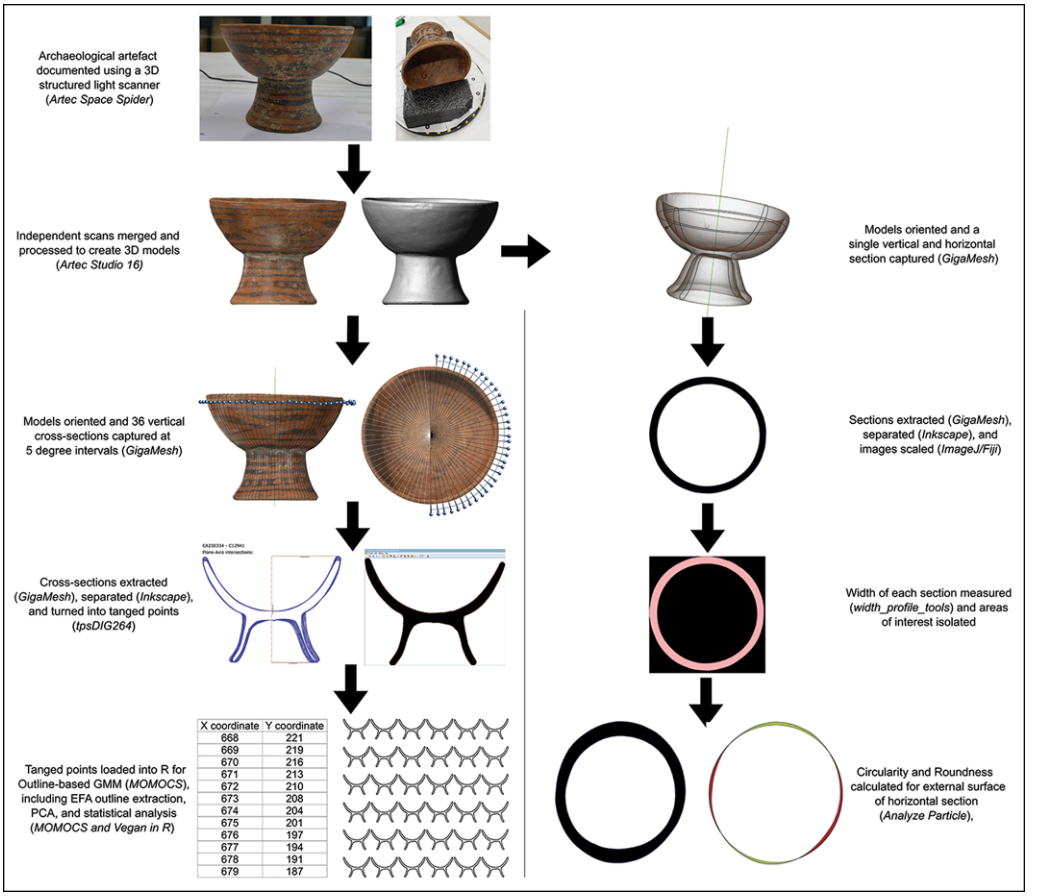


Figure 2. Methods for quantitatively assessing variability in vessel shape from 3D models of ceramic vessels: left) protocol for outline-based GMM to assess inter- and intra-vessel variation; right) protocol to calculate variation in wall thickness, circularity and roundness (figure by authors).

Morphological variance within individual vessels was tested using a permutation test of homogeneity of multivariate dispersion on the Fourier coefficients (120 coefficients for 30 harmonics) for each cross-section. This consisted of measuring the distance between all individual group members (vessel cross-sections) and the group (vessel) centroid in multivariate principal co-ordinates analysis space using the `betadisper()` function of the vegan package (v.2.6-6.1) in R (Oksanen *et al.* 2024). Groups (vessels) with higher mean distances indicated greater variance. To test if one or more groups (vessels) had a different level of morphological variability than the others, the distances of group members to the group centroid were subject to an analysis of variance. Additionally, pairwise comparisons of group mean dispersions were performed (`permutest.betadisper()`), which tested whether these distances differed between groups (vessels).

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A horizontal cross-section was extracted per vessel, and variation in wall thickness was assessed using the open-source software ImageJ/Fiji (v. 1.54) (Schindelin *et al.* 2012). Wall thicknesses were measured using the Width Profile tools in the MorphoLibJ plugin (v.1.6.2) (Legland *et al.* 2016) and calculated as the distance between a given point on one side of the wall and the other, measured perpendicular to the centreline of the vessel wall. Two hundred measurements were taken, evenly distributed across each vessel cross-section. Circularity and roundness of the horizontal section perimeter were assessed using the Analyze Particles tool in ImageJ. For full methods, datasets and scripts, see https://zenodo.org/records/18680970

Results

The first eight harmonics account for 99% of the variation in the data set, with 17 harmonics accounting for 99.9% of shape variation (Figure 3). However, given our interest in minor variations within vessels, EFA shapes produced using a larger number of harmonics were also investigated (Figure 4, OSM section S2). Thirty harmonics adequately capture vessel shape while minimising post-production variation.

Principal components (PCs) 1 and 2 capture over 90% of variance (Figure 5). Capulí vessels have negative PC1 scores, correlating to a tall pedestalled base. Conversely, Piartal and Tuza vessels have positive PC1 scores, correlating to a shorter base. PC2 describes the nature of the bowl: positive values correspond to shallower bowls with straighter sides, while negative values describe deeper, hemispherical bowls. PC2 is also able to differentiate the two Piartal subtypes previously identified (Klesner *et al.* 2025), with higher scores in Piartal-1 vessels corresponding to their more open form, while Piartal-2 vessels show lower scores (deeper bowls) similar to Tuza vessels.

The PCA plot allows an initial assessment of intra-vessel variability, as data points for some vessels form tighter clusters, reflecting greater consistency among cross-sections. To obtain a quantitative proxy for intra-vessel variation, we calculated the group distance to the centroid value (D_{Group}, Table S6) from all vessel cross-sections (Figure 6). Capulí vessels demonstrate more variability in their D_{Group} values and have larger values overall, pointing to higher intra-vessel variation and varying skill levels of producers. Some Capulí vessels do, however, have very low D_{Group} values (e.g. CA230381) and were perhaps made by a more skilled craftsperson, or by someone who placed more emphasis on maintaining internal symmetry. On average, Piartal and Tuza vessels have lower D_{Group} values and demonstrate less variability in this metric. The vessel with the lowest average value (CA230335) shows evidence of wheel turning on the base.

PCA of individual vessels reveals the specific nature of intra-vessel variation (Figure 7). To illustrate this, we selected six vessels based on their D_{Group} values: CA230335 (lowest value), CA230365 (highest value) and the vessels representing each ware's median value—CA230377 (Capulí), CA230417 (Piartal-1), CA230347 (Piartal-2) and CA230715 (Tuza). CA230365 exhibits morphological variation in PC1 due to a misalignment between the internal axes of the bowl and base, causing the vessel to appear tilted. PC2 for CA230365 highlights variation in the forming and joining of the base, particularly where it meets the bowl, indicating that the base is slightly oblong at the

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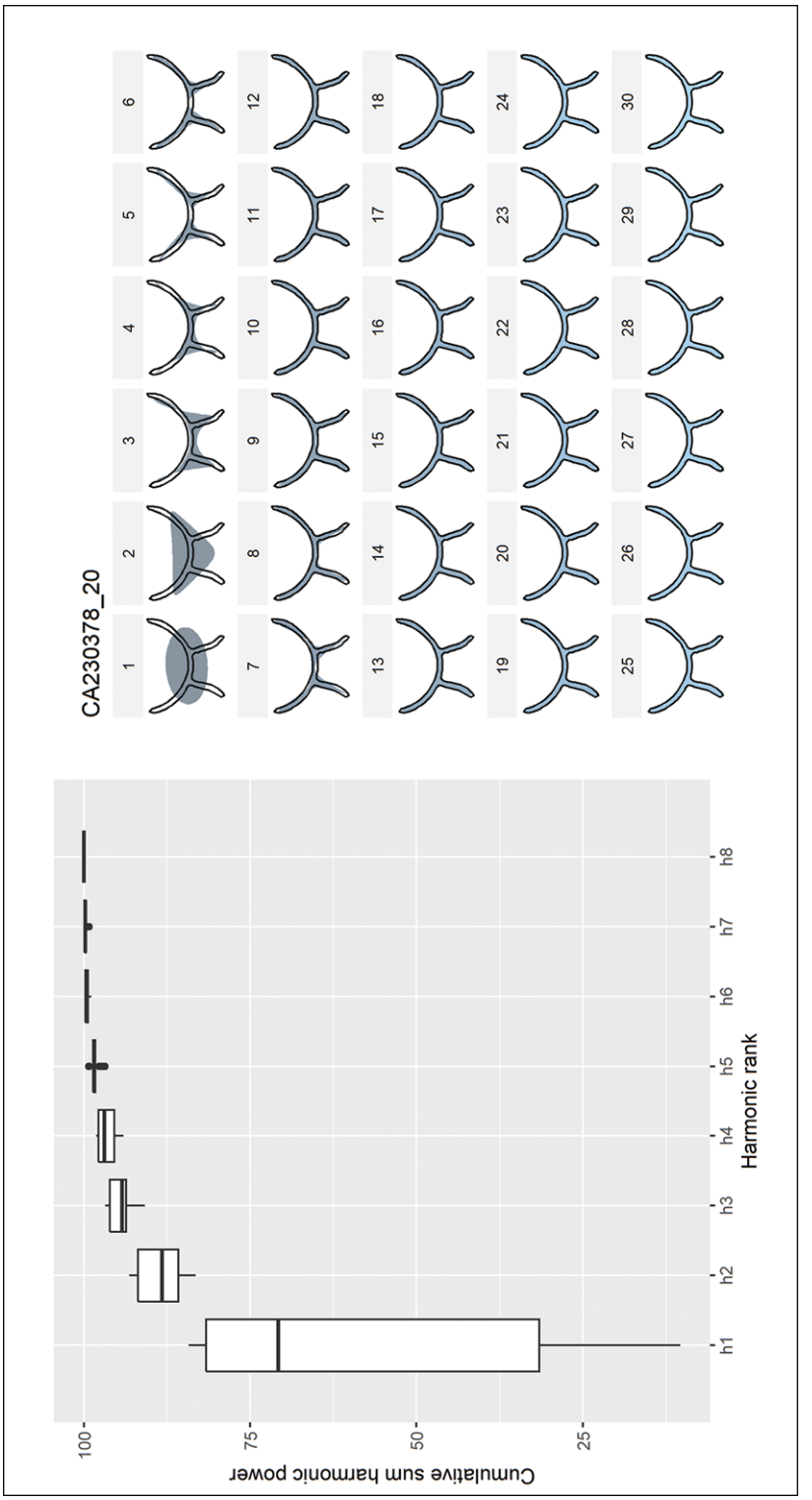


Figure 3. Cumulative harmonic power (left) and visual representation of the EFA of differential numbers of harmonics (1–30) (right) (figure by authors).

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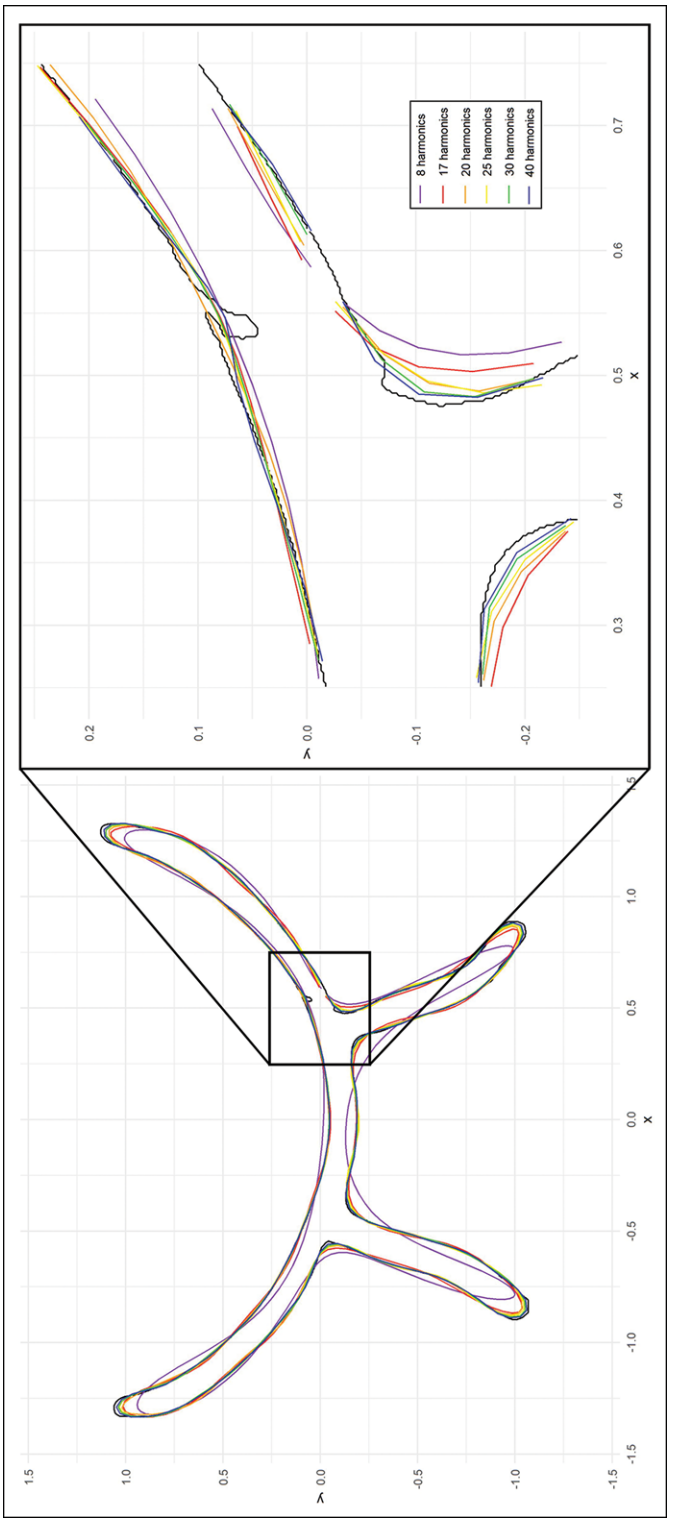


Figure 4. Outline of a cross-section (CA230378), compared to the EFA shape constructed from 8, 17, 20, 25, 30 and 40 harmonics (figure by authors).

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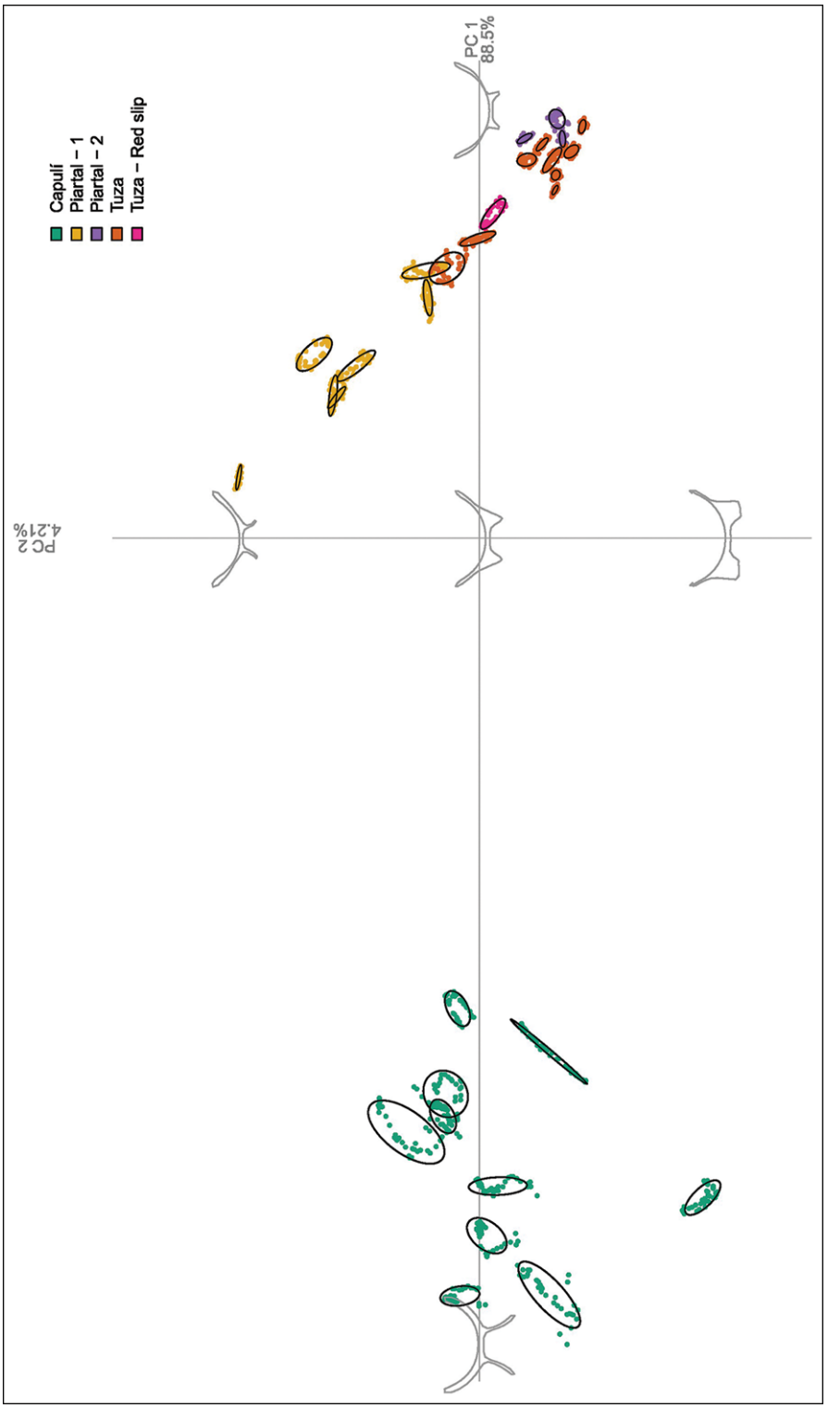


Figure 5. Biplot of PC1 versus PC2 for all cross-sections >99% preserved, with the ware of the sections indicated in colour and overlaid ellipses indicating 90% confidence intervals for cross-sections from individual vessels (figure by authors).

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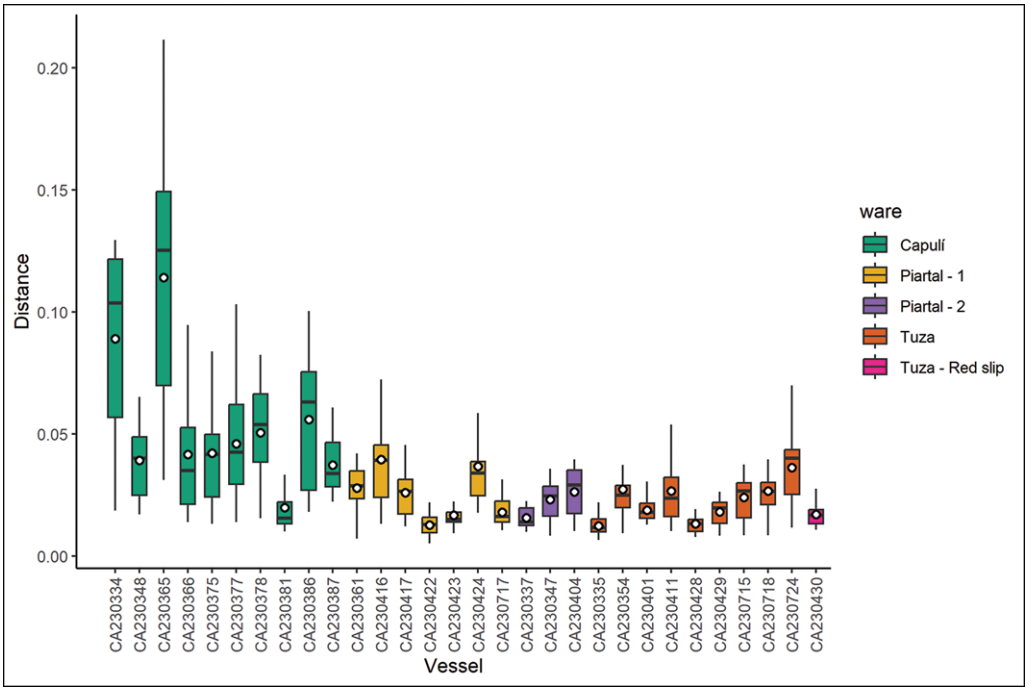


Figure 6. Boxplot showing the distribution of distance to the centroid values for each vessel by ware, used to calculate the D_{Group} (mean value indicated by white dot) (figure by authors).

join. In contrast, the Piartal-1 vessel CA230417 shows morphological variation resulting from differences in wall curvature across both the bowl and base, capturing a different idiosyncratic morphology, but with less overall variability as indicated by the D_{Group} value.

Internal symmetry was assessed through the measurements of circularity (C) and roundness (R) of the horizontal cross-sections (Figure 8A), where:

$$C = 4\pi\left(\frac{Area}{Perimeter^2}\right) \qquad R = \frac{4Area}{\pi\left(Length_{Major\ Axis}\right)^2}$$

Both parameters measure similarity to a perfect circle, expressed as a number between 0 and 1 (with 1 being a perfect circle). Circularity measures perimeter distortion across the circumference. The more deviations in the vessel symmetry, the larger the perimeter and the lower the circularity value. Capulí (average = 0.8972) and Piartal (average = 0.8971) wares have slightly lower circularity than Tuza vessels (average = 0.8986), but differences are not statistically significant. Roundness assesses how circular the vessel is regarding the aspect ratio and captures any elongation in the shape along the major axis. Capulí (average = 0.985) and Tuza (average = 0.981) wares have greater roundness than Piartal vessels (average = 0.975), but again differences are not statistically significant.

Inter- and intra-vessel variation was also examined through wall thickness. Piartal, Tuza and Capulí wares have significantly different mean wall thicknesses ($p<0.001$).

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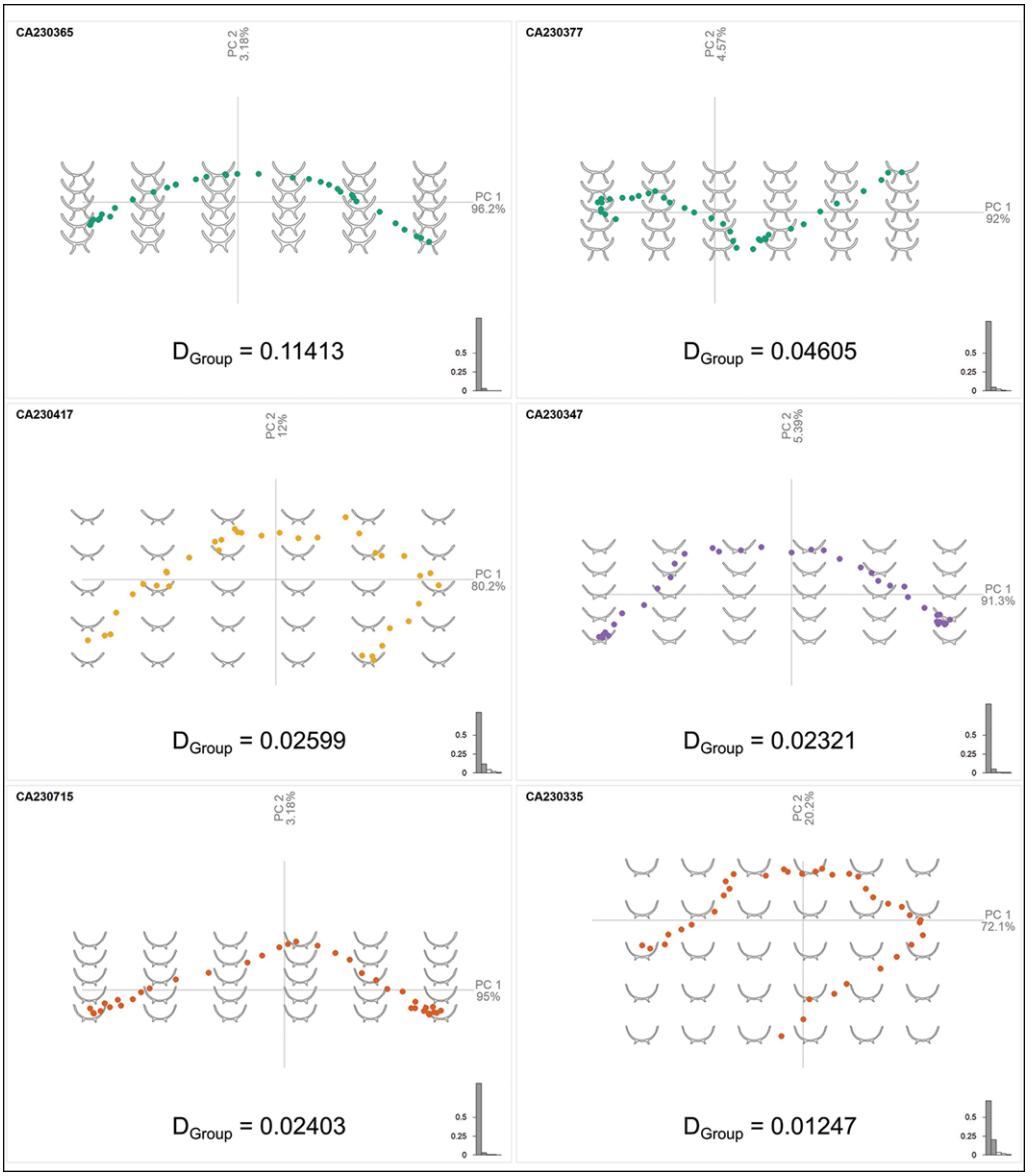


Figure 7. PC1 versus PC2 for the 36 cross-sections from each vessel (figure by authors).

Capulí vessels have thicker walls (Figure 8B, Table S7), aligning with their higher average height (109.7±19.2mm). Capulí and Piartal vessels have more inter-vessel variation in wall thickness (Table S7) compared to Tuza vessels, which are very consistent in their average wall thickness coefficient of variation (CV = 7%). However, the intra-vessel variation in wall thickness across these wares is consistent, with Capulí, Piartal and Tuza all having similar average intra-vessel CVs (see Table S8, CV = 8% for Capulí and Piartal, CV = 6% for Tuza).

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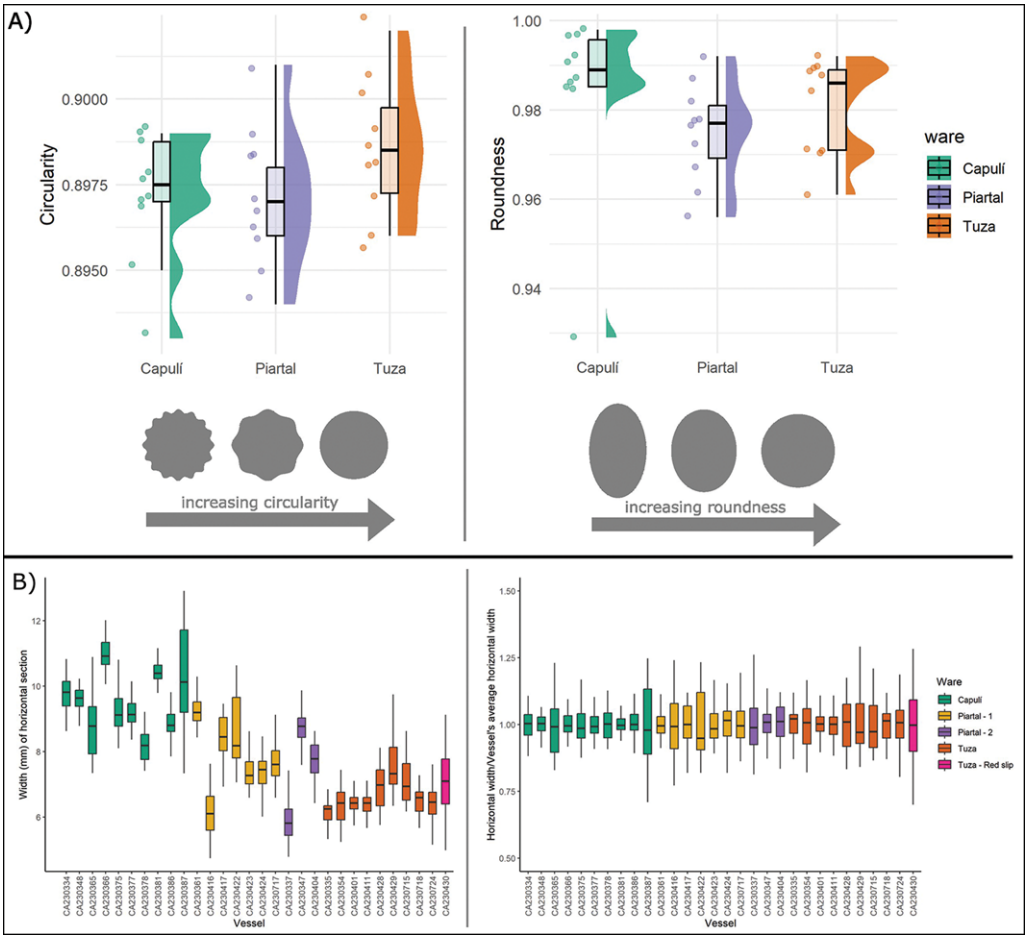


Figure 8. A) Circularity and roundness values calculated from horizontal sections; B) spread of intra-vessel wall thickness, showing the distribution of 200 width values taken sequentially for each vessel (left), and the same values normalised to the mean width of the vessel (right), grouped by their different wares (figure by authors).

Discussion

This study explores a range of metric and morphological parameters that can be readily extracted from 3D models, facilitating comparative analyses of ceramic traditions. The methods described can be applied to 3D meshes generated from a wide variety of techniques (micro-CT, structured light, photogrammetry, etc.), although assessment of wall-thickness variability requires the capture of both external and internal wall surfaces. Moreover, as circularity, roundness and the D_{Group} metric rely on exterior geometry, they can be generated from external scans of closed vessels to assess standardisation.

As this study serves as a proof-of-concept, our sample sizes are relatively small, and some differences do not reach statistical significance (Table S8). Nevertheless, our results demonstrate potential and provide a framework for future research. The foregoing

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discussion implicitly assumes that potters worked to the best of their ability in each instance to shape an 'ideal' bowl, with high rotational symmetry and low fluctuation in other metric/morphological parameters. Thus, deviations from this 'ideal' shape reflect limitations in motor skills (Thér & Wilczek 2022). Alternative explanations—such as production expediency or a high tolerance for variability by consumers—are possible, but these parameters are still useful as characterisation aids to facilitate the testing of hypotheses.

Metrics such as roundness and circularity, and variations in wall thickness, are useful proxies of skill. The CVs for each metric readily allow for comparisons within and between wares, as well as an assessment of the extent to which these variations would be perceptible. This assessment is based on experimental findings regarding the limits of human perception, the so-called Weber fraction (Eerkens & Bettinger 2001). Here, since CVs exceed 3% in practically all cases, we can assume that intra-vessel variations were perceptible and either deemed acceptable or higher standardisation was beyond the physical ability of potters. Additionally, we observe that the distribution of these values varies meaningfully. Considering internal symmetry, Capulí vessels consistently show the highest values for roundness, but not for circularity—perhaps reflective of a particular construction method, such as the use of a mould. Piartal vessels show the most variation for both parameters, which may indicate a wider range of construction methods and/or makers, and is potentially consistent with the identification of two morphological subtypes. Intra-vessel variation in wall thickness was consistent across the assemblage, which is likely indicative of their shared primary forming method, coil-construction. Prior research (Thér & Wilczek 2022) has demonstrated that coil-construction (albeit combined with wheel finishing using a turntable) shows higher variation in horizontal wall thickness compared to wheel throwing, and this is a promising metric for the exploration of differences in forming methods (see OSM section S3).

The most robust indicator of morphological variability is the D_{Group}, which encapsulates all sources of morphological variation at once and reveals statistically significant differences between wares. This approach allows for both quantitative comparisons and visualisation of the sources of variation via PCA plots. A key limitation, however, is that the D_{Group} is relative to each PCA, therefore, unlike the metrics above, the D_{Group} cannot be compared between studies unless all artefacts to be compared are analysed together. Unlike previous studies using normalised PC-score CVs (Wang & Marwick 2020; Loftus 2022), we find the D_{Group} a more suitable variability metric, as calculating CVs from inherently dimensionless PC scores is not appropriate (see OSM section S4).

In our study, Capulí vessels generally show higher D_{Group} values, indicating overall lower rotational symmetry within vessels. This ware also displays the highest levels of morphological and metric variation between vessels (Klesner *et al.* 2025). The data thus suggest a decentralised craft tradition allowing for variations in vessel size and shape, accommodating a range of skill levels but lacking virtuoso artisans (Kuijpers 2018). Notably, there is an outlier in this group (CA230381), which shows the lowest D_{Group} value and the highest roundness, and is perhaps the work of an outstanding individual.

The generally lower D_{Group} values for Piartal and Tuza vessels are potentially indicative of more highly skilled makers. Such heightened skill may itself be a product of

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more intensified production. Allowing for some variation within wares, and bearing in mind our small sample size, there are no marked differences between the internal standardisation or rotational symmetry of Piartal and Tuza vessels. This is an interesting observation given the recent suggestion that Tuza wares may mark the introduction of foreign ideas or craft knowledge, as reflected in new decorative techniques and the possible use of rotary kinetic energy to shape vessels (Klesner *et al.* 2025). Aside from a slight circularity increase, the introduction of new technical knowledge was seemingly not accompanied by an increase in product standardisation.

A particularly promising future application of our methods may be the study of variability within single deposits, such as tombs, where morphometric variability may reflect different motor habits and hence the involvement of different manufacturers. Five Piartal vessels included in this study (CA230416–CA230424) derive from a single eleventh–twelfth-century AD tomb at CIAO21 (see OSM section S1) and represent the entire range of observed D_{Group} values and wall thickness CVs for Piartal-1, and have similarly large ranges in circularity and roundness. This variation between vessels indicates that the objects interred in this tomb were likely made by multiple individuals.

Conclusions

This study highlights the value of integrating metric and morphological parameters extracted from 3D models to analyse ceramic traditions. Despite the limited sample size, the results of our case-study analysis reveal meaningful patterns in vessel variability and skill levels. Capulí vessels show greater morphological variation, both within and between vessels, suggesting decentralised production with varying skill levels, while Piartal and Tuza vessels exhibit slightly higher symmetry but no significant difference in intra-vessel standardisation. Tuza vessels exhibit the least inter-vessel variation in horizontal wall thickness, suggesting somewhat more standardised production, although the difference is not statistically significant for the sample size.

Among the various metrics assessed, the D_{Group} metric, calculated from multiple virtual cross-sections from individual vessels, emerges as the most informative measure of inter- and intra-vessel variation. This metric not only captures overall morphological variability but gives an indication of central tendencies in vessel forming and finishing, potentially reflecting both individual habits and broader communities of practice and craft traditions. This method for assessing morphological variation is applicable across a range of ceramic assemblages and vessel shapes, offering a path to a richer picture of past technological practices.

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Data availability

Datasets, code and supplementary files are also available in a Zenodo repository: https://doi.org/10.5281/zenodo.18680970

Online supplementary material (OSM)

To view supplementary material for this article, please visit https://doi.org/10.15184/aqy.2026.10323 and select the supplementary materials tab.

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