Re-assessing the notion(s) of craft standardization through diversity statistics: A pilot study on Late Chalcolithic pottery from Arslantepe in Eastern Anatolia

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Abstract

This paper proposes a new range of diversity indexes applicable to ceramic petrographic and geochemical data and potentially to any archaeological data of both metric and non-metric nature in order to assess the degree of craft standardization. The case study is the Late Chalcolithic pottery from Arslantepe in eastern Anatolia, ideal to test the standardization hypothesis, i.e. the assumed correspondence between craft standardization and increased rates of production, which in turn correlate with economic specialization. The results suggest that the procurement and processing of raw materials are more sensible indicators of standardization than vessel shape variability. Higher standardization is connected with the scale of production rather than with the use of the wheel or its rotational speed. The socio-economic centralization marks a process of labor division within the operational sequence and, more generally, a shift from communal to more segregated potting practices. As a result, the variability of both technical procedures and end products increases. In contrast univocal trends towards standardization can be found in coeval contexts from northern Mesopotamia, where the incipient urbanization served to create bonds between vessel makers, favoring the transmission of models and practices regardless of the centralized power.

Introduction

Standardization is commonly perceived as a process of reduction in artifact variability at several levels: raw materials composition, manufacturing techniques, forms and dimensions as well as decorations. The standardization of products is generally assumed to be the result of a higher rate of production that typically characterizes the economic organization of early complex societies [1–10]. The surplus centralized by the elites allowed some individuals to be exempted from the primary production and focus more intensively on craft activities in exchange for food. This enhanced the routinization and mechanization of gestures that was...
reflected in an increased homogenization of finished products [3, 11, 12]. Therefore, the increased standardization has been often viewed as indicating the activity of specialized artisans. However, the relationship between artifact standardization and craft specialization is far from linear and has been called into question by several ethnoarchaeological studies [3, 10, 13–18]. In pottery production, increased levels of standardization and specialization are commonly associated with the introduction of rotating devices in the manufacturing process. On the one hand, this technological innovation required the acquisition of specific motor skills through long apprenticeship and continuous practice and, on the other hand, it favored the repetitiveness of gestures and enhanced production times and rates [19–21].

So far, standardization studies on archaeological ceramics have mainly focused on measuring the vessels’ dimensional variation through a sophisticated range of measures [5, 18, 22–28], while non-metric attributes, such as typological and technological attributes, have received less attention [however, see 29–34]. In the last two decades the assessment of compositional variability has gained importance, but the integration between petrographic and geochemical data as well as the correlation with morphological, dimensional and technological variables need to be further explored [31, 33–39].

This paper intends to exploit the potential of compositional analyses for assessing craft specialization and artifacts’ standardization. The case study is the Late Chalcolithic (ca. 4700–3200 BCE cal.) pottery assemblage from Arslantepe in eastern Anatolia, ideal to test the standardization hypothesis. The standardization hypothesis proposes that more uniformity in the vessel assemblages is due to higher rates of production, which create task mechanization and routinization (i.e. motor habits) [3–6, 11, 27]. Many scholars consider craft standardization as evidence of specialization, thus as a key aspect in the political economy of complex societies [2, 36, 40]. As argued by Hilditch [33], craft standardization has been frequently seen as the result of a unilinear process intensified by the introduction of the potter’s wheel that enhanced both time and scale of production; however, little attention has been dedicated to single variations along the chaîne opératoire to assess where and how standardized gestures and behaviors appear.

In his paper “Does the standardization of ceramic pastes really mean specialization?” Arnold claimed that paste composition provides information primarily on the geological context rather than on the production organization [41]. His assumption was based on geochemical data of ceramic vessels produced at a household level from different ethnographic communities in Mexico, Peru and Guatemala. The present paper demonstrates instead that the variations in paste recipes can be used as indicators of production organization at least at an intra-site level. To achieve this aim, different compositional analyses—i.e. bulk geochemistry and thin section petrography—have to be integrated with selected technological and typological features. Interpretations in terms of production organization are further favored in cases of variegated pottery assemblages related to distinct levels of specialization and produced over a long time span marked by drastic socio-economic changes.

The aim of this paper is to assess whether the gradual process of economic centralization that led to the formation of an early state society by the end of the 4th millennium BCE at the site of Arslantepe (Malatya, Turkey) implied the homogenization and increased standardization of pottery production and, in particular, of the raw material procurement patterns and paste preparation modes. To this end, petrographic and geochemical data of locally-produced vessels are elaborated using procedures borrowed from diversity statistics. Finally, the trends identified are compared with vessel shape variability, manufacturing techniques and production rates, in order to detect differences and correlations in technological variations within the various steps of the chaîne opératoire.
Economic centralization, technical innovation and production serialization at Late Chalcolithic Arslantepe

Arslantepe is a multi-layered settlement located in the Malatya Plain in Eastern Anatolia, a few kilometers south of the Euphrates River and on the northern side of the Anti-Taurus Mountains (Fig 1). The Late Chalcolithic phases reveal the site’s historical relevance in the formation process of early-state societies and the emergence of social and economic inequality [42–45]. During the Late Chalcolithic period all Mesopotamia and related regions—including the upper courses of the Euphrates and Tigris in Anatolia, the Trans-Tigridian regions, and the Amuq and Susiana plains—share structural changes in the economic and political organization of the communities. These results in the emergence of complex societies characterized by political hierarchies, economic centralization and, in many areas, the first urban centers [45, 46].

The rich Late Chalcolithic pottery assemblages of Arslantepe, all found in primary contexts, refer to various spheres of pottery production and manufacturing traditions, and provide a significant record to investigate organizational, economic, and cultural changes. The Late
Chalcolithic sequence is divided into three main phases corresponding to the Late Chalcolithic 1–2, Late Chalcolithic 3–4 and Late Chalcolithic 5 in the Mesopotamian chronology [46, 47]. The first Late Chalcolithic phase (LC1-2 or Arslantepe period VIII in the site sequence: ca. 4700–3900 BCE) consists in eight levels excavated so far; all are characterized by small domed units, typically with some rooms devoted to food processing [48, 49]. The pottery is entirely handmade throughout the whole period, with surfaces either scraped or left plain, while burning and slipping rarely occur among surface treatments (Fig 2a and 2b). As for shapes, bowls predominate over beakers, basins, bottles, jars, and pithoi. Approximately 15% of the pottery is mass-produced (Fig 2b), namely light-colored coarse chaff-tempered bowls with scraped bottoms generally referred to as “Coba bowls” [50]. In the pottery assemblages of all Mesopotamia this period marks the disappearance of painted decorations and high-fired fine grit fabrics, testifying to a new role of ceramic containers within the communities [30, 48]. Pottery production loses its symbolic and representative character and becomes oriented towards efficiency, functional goals and serialization. These changes are related to increasingly repetitive and more and more widely shared social practices such as food consumption and redistribution.

Increasing social complexity at Arslantepe is more clearly visible in the subsequent Late Chalcolithic phases. During the Late LC3-4 (period VII: ca. 3900–3400 BCE), the settlement enlarges and becomes internally structured in residential and public areas [44]. Two large tripartite buildings occupied the uppermost part of the hill; their monumentality and decorations together with the thousands of clay sealings and mass-produced bowls (Fig 2e) found in them have been interpreted as evidence of ritualized redistributive activities [45: 8–10, 51]. This phase marks also the introduction of rotating devices in the ceramic manufacturing process. In addition to the wheel-finished mass-produced bowls, the pottery assemblage comprises wheel-finished plain or red-slipped burnished jarlets, beakers and jars as well as handmade and wheel-finished globular cooking pots [52, 53] (Fig 2c, 2d and 2f). The occurrence of marks on some wheel-finished vessels has been interpreted as a means for the producers to recognize their own pots in shared drying areas and firing facilities [54, 55]. At the end of the period, a few handmade red-black or monochrome burnished vessels—mainly high-stemmed bowls—of Central-Anatolian influence appeared [56], and this coincides with the first attestation at the site of a caprine-oriented husbandry strategy [57].
During the final phase of the Late Chalcolithic (LC5, Arslantepe period VIA: ca. 3400–3200 BCE) the centralization of resources progressed and a local ‘early state’ society with a proto-palatial complex was established at the site [42, 44, 58–62]. The mass-production of bowls (Fig 2h) devoted to the redistribution of meals increased due also to the hypothesized introduction of the fast wheel in the manufacturing process, and potter’s marks totally disappeared. The rest of the ceramic repertoire (Fig 2g and 2i) comprises wheel-finished light-colored jars, jarlets and high-stemmed bowls, as well as handmade storage containers and cooking pots [62–65]. The handmade red-black and monochrome burnished vessels (Fig 2i) increase in number and now exhibit a wider formal and functional repertoire including bowls, cups, jars, jarlets, typical high-stemmed bowls and a few pithoi [56, 62, 66–68].

Wares, forming techniques and morphometric analyses

At Arslantepe ceramic wares have been conventionally distinguished since the 1970s on the basis of specific macroscopic hierarchical criteria, namely texture (coarse/semifine/fine), tempering material (chaff/grit/mixed), shaping techniques (handmade/wheel-finished), surface treatments (slipping/burnishing/smoothing) and colors (red-black/black/red/brown/light-colored) [52, 62, 64, 65]. Morphological criteria have been considered separately, at another level of analysis, and formed the basis for further functional observations. This classification statistically consolidated across decades thanks to the analysis of thousands of diagnostic sherds and complete vessels found in primary contexts of deposition [48, 49, 62, 64]. Interestingly, the correlation between shapes (morphological types) and wares increases through time. It is in fact during the LC5 that the strongest correspondence between pots with a specific shape and wares occurs, with only two exceptions: the high-stemmed bowls (Fig 2i) and small jarlets with an S-shaped/sinuous profile (Fig 2g), both realized in fine light-colored wheel-finished and red-black burnished ware. In the previous LC3-4 period most vessel shapes are invariably realized in either wheel-finished or handmade wares, the former being anyway a minority of the total assemblage [69]. The term “mass-produced”, conventionally adopted in Mesopotamian Archaeology, refers to specific categories of bowls produced on a large scale—usually hundreds or even thousands of items of the same vessel category in terms of shape, function, and approximate size—and found all together in the same contexts. This term therefore crosses technical, quantitative and typological criteria.

In the late 1960s and 1970s, Alba Palmieri already argued for the introduction and frequent use of rotating devices in the manufacture of LC3-4 pottery [70] and the introduction of the fast-wheel by the LC5 due to the recurrence on some vessel shapes of inner concentric grooves and underside string cut impressions [71]. Palmieri’s initial observations were then confirmed and broadened by other scholars working on the LC material from Arslantepe [48, 52, 62, 64, 69]. I cannot discuss this hypothesis in detail here, but following the more recent contributions on wheel-based forming techniques [72] I am currently investigating the LC repertoire. My recent work demonstrates that during the LC4 (end of period VII in the site sequence) the use of turning devices consolidates by entering progressively earlier stages of the forming sequence [73, 74]. This is especially evident for the mass-produced bowls at both a microscopic and macroscopic level (Fig 3). Microscopically, the temper fraction follows strongly oriented patterns and the clay matrix shows evidence of shear stresses. Macroscopically, concentric striations/grooves spread along the entire vessel profiles, the wall thickness gets gradually thinner towards the rim, profiles gain in symmetry, while linear discontinuities and anomalies in correspondence of structural joints decrease or even disappear.

In this paper vessels were distinguished depending on whether or not they were produced with the help of rotating devices, whatever the stage of the forming sequence these devices
entered in. These two large categories are here referred to as handmade and wheel-finished vessels, even though the latter might have combined different forming techniques. This broad categorization puts the emphasis on the most significant technical innovation of the period, i.e. the introduction of turning devices, and related hypotheses on craft specialization and standardization. At Arslantepe wheel-finished vessels are mainly distinguished by horizontal and parallel striations or grooves that might appear on the different surfaces of the vessel body (Fig 4). These diagnostic traces result from finishing, thinning, shaping or cutting vessels while turning. Striations might also occur on vessel surfaces without the use of any rotating devices due to finishing procedures like smoothing and burnishing. However, striations visibly differ depending on whether or not they were generated by the application of the rotational kinetic energy (Fig 5). On wheel-finished vessels striations appear as dense, fine, ribbed, continuous and homogeneous lines, which are evenly spaced from each other and organized in horizontal parallel concentric bands. Moreover, a typical fluidized surface microtopography is often associated with these features. The striations obtained without the rotational kinetic energy are instead much more heterogeneous both in shape and orientation [72: 236–240]. Further
diagnostic features of wheel-finished vessels are regular wall thicknesses, stretched surfaces and strong symmetry of profiles.

To assess the morphological variability of the LC3-4 to LC5 pottery repertoire, Guarino and D’Anna calculated the coefficient of variation (CV) on the ratios between maximum diameter and height, rim diameter and maximum diameter, and rim diameter and height of specific
vessel types [66, 71]. Usually, an assemblage of ceramics with CV below 10% is considered to have a low level of variability as the result of specialized potters [5, 18, 22, 27]. At Arslantepe most of the LC3-5 vessels present higher CVs (Table 1). Values indicating a higher standardization surprisingly recur in the handmade vessels, while the serial production of bowls with the help of rotating devices does not inevitably imply a decreased variability. Lastly, the LC5 does not mark an increase in standardization despite the stronger incidence of the rotational kinetic energy in the manufacturing process.

**Geological setting and raw material supply**

The site of Arslantepe (Fig 6) lies on Miocene lake sediments, mainly consisting of calcareous clays, limestones and sandstones [75]. Immediately northeast of the site, at a distance of 700 m, is the remnant of the Middle Miocene Orduzu volcanic suite [76] composed of rhyolites,
Approximately 5.5 km further east we find the Late Cretaceous Baskil magmatic and the Maastrichtian to the Early Eocene Yüksekova/Elazığ complex, dominated by volcanic and intrusive rocks ranging from mafic to felsic affinities, i.e. gabbros, diorites, tonalities, monzonites, basaltic andesites, andesites, dacites and rhyolites [78, 79].

More distant and spatially widespread are the units of the Antitaurus mountain chains that start rising 7 to 10 km south of the site. The western part of these units belongs to the Malatya metamorphics distinguished by Carboniferous to Triassic meta-carbonate rocks, mica schists, phyllites, slates, meta-clastic rocks and meta-cherts [80, 81]. The eastern part is instead dominated by the Late Cretaceous Ispendere ophiolites and the Middle Eocene Maden Complex. The former exhibit an intact ophiolitic sequence intruded by granites [82], the latter a volcanosedimentary sequence with conglomerates, sandstones, limestones, mudstones, spilitic lavas, radiolarites, cherts, altered basalts and andesites [80, 81, 83].

Most of the above-mentioned formations were exploited for producing vessels at Arslantepe, with distinct patterns according to the chronological phases and/or type of wares [84–86]. The variety of geological formations locally available [87] represents a double-edged sword from a methodological point of view and especially for minero-petrographic applications. On the one hand, we are able to outline precise strategies of raw material procurement within the local landscape; on the other, we often have difficulties in distinguishing local from imported vessels. To this end, thin section petrography is integrated with geochemical analyses of both vessels and local raw materials [84–86].

### Sampling strategy and methods

The samples under investigation represent the variety of ceramic shapes and wares produced at the site along the entire Late Chalcolithic sequence (ca. 4700–3200 BCE). As illustrated above, within the assemblage of each period, wares have been macroscopically identified on the basis of the consistent co-occurrence of fabrics, manufacturing techniques, surface treatments, firing procedures, and, when present, decorations. Sampling strategies aimed at accounting for the duration of each period and the associated amount of materials recovered so far. This allows us to mitigate the cumulative blurring effect, namely the higher variability

| Manufacturing | Vessel classes                  | Considered ratios | CV ranges |
|---------------|--------------------------------|-------------------|-----------|
| wheel-finished| serving/storage jars           | Ø rim / Ø max     | 9.37–21.30|
|               | cooking pots                   | Ø rim / Ø max     | 8.44–9.87 |
|               | mass-produced bowls            | Ø rim / height    | 10.94–17.87|
| handmade      | serving/storage jars           | Ø rim / Ø max     | 17.59     |
|               | cooking pots                   | Ø rim / Ø max     | 5.94–6.82 |
| wheel-finished| mass-produced bowls            | Ø rim / height    | 13.06     |
|               | necked-jars                    | Ø max / height    | 4.6–10.5  |
|               |                                | Ø rim / Ø max     | 13.1–17.8 |
|               |                                | Ø rim / height    | 11.9–22   |
|               | fine jarlets                   | Ø rim / height    | 10.4–13.2 |
|               |                                | Ø rim / Ø max     | 10.7–11.7 |
| handmade      | cooking pots                   | Ø max / height    | 6.8–13.2  |
|               |                                | Ø rim / Ø max     | 5.1–16.5  |
|               | monochrome/red-black burnished ware | Ø rim / height     | 5.15–17.58 |

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that production events generate along longer time-spans [36]. Thus, mostly represented here is the vast vessel repertoire of the long-lasting LC3-4 phase (97 samples). By contrast, the few samples (19) from the LC1-2 refer to a single context within the entire phase and are rather intended to act as reference for a non-standardized production [48, 49]. The assemblages of the following LC3-4 and LC5 phases (51 samples)—which provide us with evidence of economic centralization, intensification of production rates and introduction of the wheel—are instead those used in this paper to test the standardization hypothesis. At any rate, this study is intended as a first small-scale experiment aimed at testing the potential of diversity statistics in

Fig 6. Selected micro-pictures illustrating the main petro-groups. Image: ÖAW-ÖAI / P. Fragnoli.

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assessing craft standardization with the objective of being subsequently applied and adjusted to a wider sampling also including other geographic and chronological frameworks. The permission for pottery sampling and analysis was kindly issued by the Turkish authorities.

Since the paper aims at assessing the uniformity of the local production modes, vessels of underrepresented foreign typology (e.g. the rare beveled rim bowls found at the site) or not matching geochemically and petrographically with local reference fields have been excluded [74, 84, 85]. The petrographic data used in this paper refer to 167 thin sections (Tables 2 and 3; Fig 6) that are grouped according to: 1) calcareous versus non-calcareous clay matrix; 2) the presence/absence of organic temper; 3) the geological origin of mineral and rock inclusions, which may refer to variegated volcanic, plutonic and metamorphic environments. Based on petrographic groupings, 60 representative samples were selected to be analyzed through wavelength-dispersive X-ray fluorescence (Table 5). Measurements were undertaken at the Archea Laboratory in Warsaw using the wavelength dispersive X-Ray Fluorescence spectrometer PANalytical AXIOS. After being ignited at 900°C, 1.5-2g powder of each sample was melted with a lithium-borate mixture and cast into small discs. Major elements were normalized to a constant sum of 100% and trace elements under the detection limit (e.g. Y, Pb, Nb, Cu) were removed. Detailed descriptions of the petro-groups as well as “more traditional” bivariate and multivariate statistical elaborations of geochemical data have already been published in the contributions of the author indicated above and for this reason are not reported again here in detail. Petrography has been applied to a higher number of samples, since it has repeatedly proven to be a more eloquent indicator of local technological practices due to the coarseness of the vessels and the occurrence of variegated and well-delimited geological formations all around the site. The selected petrographic and geochemical data considered here cover the entire local spectrum, which was previously assessed in a wider sampling and along a longer chronological span. The assessment of the diversity parameters proposed in this paper does not require any particular statistical software as they can be easily performed on Excel (S1–S3 Tables).

Assessing the variability of metric data: Pottery elemental concentrations

The geochemical variability was quantified by calculating the coefficient of variation (CV) for each element concentration measured through wavelength-dispersive X-ray fluorescence, namely SiO$_2$, TiO$_2$, Fe$_2$O$_3$, MnO, MgO, CaO, Na$_2$O, K$_2$O, P$_2$O$_5$, V, Cr, Ni, Zn, Rb, Sr, Zr and Ba. The CV is defined as the ratio between standard deviation and mean, often multiplied by 100 to be expressed as a percentage. The higher the CV, the more variable the dataset. The CV has been commonly used not only in natural sciences, medicine and psychology but also in archaeological studies on vessel formal and dimensional standardization. As shown by the latter, it differs from other indexes in providing reliable measures of variability independently of sample size and the measure of scale [22, 88–90]. Blackman and colleagues [36] also successfully used the CV to assess the geochemical variability of the 3rd millennium mass-produced bowls from Tell Leilan in northeast Syria.

Following a method proposed by Eerkens and Bettinger [22] for assessing the formal standardization of various archaeological artifacts, a scatter plot includes the mean and standard deviation of each element upon which the regression line is plotted. The regression line slopes vary according to the data variability: steeper slopes denote more variation in elemental concentrations. Furthermore, skewness and kurtosis were taken into account to estimate to what extent the data diverge from a normal distribution. In some studies on vessel formal standardization, these criteria have proven to be even more efficient than the CV to distinguish different levels of potters’ skills [90]. The skewness refers to the degree of distortion from a symmetrical
Table 2. List of the samples analyzed petrographically and related petrographic groups.

| Sample | Phase | Ceramic ware                          | Petro-group |
|--------|-------|---------------------------------------|-------------|
| 126/14 | LC1-2 | handmade plain grit ware              | NC          |
| 127/14 |       | handmade plain grit ware              | CIb         |
| 128/14 |       | handmade plain grit ware              | NC          |
| 129/14 |       | handmade plain grit ware              | CIb         |
| 130/14 |       | handmade plain ware                   | VIm         |
| 131/14 |       | handmade plain ware                   | NC          |
| 132/14 |       | handmade plain ware                   | NC          |
| 133/14 |       | handmade plain ware                   | Vla         |
| 134/14 |       | handmade burnished ware               | NC          |
| 135/14 |       | handmade burnished ware               | NC          |
| 136/14 |       | handmade burnished ware               | NC          |
| 137/14 |       | handmade burnished ware               | NC          |
| 138/14 |       | handmade burnished ware               | VIm         |
| 139/14 |       | handmade mass-produced bowl            | VIm         |
| 140/14 |       | handmade mass-produced bowl            | NC          |
| 141/14 |       | handmade mass-produced bowl            | VIm         |
| 142/14 |       | handmade plain ware                   | Vla         |
| 143/14 |       | handmade mass-produced bowl            | NC          |
| 144/14 |       | handmade mass-produced bowl            | NC          |
| 3638   | LC3-4 | wheel-finished red-slipped burnished ware | VCEm-a     |
| 3639   |       | wheel-finished red-slipped burnished ware | VCEm-a     |
| 3641   |       | wheel-finished red-slipped burnished ware | VCEm-a     |
| 3642   |       | wheel-finished red-slipped burnished ware | VCEm-a     |
| 3643   |       | wheel-finished red-slipped burnished ware | VCEm-a     |
| 3644   |       | wheel-finished red-slipped burnished ware | VCIb     |
| 3645   |       | wheel-finished red-slipped burnished ware | VCIb     |
| 3646   |       | wheel-finished kitchen ware           | VCIb        |
| 3647   |       | wheel-finished kitchen ware           | VCIb        |
| 3648   |       | wheel-finished kitchen ware           | VCIb        |
| 3649   |       | wheel-finished red-slipped burnished ware | VCIb     |
| 3650   |       | wheel-finished chaff-temperred smoothed ware | VCIb |
| 3651   |       | wheel-finished chaff-temperred smoothed ware | VCIb |
| 3654   |       | wheel-finished kitchen ware           | VCIb        |
| 3655   |       | handmade kitchen ware                 | VCIb        |
| 3656   |       | wheel-finished mass-produced bowl      | VCEm-a      |
| 3657   |       | wheel-finished mass-produced bowl      | VCIb        |
| 3658   |       | wheel-finished mass-produced bowl      | VCEm-a      |
| 3660   |       | wheel-finished mass-produced bowl      | VCEm-a      |
| 3661   |       | wheel-finished mass-produced bowl      | VCEm-a      |
| 3662   |       | wheel-finished mass-produced bowl      | VCEm-a      |
| 3663   |       | wheel-finished red-slipped burnished ware | VCEm-a+Ib  |
| 3673   |       | wheel-finished red-slipped burnished ware | VCEm-a+Ib  |
| 3674   |       | wheel-finished red-slipped burnished ware | VCEm-a+Ib  |
| 3675   |       | wheel-finished red-slipped burnished ware | VCIb     |
| 3676   |       | wheel-finished red-slipped burnished ware | VCEm-a+Ib  |

(Continued)
| Sample  | Phase | Ceramic ware                               | Petro-group |
|---------|-------|--------------------------------------------|-------------|
| 103/14  |       | wheel-finished chaff-tempered smoothed ware| VCIb        |
| 104/14  |       | wheel-finished red-slipped burnished ware  | NC          |
| 105/14  |       | wheel-finished chaff-tempered smoothed ware| Vlb         |
| 107/14  |       | wheel-finished chaff-tempered smoothed ware| Vlb         |
| 159/14  |       | wheel-finished red-slipped burnished ware  | VC          |
| 257/14  |       | wheel-finished chaff-tempered smoothed ware| VCEm-a+lb   |
| 271/14  |       | wheel-finished red-slipped burnished ware  | VCEm-a+lb   |
| 272/14  |       | handmade light-colored ware                | VC          |
| 273/14  |       | handmade light-colored ware                | Vlb         |
| 274/14  |       | handmade red-black/monochrome burnished ware| NC          |
| 275/14  |       | handmade light-colored ware                | Vlb         |
| 276/14  |       | handmade kitchen ware                      | Vlb         |
| 277/14  |       | handmade kitchen ware                      | NC          |
| 300/14  |       | wheel-finished red-slipped burnished ware  | VCEm-a+lb   |
| 301/14  |       | wheel-finished mass-produced bowl          | VCEm-a      |
| 304/14  |       | wheel-finished mass-produced bowl          | VC          |
| 305/14  |       | wheel-finished red-slipped burnished ware  | VCIb        |
| 307/14  |       | wheel-finished kitchen ware                | VMgne       |
| 309/14  |       | wheel-finished chaff-tempered smoothed ware| Vlb         |
| 370/14  |       | wheel-finished chaff-tempered smoothed ware| VMgne       |
| 371/14  |       | wheel-finished chaff-tempered smoothed ware| VCEm-a+lb   |
| 372/14  |       | wheel-finished chaff-tempered smoothed ware| Vlb         |
| 375/14  |       | wheel-finished red-slipped burnished ware  | VCEm-a+lb   |
| 376/14  |       | wheel-finished red-slipped burnished ware  | VC          |
| 109/14  |       | wheel-finished mass-produced bowl          | VCEm-a      |
| 155/14  |       | wheel-finished red-slipped burnished ware  | VCEm-a      |
| 156/14  |       | wheel-finished red-slipped burnished ware  | VCIb        |
| 157/14  |       | wheel-finished red-slipped burnished ware  | VCEm-a+lb   |
| 158/14  |       | wheel-finished red-slipped burnished ware  | VC          |
| 160/14  |       | wheel-finished red-slipped burnished ware  | VCIb        |
| 161/14  |       | wheel-finished red-slipped burnished ware  | VCEm-a      |
| 162/14  |       | wheel-finished red-slipped burnished ware  | VC          |
| 163/14  |       | wheel-finished red-slipped burnished ware  | VCEm-a      |
| 258/14  |       | wheel-finished chaff-tempered smoothed ware| VCIb        |
| 259/14  |       | wheel-finished kitchen ware                | Vlb         |
| 260/14  |       | wheel-finished chaff-tempered smoothed ware| Vlb         |
| 261/14  |       | handmade kitchen ware                      | VEm         |
| 262/14  |       | handmade kitchen ware                      | VEm         |
| 278/14  |       | handmade kitchen ware                      | NC          |
| 279/14  |       | handmade light-colored ware                | VCEm-a+lb   |
| 280/14  |       | handmade kitchen ware                      | VMqu-sc     |
| 281/14  |       | wheel-finished chaff-tempered smoothed ware| VCEm-a+lb   |

(Continued)
Table 2. (Continued)

| Sample  | Phase | Ceramic ware                                | Petro-group |
|---------|-------|---------------------------------------------|-------------|
| 282/14  |       | wheel-finished light-colored fine ware       | C           |
| 283/14  |       | wheel-finished light-colored fine ware       | C           |
| 284/14  |       | wheel-finished mass-produced bowl            | VC          |
| 285/14  |       | wheel-finished light-colored fine ware       | C           |
| 286/14  |       | wheel-finished light-colored fine ware       | C           |
| 287/14  |       | wheel-finished light-colored fine ware       | VC\text{-}a+\text{Ib} |
| 288/14  |       | wheel-finished light-colored fine ware       | NC          |
| 289/14  |       | wheel-finished light-colored fine ware       | C           |
| 290/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 291/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 293/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 294/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 295/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 296/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 299/14  |       | wheel-finished chaff-tempered smoothed ware  | VEm         |
| 302/14  |       | wheel-finished mass-produced bowl            | VEm\text{-}a |
| 303/14  |       | wheel-finished mass-produced bowl            | VC          |
| 306/14  |       | wheel-finished chaff-tempered smoothed ware  | VC          |
| 308/14  |       | wheel-finished red-slipped burnished ware    | VC\text{Ib} |
| 366/14  |       | wheel-finished red-slipped burnished ware    | VEm\text{-}a+\text{Ib} |
| 367/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 368/14  |       | wheel-finished red-slipped burnished ware    | VEm\text{-}a |
| 369/14  |       | handmade light-colored ware                  | VC          |
| 373/14  |       | handmade kitchen ware                        | VMqu\text{-}sc |
| 374/14  |       | wheel-finished chaff-tempered smoothed ware  | VEm\text{-}a+\text{Ib} |
| 450/14  |       | wheel-finished light-colored fine ware       | NC          |
| 310/14  |       | wheel-finished red-slipped burnished ware    | VEm\text{-}a |
| 3595    | LC5   | handmade red-black/monochrome burnished ware | NC          |
| 3558    |       | handmade red-black/monochrome burnished ware | NC          |
| 3560    |       | handmade red-black/monochrome burnished ware | NC          |
| 3594    |       | handmade red-black/monochrome burnished ware | NC          |
| 3554    |       | wheel-finished mass-produced bowl            | VEm\text{-}a |
| 223/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 225/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 227/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 230/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 232/14  |       | handmade red-black/monochrome burnished ware | NC          |
| 2/2015  |       | handmade red-black/monochrome burnished ware | NC          |
| 4/2015  |       | handmade red-black/monochrome burnished ware | NC          |
| 5/2015  |       | handmade red-black/monochrome burnished ware | NC          |
| 3593    |       | handmade red-black/monochrome burnished ware | VEm         |
| 3559    |       | handmade red-black/monochrome burnished ware | VEm         |
| 224/14  |       | handmade red-black/monochrome burnished ware | VMgne       |
| 229/14  |       | handmade red-black/monochrome burnished ware | VMgne       |
| 231/14  |       | handmade red-black/monochrome burnished ware | VMgne       |
| 234/14  |       | handmade red-black/monochrome burnished ware | VMgne       |
| 235/14  |       | handmade red-black/monochrome burnished ware | VMgne       |

(Continued)
data distribution, while the kurtosis measures the tailedness of this distribution, providing an indication of the presence of outliers. The closer to zero values the skewness and kurtosis are, the more normal is the distribution of data. Both skewness and kurtosis were calculated via the formulas available on Excel based on Fisher’s coefficient:

\[
\text{Skewness} = \frac{n}{(n-1)(n-2)} \sum \left( \frac{x_i - \bar{x}}{s} \right)^3
\]

\[
\text{Kurtosis} = \left\{ \frac{n(n+1)}{(n-1)(n-2)(n-3)} \sum \left( \frac{x_i - \bar{x}}{s} \right)^4 \right\} - \frac{3(n-1)^2}{(n-2)(n-3)}
\]

| Sample  | Phase                  | Ceramic ware                        | Petro-group |
|---------|------------------------|-------------------------------------|-------------|
| 228/14  | handmade red-black/monochrome burnished ware | NC                                   |
| 236/14  | handmade red-black/monochrome burnished ware | VMmetag                             |
| 1/2015  | handmade red-black/monochrome burnished ware | VMmetag                             |
| 3/2015  | handmade red-black/monochrome burnished ware | VMmetag                             |
| 253/14' | handmade kitchen ware | NC                                   |
| 254/14' | handmade kitchen ware | NC                                   |
| 250/14' | handmade kitchen ware | VMmetag                             |
| 255/14' | handmade kitchen ware | VMmetag                             |
| 249/14' | handmade kitchen ware | VMgne                                |
| 252/14' | handmade kitchen ware | VMgne                                |
| 247/14' | wheel-finished light-colored semifine ware | VCEm-a+Ib                            |
| 3554    | wheel-finished mass-produced bowl | VCEm-a                               |
| 3555    | wheel-finished light-colored semifine ware | VCEm-a                               |
| 241/14' | wheel-finished light-colored fine ware | VCEm-a                               |
| 240/14' | wheel-finished light-colored fine ware | VClb                                 |
| 242/14' | wheel-finished light-colored fine ware | VClb                                 |
| 3548    | wheel-finished light-colored fine ware | VClb                                 |
| 3600    | wheel-finished light-colored fine ware | VClb                                 |
| 248/14' | wheel-finished light-colored semifine ware | CEb-m                                |
| 3551    | wheel-finished light-colored fine ware | CEb-m                                |
| 239/14' | wheel-finished light-colored fine ware | CEb-m                                |
| 238/14' | wheel-finished light-colored fine ware | CEb-m                                |
| 3601    | wheel-finished light-colored fine ware | CEb-m                                |
| COLL206/16' | wheel-finished mass-produced bowl | VCEm-a+Ib                            |
| COLL202/16' | wheel-finished mass-produced bowl | VCEm-a+Ib                            |
| COLL222/16' | wheel-finished mass-produced bowl | VCEm-a+Ib                            |
| COLL208/16' | wheel-finished mass-produced bowl | VCEm-a+Ib                            |
| COLL163/16' | wheel-finished light-colored semifine ware | VCEm-a+Ib                            |
| COLL219/16' | wheel-finished light-colored semifine ware | VCEm-a+Ib                            |
| COLL188/16' | wheel-finished light-colored fine ware | VCEm-a+Ib                            |

Each petrographic group is mentioned according to the following acronyms: V = organic tempered pastes; C = calcareous clay; E, M and I = Inclusions of effusive, metamorphic and intrusive origin; b, m, a = basic, intermediate and acid composition; for the metamorphic rocks gne, metag and qu-sc are abbreviations of gneiss, metagabbro and quartz-schist. NC (not classifiable) refers to petro-loners. The samples marked with an asterisk are new, while the other ones have been already published [74, 84, 85].

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where \( n \) is the number of variables, \( x_i \) the 1\textsuperscript{st} random variable, \( \bar{x} \) the mean of the distribution and \( s \) the standard deviation of the distribution.

The CVs calculated separately on each element have the disadvantage of overlooking the correlations between elemental patterns existing in ceramic artifacts. To obviate this, a series of variation matrixes (S1 Table) were produced following the method introduced by Aitchison [91, 92] and further developed for pottery analysis by Buxeda i Garrigós and Kilikoglou [37, 93]. Variation matrixes are defined by the variances of the natural log-ratios calculated on every pair of elements present in the data set. From the variation matrix one can calculate the total variation, which quantifies the variability of the data set and is also related to the Euclidean distances among all specimens [94]. The total variation is defined as the sum of all the variances in the variation matrix divided by two times the number of elements determined. The variation matrix can also be used to determine the variance of an element, which is equal to the sum of the variances calculated on all the log-ratios that use this element as divisor. This value gives an estimate of the contribution of this element to the total variation of the data set [91, 93]. In ceramic studies the total variation has frequently been applied to estimate intra-deposit variations, post-depositional alterations as well as the monogenic vs. polygenic nature of the data set. However, it is rarely coupled with thin section petrography to assess the level of standardization of raw material procurement and processing.

### Assessing the variability of non-metric data: Pottery petrographic grouping

Petrographic analyses of archaeological vessels usually aim at grouping thin sections into reference groups that ideally represent the ceramic pastes prepared in a certain way and place. The

| Petro-group | Main inclusions | Inclusion max. size/amount |
|-------------|----------------|--------------------------|
| C           | ca, for, qu, bt| 1.4mm/7%                 |
| Ceb-m       | ca, pl, qu, basaltic andesite, bt, qu-kfds aggregate, amph, cpx, ox, mu | 0.7mm/15% |
| CEm-a       | ca, trachyte-rhyolite, limestone, pl, ox, mu, amph, bt | 1.4mm/7% |
| Clb         | gabbro, pl, ca, for | 2mm/10% |
| VC          | veg, qu, ca, pl | 3.3mm/7% |
| VCEm        | veg, ca, pl, andesite, amph, bt, cpx, pumice, qu, ox | 2mm/25% |
| VCEm-a      | veg, ca, trachyte-rhyolite, limestone, qu, pl, ox, amph, bt, mu, sandstone | 3.7mm/10% |
| VCEm-a+1b   | veg, ca, trachyte-rhyolite, gabbro, pl, qu, limestone, amph, ox, sandstone | 5.6mm/10% |
| VClb        | veg, ca, gabbro, pl, ox, cpx, trachyte-rhyolite, limestone, sandstone, for, granite, qu, opx | 7mm/15% |
| VEm         | veg, pl, andesite, amph, bt, qu, cpx, pumice, opx | 3.7mm/25% |
| V1a         | veg, granite, qu, kfds, pl, bt, amph | 2mm/15% |
| V1b         | veg, gabbro, pl, ox, cpx, trachyte-rhyolite, qu, granite | 7.8mm/20% |
| V1m         | veg, diorite, qu, pl, kfds, amph | 4mm/20% |
| VMgne       | veg, gneiss, qu, amph, pl, bt, kfds | 5mm/20% |
| VMmetag     | veg, metagabbro, cpx, gneiss, amphibolite, qu, pl, kfds | 5.17mm/24% |
| VMqu-sc     | veg, mu-schist, qu-schist, mu, qu, bt, ox | 4.8mm/30% |

The types of inclusions are listed in decreasing order of importance. Abbreviations: veg = vegetal fibers; ca = calcite; pl = plagioclase; qu = quartz; bt = biotite; amph = amphibole; cpx = clinopyroxene; mu = muscovite; for = foraminifera; Kfds = K-feldspar; ox = oxide; opx = orthopyroxene. Further details have been reported in previous publications [74, 84, 85].

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results are non-metric classifications similar to those obtained through typological methods. To assess the variability of such non-metric classification I applied three necessary and inextricably linked properties of diversity, which are employed across a full range of disciplines according to different degrees of prioritization and terminologies [95–97]. Here I will call these properties richness, evenness, and disparity (Fig 7). Richness can be also referred to as “variety”, and considers the number of categories—represented by petro-groups in this paper—in which elements are sorted. Evenness quantifies how equal is the distribution of elements across categories. In the present case it expresses how ceramic thin sections are distributed into each petro-group. Thus, evenness is analogous to statistical variance and can also be defined as “balance” or “concentration”. Ecological studies tend to focus on questions of richness and evenness due to the occurrence of well-established taxonomic schemes [96]. The concept of disparity—taken from paleontology and extensively used in conservation biology—indicates to what extent categories, for instance petro-groups, are different from each other, and is usually based on some form of distance measure. Typically, the greater the richness, evenness and disparity, the greater the diversity.

To quantify richness, evenness and variety I applied several indexes to the petrographic classification (Table 4). As for richness, I first considered the percentage of petro-loners. Petro-loners are composed of minerals and rocks of all local origin but differently combined with each other and in distinct grain-size distributions compared to the samples classified into petro-groups. In other words, these are vessels produced with different local deposits and/or recipes. Thus, petro-loners are random local recipes, which are comparable to *unica* in taxonomic classifications. Within single categories (e.g. periods, wares, manufacturing techniques) petro-groups that are represented by only one sample have been counted as petro-loners, even though they share features with samples outside the considered category. For instance, the

Table 4. Parameters considered for assessing the three different properties of diversity at a petrographic level.

| Richness       |            |            |
|----------------|------------|------------|
|                | % petro-loners | Menhinick’s index |
|                |            | Shannon’s index |
| Evenness       | Highest disparity in recipe abundance | Average number of samples per petro-group |
|                | Pielou’s index | Shannon’s index |
| Disparity      | Jaccard’s dissimilarity % |

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handmade kitchen ware 262/14 is a loner within the handmade wares of the LC3-4, but not
within the LC3-4 as a whole, since in this period two wheel-finished vessels (samples 261/14
and 299/14) present the same recipe (petro-group VEm). The richness was also quantified
through the Menhinick’s and Shannon’s indexes (S2 Table), both commonly adopted in the
ecological literature as a measure of biodiversity [98]. The Menhinick’s index is a simple species
counting that attempts to reduce the effect of sample size on richness quantification, i.e.
increased richness with larger sampling, by dividing the number of species recorded by the
number of individuals in the sample. It is given here by the number of petro-groups divided
the square root of the number of thin sections analyzed. The Shannon’s index was originally
used within information theory to measure the entropy contained in a text based on the num-
ber and abundance of letter types [99]. The idea behind ecological applications is that the
diversity of a community is similar to the amount of information in a code or message. For the
purpose of calculations, the number of samples recurring in each recipe, including both petro-
groups and loners, was divided by the total number of samples; this proportion was multiplied
by its natural logarithm; the resulting product was summed across recipes and multiplied
by -1:

\[
\text{Shannon's index } = -\sum_{i=1}^{s} p_i \ln p_i
\]

where \( p_i \) is the proportion of the population made of species \( i \) and \( s \) the number of species.

Since Shannon’s index considers not only the number of petro-groups but also the distribu-
tion of thin sections into petro-groups, it has also been considered to assess the evenness.
Evenness was also evaluated through the relative abundance of each recipe and especially
through the maximum difference in abundance between the most and the least represented
recipe. Both petro-groups and petro-loners were counted as more and less established recipes,
respectively. In order to assess the evenness of only well-established recipes a further parame-
ter was calculated by excluding the petro-loners, namely the average number of samples per
petro-group. Last but not least, I calculated the Pielou’s index (S2 Table), which is obtained by
dividing the Shannon’s index with the highest possible value this index could have in case of
highest variability. Disparity measures are generally based on distances or dissimilarity coeffi-
cients, which indicate how dissimilar two cases are considering simultaneously all the variables
for which they have been defined [100]. Dissimilarity coefficients are obtained by subtracting 1
from similarity coefficients. There are different similarity/dissimilarity coefficients according
to the considered variables, of either a quantitative or qualitative nature. In this paper, I took
into account and converted into percent the Jaccard distance based on the presence and
absence of some basic ingredients that may occur across different petro-groups (S3 Table):

\[
\text{Jaccard's dissimilarity } \% = 1 - \text{Jaccard's coefficient} \times 100
\]

where

\[
\text{Jaccard's coefficient } = \frac{\text{number of present} - \text{present matches}}{\text{number of present} - \text{present matches} + \text{mismatches}}
\]

These basic ingredients correspond to the main discriminating criteria adopted for group-
ing ceramic thin sections [85] and are registered in the acronyms of each petro-group
(Table 2). These are organic temper (V), calcareous matrix (C), granite (Ia), diorite (IIm),
quartz-schist (qu-sc), gabbro (Ib), trachyte-rhyolite (Em-a), andesite (Em), basaltic andesite
(Eb-m), metagabbro (metag) and gneiss (gne). The Jaccard’s distance has not been calculated
on petro-loners, which in a sense already represent an index of maximal disparity due to their
lack of affinity with any other sample. While the assessment of disparity finds many applications in archaeology (e.g. cemetery analyses), richness and evenness are rarely considered even in specialized handbooks [100]. However, these latter indexes allow us to further nuance the concept of diversity and could be successfully applied to any kind of archaeological classification—e.g. morpho-functional, typological and stylistic—beyond standardization studies.

In summary, a high standardization of ceramic recipes should ideally correspond to low values of all diversity indexes (i.e. Menhinick’s, Shannon’s, Pielou’s and Jaccard’s), a reduced number of petro-loners, an unequal distribution of samples across petro-groups, and a high average number of samples per petro-groups.

Results
Geochemical homogenization as a result of production serialization

In order to compare each Late Chalcolithic phase—i.e. LC1-2 (Arslantepe VIII), LC3-4 (VII) and LC5 (VI A)—I plotted on a line graph the mean of the CVs calculated for each element (Table 5 and Fig 7a) and I found that the geochemical variability tends to decrease throughout the LC period in terms of both major and trace elements. An identical trend can be inferred from the scatterplot (Fig 7b) relating the standard deviation with the mean of all elements: the regression line of the LC1-2 is steeper compared to those of the following phases, suggesting a higher compositional variability. The geochemical homogenization across the Late Chalcolithic becomes even more pronounced when considering the elemental variance and the total variation (Fig 8, Table 5). The elements responsible for the highest variability of the first Late Chalcolithic phase are Al₂O₃, TiO₂, MnO, MgO, Na₂O and Zr.

The diachronic trend towards normality revealed by the skewness and kurtosis (Table 5 and Fig 9a–9c) is not as gradual as that towards homogeneity mentioned above: after the LC1-2 (Fig 9a), the LC3-4 marks a break distinguished by the most asymmetric and heavy-tailed distribution of data due especially to Fe₂O₃, MnO, P₂O₅, Zn and Ba concentrations (Fig 9b), followed by the final Late Chalcolithic phase (5) that shows the highest normality (Fig 9c).

Within each Late Chalcolithic sub-phase, the variability indexes noticeably fluctuate according to the production rate and manufacturing techniques (Tables 6 and 7; Figs 10a–10c and 11a–11c). In the first Late Chalcolithic phase, when the whole production is still entirely handmade, the mass-produced bowls show slightly lower values of elemental CVs and variances as well as of total variation (Tables 6 and 7; Figs 10a and 11a), while the burnished ware exhibits the highest geochemical variability for all the considered parameters. In the following phases (Tables 6 and 7; Figs 10b, 10c, 11b and 11c), that part of the assemblage which is now shaped on the wheel is chemically more homogeneous than handmade vessels. The calculations on LC3-4 wheel-finished vessels also include mass-produced bowls; when extrapolated, mass-produced bowls show a wider gap with the rest of the wheel-finished vessels (difference in total variation = 1.67) than that separating these latter from handmade exemplars (difference in total variation = 0.5). Chemical CVs and total variations calculated separately (S1 Table; Tables 8 and 9) on each single ware of the LC3-4 period evidence further interesting trends. The handmade monochrome/red-burnished and kitchen wares stand out for their chemical variability, while a much more homogeneous composition occurs in the wheel-finished mass-produced bowls and chaff-tempered smoothed ware as well as in the handmade light-colored ware. Intermediate values were instead obtained for the wheel-finished red-slipped burnished, kitchen and light-colored fine wares. Thus, the LC3-4 chemical variability is affected not only by the forming techniques and production rates but also by the type of surface treatments, firing conditions and the calcareous content of the clay matrix. Chemically more heterogeneous are the vessels with a non-calcareous clay matrix, burnished and fired in...
Table 5. Major (weight %) and trace element (parts per million) concentrations as well as associated means, standard deviations (dev std), coefficients of variation (CV), skewness, kurtosis, elemental variance and total variation within each LC sub-phase.

| Sample       | Phase                      | Ceramic ware                  | TiO2 | TiO3 | Al2O3 | FeO   | MnO  | MgO  | CaO  | Na2O | K2O  | P2O5 | V    | Cr   | Ni   | Zn   | Rb   | Sr   | Zr   | Ba   |
|--------------|----------------------------|-------------------------------|------|------|-------|-------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 301/14       | wheel-finished mass-produced bowl | 44.41 0.44 9.18 3.95 0.07 4.03 33.25 0.91 3.37 0.39 81 306 154 69 53 746 111 263 |
| 304/14       | wheel-finished mass-produced bowl | 37.46 0.53 8.89 4.58 0.08 3.55 41.24 0.42 3.08 0.26 77 394 146 79 32 478 117 236 |
| 109/14       | wheel-finished mass-produced bowl | 45.73 0.56 10.72 5.02 0.08 4.57 29.68 0.73 2.64 0.23 92 515 182 67 55 542 120 270 |
| 285/14       | wheel-finished mass-produced bowl | 39.16 0.41 8.82 4.76 0.06 4.25 38.02 0.67 3.57 0.27 76 315 238 106 29 884 96 375 |
| 302/14       | wheel-finished mass-produced bowl | 48.41 0.50 11.43 5.10 0.08 4.56 25.36 0.89 3.37 0.30 74 223 211 93 56 475 115 275 |
| 303/14       | wheel-finished mass-produced bowl | 38.48 0.50 8.70 4.84 0.07 5.71 38.78 0.35 2.39 0.17 91 604 246 83 39 541 109 195 |
| 192/15       | wheel-finished mass-produced bowl | 49.35 0.50 11.27 4.53 0.08 4.46 25.27 1.16 3.06 0.31 70 329 162 60 64 549 127 331 |
| 193/15       | wheel-finished mass-produced bowl | 33.55 0.30 6.36 4.45 0.07 10.54 43.00 0.23 1.37 0.12 71 634 257 69 21 518 53 399 |
| 171/15       | wheel-finished mass-produced bowl | 33.94 0.35 6.56 4.89 0.08 10.28 42.17 0.29 1.22 0.21 90 786 286 67 23 682 65 118 |
| 271/14       | wheel-finished red-slipped burnished ware | 62.29 0.96 19.03 8.93 0.15 2.62 89.93 1.22 3.70 0.22 160 307 147 137 104 109 189 685 |
| 308/14       | wheel-finished red-slipped burnished ware | 37.01 0.64 8.46 5.02 0.08 8.27 37.70 0.76 1.92 0.14 116 329 244 76 37 770 101 218 |
| 103/14       | wheel-finished red-slipped burnished ware | 48.28 1.69 13.42 7.64 0.10 5.25 18.87 1.95 2.52 0.29 201 226 171 100 50 636 164 457 |
| 157/14       | wheel-finished red-slipped burnished ware | 44.95 0.92 11.63 6.25 0.08 25.26 23.56 1.53 2.79 0.22 100 326 239 93 31 518 108 381 |
| 160/14       | wheel-finished red-slipped burnished ware | 43.46 1.16 10.76 6.39 0.08 9.25 24.85 1.40 2.47 0.19 152 549 232 102 29 568 133 284 |
| 161/14       | wheel-finished red-slipped burnished ware | 47.26 0.54 10.49 5.02 0.08 5.72 26.73 0.91 3.05 0.18 90 545 243 88 57 533 129 293 |
| 162/14       | wheel-finished red-slipped burnished ware | 42.47 0.51 9.31 5.37 0.09 6.38 32.19 0.55 2.93 0.20 98 536 201 95 39 753 109 239 |
| 163/14       | wheel-finished red-slipped burnished ware | 45.12 0.42 9.05 4.58 0.07 6.96 29.79 0.98 2.86 0.16 79 388 274 97 47 669 97 280 |
| 282/14       | wheel-finished light-colored fine ware | 40.84 0.43 8.79 6.00 0.09 7.76 32.20 0.86 2.63 0.41 103 427 358 99 25 802 95 404 |
| 284/14       | wheel-finished light-colored fine ware | 43.68 0.53 9.23 5.03 0.10 4.99 32.63 0.53 3.00 0.28 90 592 230 88 43 608 117 247 |
| 286/14       | wheel-finished light-colored fine ware | 46.75 0.63 10.65 6.33 0.13 3.84 25.92 0.45 2.98 0.31 126 332 287 106 44 535 111 715 |
| 287/14       | wheel-finished light-colored fine ware | 51.24 1.10 14.71 7.22 0.09 4.60 15.88 1.81 3.06 0.19 141 222 161 111 45 335 112 662 |
| 288/14       | wheel-finished light-colored fine ware | 54.83 0.99 16.80 10.26 0.14 7.33 5.75 1.35 2.34 0.20 168 345 308 108 63 115 53 457 |
| 105/14       | wheel-finished stewart tempered ware | 48.88 1.52 13.63 7.40 0.10 5.11 18.55 1.64 2.79 0.27 167 249 194 89 45 598 164 312 |

(Continued)
Table 5. (Continued)

| Sample          | Phase                              | Ceramic ware                                                                 | SiO₂ | TiO₂ | Al₂O₃ | Fe₂O₃ | MnO | MgO | CaO | Na₂O | K₂O | P₂O₅ | V    | Cr  | Ni  | Zn  | Ba  | Rb  | Sr  | Zr  | Ba  |
|-----------------|------------------------------------|------------------------------------------------------------------------------|------|------|-------|-------|-----|-----|-----|------|-----|------|------|-----|-----|-----|-----|-----|-----|-----|-----|
| 257/14          | wheel-finished chaff-tempered ware | 61.63 1.22 18.18 6.91 0.09 2.46 3.76 2.72 2.83 0.20 122 156 87 72 34 79 194 383 |
| 106/14          | wheel-finished chaff-tempered ware | 54.89 0.92 14.00 5.89 0.08 3.40 15.31 1.85 3.36 0.31 113 266 154 78 74 510 147 308 |
| 258/14          | wheel-finished chaff-tempered ware | 49.21 1.74 14.68 7.48 0.10 3.72 17.05 2.30 2.59 0.24 180 297 126 87 48 597 185 295 |
| 260/14          | wheel-finished chaff-tempered ware | 51.66 1.68 14.46 7.68 0.11 4.56 14.29 2.23 2.88 0.45 201 300 187 99 54 544 167 275 |
| 281/14          | wheel-finished chaff-tempered ware | 62.09 1.26 18.07 6.69 0.09 2.57 3.87 2.89 3.13 0.17 119 289 72 70 75 347 217 413 |
| 272/14          | handmade light-colored ware        | 52.33 0.82 13.03 6.17 0.07 3.15 20.21 1.01 2.95 0.26 136 314 140 91 58 356 167 377 |
| 273/14          | handmade light-colored ware        | 53.25 1.76 15.51 7.98 0.08 2.98 13.48 2.22 2.54 0.20 183 204 98 96 61 392 196 264 |
| 278/14          | handmade kitchen ware              | 55.58 1.56 17.57 6.66 0.09 2.68 13.85 1.90 2.27 0.32 265 911 112 160 42 223 161 433 |
| 307/14          | wheel-finished kitchen ware        | 60.48 0.80 20.47 5.07 0.09 2.27 5.02 3.52 2.15 0.13 85 142 63 58 89 477 175 316 |
| 278/14          | handmade kitchen ware              | 48.97 0.65 11.22 7.45 0.14 4.14 23.80 0.45 3.00 0.20 134 643 291 106 51 435 95 661 |
| 280/14          | handmade kitchen ware              | 64.37 1.02 18.05 6.45 0.05 2.98 12.51 1.18 4.18 0.23 144 223 167 130 128 205 225 514 |
| 259/14          | wheel-finished kitchen ware        | 63.16 0.56 15.65 6.62 0.10 3.19 5.74 1.42 3.43 0.14 152 235 116 69 84 169 141 326 |
| 261/14          | wheel-finished kitchen ware        | 56.90 2.02 18.28 8.73 0.11 2.67 5.35 3.26 2.31 0.25 182 118 66 83 63 401 231 308 |
| 274/14          | handmade red-black/monochrome burnished ware | 63.02 0.91 17.01 8.06 0.08 1.92 4.70 0.73 3.23 0.32 138 167 98 80 80 90 158 1002 |
| 291/14          | handmade red-black/monochrome burnished ware | 62.91 0.66 20.19 4.43 0.05 1.70 3.86 3.15 2.69 0.36 60 79 53 65 84 460 159 301 |
| skewness        | 0.08 0.85 0.31 1.42 2.06 0.91 0.01 -0.42 1.82 0.91 0.72 0.11 1.13 0.99 -0.35 0.31 1.99 |
| kurtosis        | -0.89 -0.33 -1.07 2.95 5.85 0.21 -1.24 -0.24 1.23 5.02 0.73 -0.25 -0.92 2.19 1.40 -0.11 -0.51 5.34 |
| variance        | 4.36 7.35 5.31 4.47 4.46 7.61 21.76 11.82 4.58 5.83 2.53 1.89 7.85 4.27 7.00 9.02 5.43 6.26 |
| mean            | 49.69 0.88 13.30 6.32 0.09 4.82 20.64 1.40 2.78 0.26 122.93 359.38 187.10 89.42 54.75 491.76 138.27 367.17 |
| std             | 8.71 0.16 4.11 1.77 0.03 2.28 13.06 0.90 0.57 0.11 45.85 172.50 79.71 20.98 22.87 191.51 43.03 161.84 |
| CV              | 17.53 52.42 31.39 28.00 0.30 70.74 63.26 64.10 20.60 43.08 37.29 30.83 42.60 23.47 41.78 38.94 31.12 44.08 |
| skewness        | 0.08 0.85 0.31 1.42 2.06 0.91 0.01 -0.42 1.82 0.91 0.72 0.11 1.13 0.99 -0.35 0.31 1.99 |
| kurtosis        | -0.89 -0.33 -1.07 2.95 5.85 0.21 -1.24 -0.24 1.23 5.02 0.73 -0.25 -0.92 2.19 1.40 -0.11 -0.51 5.34 |
| variance        | 4.36 7.35 5.31 4.47 4.46 7.61 21.76 11.82 4.58 5.83 2.53 1.89 7.85 4.27 7.00 9.02 5.43 6.26 |

Re-assessing the notion(s) of craft standardization

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reducing or mixed atmospheres, such as the monochrome/red-burnished and kitchen wares. By contrast, more homogeneous compositions occur in calcareous-rich, light-colored, smoothed or plain vessels including the mass-produced, chaff-tempered smoothed and light-colored wares. In contrast, functionality does not play a significant role on the chemical standardization, as the same vessel shape might show very different chemical indexes. As opposed to LC3-4, the few wares of the LC5 period do not differ that much from each other in terms of chemical variability.

Independently of periods and wares, elemental CVs and variances are respectively higher for CaO, Na\textsubscript{2}O, Cr, V, Ni, P\textsubscript{2}O\textsubscript{5}, Sr, Ba and CaO, Na\textsubscript{2}O, Sr (Table 5; Figs 7 and 8). Based on the skewness and kurtosis the V, Cr, Zn and Rb concentrations diverge most extensively from a normal distribution (Table 5; Fig 9a–9c). Although some of these more variable elements are known to be sensitive to post-depositional processes (e.g. CaO, P\textsubscript{2}O\textsubscript{5}), most of them are instead related to distinct local strategies in raw material procurement and paste preparation. Indeed, previous studies have already demonstrated that the geochemical variation in the ceramics from Arslantepe is mostly linked to the exploitation of more and less calcareous clay deposits tempered with materials characterized by different mafic/felsic/alkaline affinities [85]. Calcareous and non-calcareous deposits are respectively available in the plain and in the southern Anti-Taurus Mountains. Clay pastes tempered with acid rocks (e.g. petro-groups CEm-a and VCEm-a) are richer in Ba, Rb, K\textsubscript{2}O, SiO\textsubscript{2} and poorer in TiO\textsubscript{2}, Fe\textsubscript{2}O\textsubscript{3}, V, MnO, MgO, Cr.

![Fig 8. Elemental variance within each LC sub-phase.](https://doi.org/10.1371/journal.pone.0245660.g008)

Fig 8. Elemental variance within each LC sub-phase. The variance of an element is equal to the trace of the variance-covariance matrix of the log-ratio transformed data using this element as divisor [91, 93].

![Fig 9. Skewness and kurtosis calculated for each element within the LC1-2 (a), LC3-4 (b) and LC5 (c).](https://doi.org/10.1371/journal.pone.0245660.g009)
Table 6. Average CVs calculated on each element according to the different ceramic classes, manufacturing techniques and production rates occurring in the LC1-2, LC3-4 and LC5 phases.

| Average CVs | LC1-2 | Burnished ware | Mass-produced bowls | Handmade wares | Wheel-finished wares | Handmade wares | Wheel-finished wares |
|-------------|-------|----------------|---------------------|----------------|---------------------|----------------|---------------------|
| SiO₂        | 3.12  | 11.43          | 3.13                | 2.37           | 10.37              | 9.17           | 7.69                |
| TiO₂        | 33.81 | 35.10          | 46.05               | 34.20          | 44.49              | 17.61          | 19.61               |
| Al₂O₃       | 0.79  | 37.36          | 10.80               | 15.01          | 19.98              | 11.09          | 8.93                |
| Fe₂O₃       | 16.10 | 55.48          | 18.53               | 35.58          | 18.80              | 13.63          | 10.61               |
| MnO         | 4.28  | 95.25          | 15.98               | 33.35          | 15.37              | 16.31          | 10.06               |
| MgO         | 16.39 | 108.92         | 13.63               | 11.53          | 29.86              | 26.92          | 27.95               |
| CaO         | 11.58 | 87.33          | 14.70               | 43.92          | 30.72              | 56.85          | 16.77               |
| Na₂O        | 15.57 | 106.73         | 21.45               | 75.97          | 41.04              | 17.10          | 12.06               |
| K₂O         | 12.15 | 46.44          | 8.09                | 17.39          | 20.31              | 16.34          | 7.66                |
| P₂O₅        | 62.24 | 9.95           | 7.91                | 19.23          | 48.52              | 40.96          | 29.03               |
| V           | 15.65 | 25.28          | 9.96                | 45.32          | 36.48              | 25.22          | 23.81               |
| Cr          | 37.69 | 77.93          | 1.92                | 52.00          | 36.48              | 25.22          | 23.81               |
| Ni          | 42.80 | 93.89          | 12.20               | 43.06          | 28.23              | 28.55          | 18.62               |
| Zn          | 14.04 | 47.97          | 13.17               | 17.89          | 13.69              | 11.96          | 13.03               |
| Rb          | 0.62  | 54.24          | 6.61                | 15.02          | 28.51              | 14.39          | 18.69               |
| Sr          | 1.01  | 69.16          | 27.94               | 59.78          | 37.92              | 30.01          | 15.34               |
| Zr          | 8.80  | 80.78          | 2.42                | 11.19          | 21.04              | 23.56          | 15.36               |
| Ba          | 19.96 | 61.90          | 30.02               | 51.87          | 26.74              | 20.21          | 18.47               |
| Mean        | 17.59 | 61.40          | 14.70               | 32.53          | 27.70              | 22.63          | 16.23               |

Table 7. Elemental variance and total variation according to ceramic classes, manufacturing rates and production rates.

| Phase | Ceramic classes | Total variation | Elemental variance |
|-------|-----------------|-----------------|--------------------|
| LC1-2 | Plain ware      | SiO₂ 1.25, TiO₂ 1.96, Al₂O₃ 1.08, Fe₂O₃ 0.98, MnO 0.98, MgO 2.22, CaO 0.92, Na₂O 2.14, K₂O 1.84, P₂O₅ 6.64, V 0.97, Cr 2.35, Ni 1.81, Zn 0.89, Rb 0.88, Sr 0.91, Zr 3.48, Ba 2.59 |
|       | Mass-produced bowls | SiO₂ 0.88, TiO₂ 4.69, Al₂O₃ 0.95, Fe₂O₃ 1.34, MnO 1.32, MgO 1.98, CaO 2.20, Na₂O 1.46, K₂O 0.88, P₂O₅ 1.09, V 0.93, Cr 0.93, Ni 1.81, Zn 0.89, Rb 0.88, Sr 0.88, Zr 0.91, Ba 3.48 |
|       | Burnished ware   | SiO₂ 24.64, TiO₂ 34.74, Al₂O₃ 40.44, Fe₂O₃ 23.86, MnO 27.28, MgO 37.97, CaO 15.28, Na₂O 30.52, K₂O 12.07, P₂O₅ 17.30, V 15.63, Cr 12.52, Ni 16.18, Zn 12.07, Rb 20.74, Sr 67.69, Zr 12.81, Ba 12.81 |
| LC3-4 | Wheel-finished | SiO₂ 3.19, TiO₂ 7.11, Al₂O₃ 4.26, Fe₂O₃ 3.88, MnO 3.79, MgO 6.53, CaO 18.85, Na₂O 10.58, K₂O 4.09, P₂O₅ 5.45, V 4.56, Cr 8.15, Ni 6.78, Zn 3.68, Rb 5.89, Sr 7.72, Zr 4.73, Ba 5.22 |
|       | Mass-produced bowls | SiO₂ 1.52, TiO₂ 1.65, Al₂O₃ 1.95, Fe₂O₃ 1.77, MnO 1.75, MgO 5.20, CaO 2.99, Na₂O 5.93, K₂O 3.47, P₂O₅ 3.15, V 1.87, Cr 5.66, Ni 3.15, Zn 2.18, Rb 2.42, Sr 2.59, Zr 3.82, Ba 2.59 |
|       | Handmade | SiO₂ 3.68, TiO₂ 4.53, Al₂O₃ 5.57, Fe₂O₃ 4.76, MnO 4.61, MgO 6.27, CaO 4.22, Na₂O 19.59, K₂O 14.84, P₂O₅ 4.87, V 6.15, Cr 5.90, Ni 8.57, Zn 7.53, Rb 4.83, Sr 7.37, Zr 9.95, Ba 5.41, Zr 7.40 |
| LC5   | Wheel-finished | SiO₂ 0.73, TiO₂ 1.44, Al₂O₃ 0.80, Fe₂O₃ 0.85, MnO 0.87, MgO 2.01, CaO 1.26, Na₂O 0.87, K₂O 1.37, P₂O₅ 3.19, V 2.31, Cr 2.43, Ni 1.32, Zn 1.00, Rb 1.53, Sr 1.14, Zr 1.04, Ba 1.91 |
|       | Handmade | SiO₂ 1.01, TiO₂ 1.57, Al₂O₃ 1.14, Fe₂O₃ 1.40, MnO 1.37, MgO 1.47, CaO 2.08, Na₂O 6.89, K₂O 1.87, P₂O₅ 1.95, V 2.96, Cr 2.68, Ni 1.70, Zn 1.66, Rb 1.16, Sr 1.37, Zr 1.86, Ba 1.76, Zr 1.56 |

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and Ni. Opposite geochemical trends characterize the samples containing minerals and rocks of mafic origin (petro-groups C Eb-m, Clb, VClb, Vlb, VMetag). In particular, metagabbroic pastes (petro-group VMetag) are strongly enriched in V, related to ultramafic rocks of ophiolite-related petrogenesis. Ceramic pastes with intermediate rocks (e.g. VCEm, VEm) show intermediate features between the terms mentioned above, but they are distinguished by high Al₂O₃, K₂O, Na₂O and Sr values.

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### Table 8. Average CVs calculated on each element according to the different ceramic wares occurring in the LC3-4 and LC5 phases.

| Average CVs | LC3-4 ceramic wares | LC5 ceramic wares |
|------------|---------------------|-------------------|
|            | Handmade            | Wheel-finished    | Handmade | Wheel-Finished |
|            | Light-colored       | Red-black/monochrome burnished | Kitchen | Fine light-colored | Red-slipped burnished | Chaff-tempered smoothed | Mass-produced | Kitchen | Light-colored semifine | Light-colored fine |
| SiO₂       | 1.24                | 0.12              | 11.59    | 5.22      | 11.91          | 14.56               | 10.80         | 14.53   | 9.17          | 9.50          | 5.88       |
| TiO₂       | 51.42               | 23.06             | 39.24    | 67.90     | 39.80          | 49.99               | 22.54         | 18.85   | 17.61         | 11.53         | 27.70      |
| Al₂O₃      | 12.32               | 12.09             | 23.54    | 14.39     | 29.43          | 28.18               | 13.30         | 20.18   | 11.09         | 3.58          | 14.28      |
| Fe₂O₃      | 18.07               | 41.16             | 41.91    | 22.07     | 28.70          | 23.02               | 9.42          | 7.50    | 13.63         | 9.19          | 12.03      |
| MnO        | 10.16               | 33.89             | 55.47    | 13.08     | 24.42          | 24.41               | 9.73          | 7.49    | 16.31         | 10.74         | 9.38       |
| MgO        | 3.96                | 8.68              | 24.81    | 23.51     | 22.91          | 33.37               | 29.18         | 46.67   | 26.92         | 30.69         | 25.20      |
| CaO        | 28.25               | 13.83             | 119.75   | 8.68      | 51.35          | 40.59               | 55.02         | 20.00   | 56.85         | 16.83         | 16.72      |
| Na₂O       | 53.03               | 88.22             | 74.42    | 39.07     | 57.51          | 37.80               | 21.38         | 51.41   | 17.10         | 16.38         | 7.75       |
| K₂O        | 10.68               | 13.09             | 32.72    | 24.42     | 10.98          | 17.38               | 12.45         | 32.23   | 16.34         | 3.16          | 12.16      |
| P₂O₅       | 18.80               | 7.70              | 42.73    | 61.25     | 31.91          | 67.75               | 36.90         | 32.06   | 40.96         | 28.78         | 29.29      |
| V           | 20.94               | 55.71             | 48.93    | 31.95     | 24.54          | 34.77               | 24.74         | 10.77   | 27.44         | 2.27          | 34.35      |
| Cr          | 29.86               | 50.51             | 77.12    | 40.65     | 35.82          | 30.42               | 30.17         | 41.16   | 25.22         | 6.07          | 41.56      |
| Ni          | 24.82               | 42.63             | 62.16    | 28.92     | 28.18          | 21.96               | 37.25         | 24.14   | 28.55         | 21.85         | 15.40      |
| Zn          | 3.70                | 15.06             | 37.74    | 11.74     | 9.09           | 16.78               | 13.50         | 19.30   | 11.96         | 11.24         | 14.82      |
| Rb          | 3.09                | 3.11              | 50.76    | 14.94     | 30.55          | 47.44               | 24.01         | 39.17   | 14.39         | 8.07          | 29.30      |
| Sr          | 6.90                | 95.10             | 42.03    | 45.92     | 54.97          | 33.30               | 24.78         | 22.60   | 30.01         | 26.35         | 4.33       |
| Zr          | 11.36               | 0.27              | 32.86    | 24.60     | 10.36          | 26.68               | 13.93         | 26.05   | 23.56         | 12.61         | 18.11      |
| Ba          | 25.09               | 76.12             | 30.15    | 16.69     | 36.85          | 41.78               | 16.40         | 32.05   | 20.21         | 15.90         | 21.04      |
| Mean        | 18.54               | 32.24             | 47.11    | 27.50     | 29.96          | 32.79               | 22.53         | 25.90   | 22.63         | 13.60         | 18.86      |

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Table 9. Elemental variance and total variation according to the different ceramic wares occurring in the LC3-4 and LC5 phases.

| Phase         | Ceramic wares          | Total variation | Elemental variance |
|---------------|------------------------|-----------------|--------------------|
|               |                        | SiO₂ | TiO₂ | Al₂O₃ | Fe₂O₃ | MnO | MgO | CaO | Na₂O | K₂O | P₂O₅ | V   | Cr  | Ni  | Zn  | Rb  | Sr  | Zr  | Ba  |
| LC3-4         | Wheel-finished         |      |      |       |       |     |     |     |      |     |      |     |     |     |     |     |     |     |     |
| Kitchen       |                        | 1.94 | 2.22 | 8.01  | 2.22  | 2.48| 2.19| 3.31| 2.25 | 4.79| 3.50 | 8.66| 3.94| 5.49| 4.26| 2.00| 2.81| 6.49| 2.47| 2.60|
| Mass-produced bowls |                  | 1.52 | 1.65 | 1.95  | 1.58  | 1.77| 1.75| 5.20| 2.99 | 5.93| 3.47 | 3.15| 1.87| 5.66| 3.15| 2.18| 3.71| 2.42| 2.59| 3.82|
| Fine light-colored |                  | 2.56 | 2.80 | 5.40  | 3.98  | 3.71| 3.48| 3.40| 12.37| 8.90| 2.85 | 4.32| 3.50| 5.18| 4.16| 2.65| 4.58| 13.20| 2.84| 4.70|
| Red-slipped burnished |                | 3.01 | 3.37 | 6.25  | 3.94  | 3.63| 3.88| 6.20| 24.84| 4.93| 3.70 | 5.96| 4.48| 5.20| 4.52| 3.56| 5.87| 8.91| 3.85| 5.33|
| Chaff-tempered smoothed |              | 1.26 | 2.07 | 1.98  | 2.23  | 1.45| 1.44| 1.96| 9.25 | 2.92| 1.58 | 2.45| 1.74| 2.19| 2.99| 1.28| 3.38| 1.82| 2.19| 2.54|
| Handmade      |                        |      |      |       |       |     |     |     |      |     |      |     |     |     |     |     |     |     |     |     |
| Light-colored |                        | 1.06 | 1.06 | 5.71  | 1.21  | 1.47| 1.15| 1.15| 2.86 | 6.06| 1.40 | 1.93| 1.64| 3.06| 2.48| 1.06| 1.06| 1.08| 1.18| 2.51|
| Red-black/monochrome burnished |            | 4.26 | 4.38 | 4.66  | 5.01  | 6.35| 5.50| 4.26| 4.31  | 26.73| 4.30 | 4.72| 8.86| 7.82| 6.55| 4.34| 4.49| 31.77| 4.39| 14.86|
| Kitchen       |                        | 4.97 | 5.85 | 7.19  | 7.26  | 6.45| 9.83| 5.36| 29.35 | 21.13| 6.94 | 6.94| 7.50| 11.31| 10.96| 7.11| 11.72| 9.35| 8.52| 6.05|
| LC5           | Wheel-finished         |      |      |       |       |     |     |     |      |     |      |     |     |     |     |     |     |     |     |     |
| Light-colored semifine |                | 0.47 | 0.65 | 0.73  | 0.50  | 0.64| 0.69| 2.17| 0.95  | 0.93| 0.49 | 2.05| 0.48| 0.52| 1.30| 0.71| 0.57| 1.70| 0.78| 0.95|
| Light-colored fine |                  | 0.81 | 0.86 | 1.99  | 1.07  | 0.91| 0.90| 2.18| 1.61  | 0.86| 0.90 | 1.66| 3.12| 4.10| 1.50| 1.22| 2.32| 1.00| 1.24| 1.80|
| Handmade      |                        | 1.01 | 1.57 | 1.14  | 1.41  | 1.35| 1.47| 2.11| 6.89  | 1.87| 1.95 | 2.96| 2.68| 1.70| 1.66| 1.16| 1.37| 1.86| 1.74| 1.56|

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The various indexes and forms applied to explore the petrographic variability of Late Chalcolithic vessel from Arslantepe (Table 10) evidence different trends than those obtained through the elaboration of geochemical data: at a petrographic level it is the LC3-4 and not the final LC5 that shows the lowest variability. Indeed, the lowest richness, evenness and disparity unequivocally characterize the LC3-4 phase, as the various diversity indexes provide the lowest values; petro-loners occur more rarely; samples are unevenly apportioned into petro-groups; and the average number of samples per petro-group is higher.

By applying the same parameters to the different wares within each Late Chalcolithic sub-phase it was possible to identify differences related to manufacturing techniques, ceramic style and traditions as well as production rates and morpho-functional features (Tables 9 and 10). Concerning the first Late Chalcolithic phase (LC1-2), the burnished ware is distinguished by the highest variability in terms of both richness and evenness (Table 11). The plain grit ware presents the highest petrographic homogeneity, closely followed by the mass-produced bowls and plain ware. Geochemical data are not available for the plain grit ware; however, they also evidenced a higher homogeneity for the mass-produced bowls. During the following LC3-4 period, the lowest petrographic variability occurs in the wheel-finished vessels. Diversity indexes provide lower values, petro-loners are rare, petro-groups are wider and samples are unevenly distributed across petro-groups. This data fits with geochemical results too. As for handmade vessels (Table 12), it is mostly the monochrome and red-black burnished ware (M/RBBW) that is responsible for the high petrographic variability of this varied group of containers. Indeed, when we exclude this ware from the calculations, the handmade vessels become much closer to the wheel-finished ones. Parameters that still suggest a much stronger variability are the high incidence of petro-loners, the low average number of samples per petro-group and the high Jaccard’s dissimilarity. By distinguishing the various wheel-finished wares (Table 12), we notice that the mass-produced bowls are the least variable for almost all the considered parameters. Further significant data emerge when we compare vessels sharing similar formal and functional features but differing in the forming procedures. For instance, kitchen wares can be invariably handmade or finished on the wheel, but this has no influence on the standardization degree of recipes, as both categories exhibit quite similar values.

The variability indexes assessed for each ware (Table 12) allow us to nuance the trends obtained chemically. Consistently with chemical results, the handmade monochrome/red-black burnished wares are associated with kitchen wares as it concerns the high petrographic variability. Both handmade and wheel-finished kitchen wares show high percentages of petro-loners, high Pielou’s and Shannon’s indexes, a low disparity in petro-group abundance as well as a low average number of samples per petro-group. The wheel-finished red-slipped burnished ware, which has an intermediate chemical variability, exhibits the highest Menhinick’s

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**Table 10. Values of the diversity parameters considered for each LC sub-phase.**

|               | LC1-2 | LC3-4 | LC5  |
|---------------|-------|-------|------|
| % petro-loners| 57.89 | 15.46 | 31.37|
| Menhinick’s Disparity in recipe abundance | 3.21 | 2.44 | 3.64 |
| Average nr of samples per petro-group | 16 | 18 | 12 |
| Pielou’s Shannon’s Jaccard’s dissimilarity % | 2.67 | 9.11 | 3.5 |
| 0.95 | 0.79 | 0.92 |
| 2.51 | 2.51 | 3 |
| 88.89 | 66.38 | 66.48 |

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**Petro-chemical discrepancies in diachronic trends towards standardization**

The various indexes and forms applied to explore the petrographic variability of Late Chalcolithic vessel from Arslantepe (Table 10) evidence different trends than those obtained through the elaboration of geochemical data: at a petrographic level it is the LC3-4 and not the final LC5 that shows the lowest variability. Indeed, the lowest richness, evenness and disparity unequivocally characterize the LC3-4 phase, as the various diversity indexes provide the lowest values; petro-loners occur more rarely; samples are unevenly apportioned into petro-groups; and the average number of samples per petro-group is higher.
index, but the lowest percentage of petro-loners, the highest average number of samples per petro-group and a relatively high disparity in abundance between the most and less represented petro-group. By contrast, the handmade light-colored ware, the wheel-finished chaff-tempered smoothed, and fine light-colored ware, which are chemically more homogeneous than the red-slipped burnished ware, have more loners, smaller group sizes, a generally higher Pielou’s index and a lower disparity in petro-group abundance, although their Menhinick’s and Shannon’s indexes still appear lower.

The average number of samples per petro-group and the Jaccard’s dissimilarity % were not calculated in cases of low number of samples and/or high incidence of petro-loners.

In the final phase of the LC, the wheel-finished vessels still show a lower petrographic variability compared to the handmade ones (Table 11), but the difference is now less marked especially in terms of evenness. Among the handmade wares (Table 12), the monochrome and red-black burnished ware (M/RBBW) again exhibits the highest variability. If we exclude this ware from the calculations, the handmade vessels become even less variable than the wheel-finished ones in terms of Mehinick’s and Shannon’s indexes, while the incidence of petro-loners and Jaccard’s dissimilarity continue to suggest a higher variability. As for the various

Table 11. Values of the diversity parameters considered for the different ceramic wares and manufacturing techniques within each LC sub-phase.

|                | RICHNESS       | EVENNESS       | RICHNESS +EVENNESS | DISPARITY |
|----------------|----------------|----------------|-------------------|-----------|
|                | % petro-loners | Menhinick’s    | Disparity in      | Pielou’s  |
|                |                | recipe         | abundance         | Shannon’s |
|                | Average nr     |                |                   |           |
|                |                |                | of samples        |           |
|                |                |                | per petro-group   |           |
| LC1-2          | handmade       | 60             | 1.79              | 20        |
|                | mass-produced |                |                   | /         |
|                | bowls          |                |                   | 0.96      |
|                | handmade       | 60             | 1.79              | 20        |
|                | plain ware     |                |                   | /         |
|                | handmade       | 100            | 2.24              | 0         |
|                | burnished      |                |                   | /         |
|                | ware           |                |                   | 1         |
|                | handmade       | 50             | 1.5               | 25        |
|                | plain grit     |                |                   | /         |
|                | ware           |                | 0.95              | 1.04      |
|                |                |                |                   | /         |
| LC3-4          | handmade       | 65             | 3.84              | 11        |
|                | wares          |                |                   | 2.33      |
|                | handmade       | 41.67          | 2.67              | 15        |
|                | — M/RBBW       |                |                   | 2.33      |
|                | wheel-finished | 5.19           | 1.37              | 22        |
|                | wares          |                |                   | 9.12      |
|                | handmade       | 51.72          | 3.34              | 21        |
|                | wares          |                |                   | 4.67      |
|                | handmade       | 33.33          | 1.63              | 16        |
|                | — M/RBBW       |                |                   | 2         |
|                | wheel-finished | 4.54           | 1.7               | 19        |
|                | wares          |                |                   | 3         |

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wheel-finished wares (Table 12), the mass-produced bowls still show the lowest petrographic richness, as in the previous phases, but evenness is now higher than in other wheel-finished vessels. Indeed, Pielou’s index provides higher values and thin sections are more evenly distributed across petrographic groups.

When we compare vessel categories that recur both in the LC3-4 and LC5, interesting diachronic trends emerge. Diversity indexes change differently through time according to forming techniques. The handmade production shows an unequivocal trend from the LC3-4 to LC5 towards a petrographic homogenization in terms of both richness and evenness, while the wheel-finished production tends to lose in homogeneity (Table 11) despite an increased use of rotating devices in LC5. With time the values of almost all diversity indexes increase and petro-group sizes decrease. As for mass-produced bowls (Table 12), although always more homogenous than other coeval wheel-finished wares, they do not show univocal trends when

|                      | RICHNESS | EVENNESS | RICHNESS + EVENNESS |
|----------------------|----------|----------|---------------------|
|                      | % petro- | Menhinick’s | Disparity in petro-group | Average nr of samples per petro-group | Pielou’s | Shannon’s |
|                      | loners   | Menhinick’s | abundance           |                                   |          |          |
| LC3-4    | Handmade | M/RBBW   | 100 | 3 | 1 | / | 1 | 2.2 |
|          |          | kitchen | 42.86 | 1.89 | 15 | / | 0.96 | 1.55 |
|          |          | light- | 60 | 1.79 | 20 | / | 0.96 | 1.33 |
|          |          | colored |     |     |   |   |   |     |
|          |          | ware    |     |     |   |   |   |     |
|          |          | kitchen | 42.86 | 3.78 | 15 | 2 | 0.96 | 1.55 |
|          |          | light- | 37.5 | 3.89 | 49 | 5 | 0.77 | 1.07 |
|          |          | colored |     |     |   |   |   |     |
|          |          | fine   |     |     |   |   |   |     |
|          |          | ware    |     |     |   |   |   |     |
|          |          | red-slip- | 6.25 | 5.93 | 28 | 7.5 | 0.86 | 1.54 |
|          |          | ped burnished |     |     |   |   |   |     |
|          |          | ware    |     |     |   |   |   |     |
|          |          | mass- | 7.69 | 3.88 | 53 | 6 | 0.78 | 0.86 |
|          |          | produced |     |     |   |   |   |     |
|          |          | bowls   |     |     |   |   |   |     |
|          |          | chaff- | 17.65 | 4.5 | 23 | 4.67 | 0.92 | 1.66 |
|          |          | tempered |     |     |   |   |   |     |
| LC5      | Handmade | M/RBBW   | 56.52 | 3.33 | 18 | 3.33 | 0.89 | 2.31 |
|          |          | kitchen | 33.33 | 1.63 | 16 | 2 | 0.95 | 0.56 |
|          |          | light- | 27.27 | 1.8 | 19 | 2.66 | 0.93 | 1.67 |
|          |          | colored |     |     |   |   |   |     |
|          |          | fine   |     |     |   |   |   |     |
|          |          | ware    |     |     |   |   |   |     |
|          |          | light- | 40 | 1.34 | 40 | 3 | 0.86 | 0.95 |
|          |          | colored |     |     |   |   |   |     |
|          |          | semi-fine |     |     |   |   |   |     |
|          |          | ware    |     |     |   |   |   |     |
|          |          | mass- | 0 | 1.22 | 1 | 2 | 1 | 1.09 |
|          |          | produced |     |     |   |   |   |     |
|          |          | bowls   |     |     |   |   |   |     |

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considered diachronically: their petrographic richness tends to decrease, while their petrographic evenness and disparity increases. Kitchen wares become instead petrographically more homogeneous even though by the LC5 they are exclusively fashioned by hand. The hand-made monochrome/red-black burnished ware exhibits the highest variability within each period, but clearly tends towards a petrographic homogenization in the course of time, as revealed by the significant decrease in petro-loners and evenness by the final Late Chalcolithic phase. Finally, consistently with the chemical trends, the LC5 differs from the LC3-4 by the lower disparity in petrographic variability that separates the single wares (Table 12).

Discussion and conclusions

The application of diversity statistics to geochemical and petrographic data sheds light on the craft organization of Arslantepe Late Chalcolithic pottery. All data suggest that the higher standardization of ceramic recipes is connected with the scale or rate of production rather than with the use of rotating devices. Mass-produced vessels, both the handmade ones (LC1-2 and partially in LC3-4) and the ones shaped on the wheel (partially LC3-4 and LC5), indeed display the lowest compositional variability within each period. A close relation between the emergence of serial production and the progressive homogenization of the chaîne opératoires, involving also a stronger selection of paste recipes, has been already identified in the Late Chalcolithic contexts from northern Mesopotamia and the Levant [30]. According to the CVs calculated on morphometric values of different types of wheel-finished and handmade vessels (Table 1), the increasing use of the wheel by the final Late Chalcolithic did not even perfectly match an increased standardization of vessel shapes [64, 69]. This evidence is not surprising: several ethnographic studies demonstrate that the forming technique does not usually affect the morphological variability of ceramic assemblages [27, 88]. This data has been recently questioned by Balossi Restelli [52: 488–489] at least concerning the LC3-4 mass-produced bowls, which provide progressively lower formal CVs throughout time as the implementation of rotational kinetic energy (RKE) increases. However, these figures still display a higher formal standardization than the LC5 mass-produced bowls, in which the use of RKE is further increased. At Arslantepe morphometric CVs do not even evidence clear differences between mass-produced bowls and other vessels [64, 69]. Thus, variations in the production rate affect the strategies of raw material supply and processing rather than vessel shape variability. Morphometric features might depend on many factors besides craft specialization and production rate, such as contexts of use, vessel sizes, levels of care and number of individuals involved in the production [101]. Hruby [101] interpreted for instance the high metrical variability of ceramics found in the Mycenaean palace of Nestor as the result of the high speed of production in a context intended for consumption by people of lower rank. This hypothesis could also fit the mass-produced bowls from Arslantepe that provided a clear evidence of negligence and time pressure along the manufacturing sequence (e.g. drying cracks, finger imprints, rough repairs, extended dark cores, black firing spots) [73]. Gosselain provides further clues to interpret the differences in variations between morpho-chemical and petro-chemical features observed in this case-study [102]. As opposed to raw material procurement and processing, procedures such as vessel shaping rely on an embodied knowledge acquired through learning networks and non-discursive cognitive processes, which leaves wider space for individual variance from models. Furthermore, the raw material and selection have the lowest visual impact on finished vessels and as such most closely reflect traditions of potters and changes in craft standardization. In any case, as argued by Kotsonas [24], standardization is a relative concept that can only be approached by comparing different vessel attributes (e.g. fabrics, shapes, dimensions, decorations).
During the LC3-4, the geochemical and petrographic variability is also influenced by the types of surface treatments and firing conditions. Within the wheel-finished productions, the red-slipped burnished ware has relatively variable raw materials and paste recipes, which are both widely used and never the result of random choices. This could indicate that they were realized in multiple but well-established production nuclei. This seems to corroborate previous petrographic and geochemical results [85], which indicated for this ware the use of distinct raw materials and paste preparation for open- and closed-shaped vessels. By contrast, although both wheel-finished and handmade non-mass-produced light-colored wares indicate the exploitation of relatively homogeneous clay sources (i.e. homogeneous geochemistry), the modes of processing them (e.g. tempering and mixing) did not follow fixed criteria. Kitchen wares, whether handmade or wheel-finished, are often the most heterogeneous just behind the handmade red-black/monochrome burnished ware, with which they sometimes share similar surface treatments and firing procedures. The affinity between these two classes of handmade vessels will further consolidate in the following LC5 phase, when both share exactly the same raw materials and paste recipes [84].

Among the various indexes applied in this paper the incidence of petrographic loners has repeatedly been shown to be an eloquent indicator of lower standardization. This result has twofold methodological outcomes: at the level of petrographic analysis of ceramic artifacts, we should as much as possible avoid forcing a grouping of thin sections in cases of insufficient common features; and at a more general level, we should dedicate more attention to what is outside of normality (deviant and variant types) among local assemblages, since local outliers best express the peak of diversity—in terms of both richness and disparity—that can be reached in a production place.

While issues related to taxonomic classifications have been extensively discussed in archaeology, above all concerning typological methods, they have not been exhaustively examined in the field of archaeometric applications. In grouping and interpreting archaeological artifacts based on chemical and mineralogical compositions, we should more often remember the words of Foucault in the preface of “The Order of Things: An Archaeology of the Human Sciences”: “there is nothing more tentative, nothing more empirical (superficially, at least) than the process of establishing an order among things [. . .]. There is no similitude and no distinction, even for the wholly untrained perception, that is not the result of a precise operation and of the application of a preliminary criterion” [103: xxi]. From the Foucauldian perspective, taxonomic classifications, though providing a ground grid for the scientific study, present clear limitations as a result of a subjective reality representing only one among numerous alternative schemes.

Going back to our case study, different diachronic trends emerge among handmade and wheel-shaped vessels. The former univocally tend towards a higher standardization that reaches its peak in the final Late Chalcolithic phase, when economic centralization increases, the political and administrative power of the elites appears more pervasive, and food distribution became detached from the ritual sphere [45: 7–19]. The handmade red-black/monochrome burnished ware, which constantly exhibits the highest diversity within each period, is no exception to this trend. Nevertheless, in this case changes in the strategies of subsistence and mobility practices might have also played a significant role: the handmade red-black/monochrome burnished ware is commonly associated with mobile pastoral groups that gradually established themselves at, and possibly around, the site [104: 53, 105: 171]; from LC3-4 to LC5, as the sedentariness of these groups and their integration with the more sedentary components of the Malatya Plain communities increased, I believe that the areas exploited for the procurement of raw materials became closer and narrower and the resulting recipes more standardized [84]. This process continued and became more evident in the following Early
Bronze Age 1 phase (3000–2800 BCE), when the exploitation of the Malatya metamorphics distributed over an area of 10 to 30 km south of the site drastically decreased in favor of the much closer Orduzu volcanics [84]. As for wheel-shaped vessels, the last Late Chalcolithic phase 5 marks a geochemical homogenization but a petrographic and dimensional diversification, which might suggest an increased standardization in the exploitation of clay sources but a decreased standardization in paste recipes and forming procedures. I would like to propose a hypothesis, which however needs further data to be verified, and namely that this might indicate a process of division within the operational sequence between people that procured the raw material and those dedicated to potting, that is to the subsequent production stages. During the LC5 period, the procurement of raw materials for the wheel-finished wares possibly occurred at a collective level according to a higher degree of interaction and co-operation. It is also possible that, compared to the past, the processing of raw materials and vessels’ shaping might have involved more individuals, who acted more independently and in more isolated ways from each other, and this would account for the increased metrical diversity within each morphological type. Another piece of evidence needs to be recalled here: the disappearance of potters’ marks in the LC5 period, marks that during the LC3-4 had allowed the producers to recognize their own vases in communal drying and firing areas, further corroborates the hypothesis of a reduced interaction among potters, and possibly the disintegration or reconfiguration of former communities of practices [64, 106]. The more LC5 centralized system conceivably exercised more control over the exploitation of resources rather than over other steps of the manufacturing sequence, which left wider space for individual choice and creativity. More generally at a macroscopic level, the pronounced labor division led to a reduced amount of types and wares that, however, differ more strongly from each other [52, 62, 64, 65]. In terms of diversity statistics, the general richness of ceramic assemblages decreases, but their disparity increases, which implies a strong morpho-functional specialization [64]. Peculiar to the LC5 is also the reduced gap between the diversity indexes calculated on the petrographic and geochemical data of each ware. Unlike in the LC3-4, the combination of technological and functional features represented by each ware do not correspond to a specific standardization level in raw materials and paste recipes. This set of results prompts us to reconsider the direct relationships often simplistically established between standardization and specialization. As we can clearly observe at Arslantepe, the specialization of tasks within the chaîne opératoire that marks the end of the Late Chalcolithic period does not coincide with an increased standardization but, on the contrary, with a higher variability of both technical procedures and end products. Further south of Arslantepe, in the northern Mesopotamian sites of Hamoukar and Tell Brak (Khabur basin), diachronic trends towards standardization appear more univocal and visible through an increased uniformity both at a typological and technological level [29]. The higher degree of urbanization reached in those areas [107] might have created a spatial and social conjunctive tissue enhancing the transmission and sharing of models and practices between vessel makers.

At Arslantepe, the mass-produced bowls illustrate especially well the shift from communal to more centralized—but possibly less integrated—potting practices in relation with increased social complexity, production rate and rotational speed of the wheel. Indeed, the diversity parameters of the mass-produced bowls indicate a clear trend towards the use of a reduced range of recipes, all equally well-established and markedly differing from each other. This is accompanied by a progressive diversification of manufacturing procedures, shapes and sizes [64, 69, 73].

This work questioned the assumed unilinear correspondence between the increase in craft standardization, the use of the rotational kinetic energy and the emergence of economic centralization. The results obtained encourage us to explore artifacts’ standardization through a
threefold scheme of diversity in relation to various compositional, technological, typological and morphometric features in order to account for the complexity of the social organization of the pottery production. By de-structuralizing the concepts of diversity and operational sequence we can better understand the modalities and causes of standardized behaviors and gestures [33] and gain significant clues about the control over natural resources and labor division exercised by centralized political and economic systems. In the future, standardization studies should dedicate more attention to assessing and comparing the variability of non-metric data such as the petrographic and typological classifications, thus focusing on the different forms and degrees of specialization. As this paper clearly demonstrates, there is no single notion of specialization and standardization, for which we have to think plural. The present approach has shown to be suited to diachronic investigations at an intra-site level and seems appropriate in cases of variegated artifact assemblages and geological landscapes. However, petro-loners as well as the indexes used to assess the petrographic evenness could also be theoretically employed for inter-site comparisons as they are not influenced by the geological variability. The results allowed us to speculate on key aspects of socio-economic relationships and modes of labor organization in the crucial time of state formation. On this basis, an enlargement of samples and a further statistical elaboration are planned to test the method on different archaeological and geological contexts and support inter-site comparisons of pottery craft standardization. Ultimately, this paper intends to provide food for transdisciplinary thoughts on the fluid concept of diversity and to question human schemes of categorization and hierarchization of things.

Supporting information

S1 Table. Series of variation matrixes calculated on: LC sub-phases, ceramic wares and assemblages fashioned with different techniques and/or production rates.
(XLSX)

S2 Table. Calculations of Mehinik’s, Pielou’s and Shannon’s indexes.
(XLSX)

S3 Table. Calculations of Jaccard’s dissimilarity indexes based on presence/absence variables.
(XLSX)

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