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Learning Across the Divide: Understanding Knowledge Sharing Through Petrographic Analysis on Ceramics From the Rhine-Meuse Delta During the Middle to Late Neolithic Transition (3400–2200 BCE)

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ABSTRACT

Vlaardingen (VL) communities on the Dutch West coast (3400–2200 BCE) are part of a unique, long-term continuity in the European Neolithic. Despite large-scale changes in European populations during the Neolithic, the genomic diversity and cultural practices of VL communities can be retraced to the Mesolithic. The resilience of VL communities is attributed to their settlement system: a hypothesised network connecting diverse VL settlements and enabling optimal exploitation of the dynamic Dutch wetland environments. However, no systematic evaluations of this settlement system exist to date. This study sheds light on the VL settlement system through ceramic petrography. We conduct the first large-scale petrographic survey of VL vessels, incorporating new and legacy data. Moreover, we introduce a novel statistical approach to petrographic data which detects knowledge sharing about paste recipes between VL settlements. Ethnographic studies show that knowledge about paste recipes is transmitted within households. Therefore, the diversity and similarity in paste recipes at, and knowledge sharing about paste recipes between, VL sites should reflect the community structures and intersite relations proposed by the VL settlement system. The results point towards more complex intersite mobility of persons, ceramics and/or knowledge than envisioned in the VL settlement system. VL potters shared knowledge about paste recipes irrespective of spatial proximity. Moreover, VL potters at specific sites experimented with paste recipes and vessel shapes from neighbouring FBW and CW communities, respectively. This willingness to exchange knowledge and to experiment with novel behaviours from across social boundaries may explain the millennia-long persistence of communities in the Dutch wetlands.

1 | Introduction

Vlaardingen (henceforth VL) communities in the Dutch wetlands (ca. 3400–2200 BCE) represent a remarkable continuity in the European Neolithic. In terms of cultural practices and subsistence economy, these communities adhere to traditions which go back to the Late Mesolithic (Amkreutz 2013; Beckerman 2015). In addition, recent ancient DNA studies have demonstrated the persistence of high amounts of western hunter–gatherer ancestry in VL communities, despite major shifts to early farmer ancestry and steppe ancestry in communities across Europe during this time (Olalde et al. 2026). A key factor in explaining the resilience of VL communities is their settlement system (Louwe Kooijmans 1993; Raemaekers 2003;

Amkreutz 2013). However, robust evidence for this settlement system is sparse to date.

VL communities inhabited a highly dynamic wetland landscape in which the available food sources at any one location constantly fluctuated (Amkreutz 2013, 308; Raemaekers 2003, 744–745). As a result, each VL settlement featured activities tailored to its local environment. The VL settlement system is thought of as a support network which encompasses and connects these varied VL settlements. VL communities would shift people and resources between these sites on various time-scales (e.g., seasonal) to optimally exploit these environments, enabling them to thrive in these highly varied wetland settings (Amkreutz 2013; Louwe Kooijmans 1993; Raemaekers 2003). This explanatory model for VL sites has been criticised on theoretical (Amkreutz 2013) and empirical grounds (e.g., Van den Dikkenberg and Van Gijn 2024; Van den Dikkenberg et al. 2024), but a systematic test is absent to date. Consequently, a core characteristic of VL society and key explanatory factor for their remarkable resilience remains poorly understood.

Here, new light is shed on the VL settlement system with a novel approach to ceramic petrography. We conduct the first comprehensive petrographic survey of VL ceramics, incorporating both new (De Bruin 2024) and legacy (Kroon et al. 2019) data from settlements across Dutch West coast (see Figure 1). Our analysis departs from classic petrographic studies in archaeology (e.g., Whitbread 1989; Quinn 2013) by focussing on potters' choices during raw materials selection and paste preparation. These technical choices, referred to here as paste recipes, are learned knowledge which was passed on within local communities (Arnold 2018). We apply statistical tools from ecology (Simpson 1949) and probability theory (see Kroon 2024) to test whether the diversity in, and knowledge sharing about, paste recipes conform to the intersite interactions proposed in the VL settlement system.

2 | Materials

VL communities have three core characteristics. The first is a specific ceramic style featured in hand-made pottery (Beckerman and Raemaekers 2009). The second characteristic is a subsistence economy focussed on the exploitation of wild resources but also incorporating agriculture and domesticated animals (Raemaekers 2003). Lastly, VL communities prefer to locate settlements on high grounds next to open surface water (see below). The characteristic settlement system of VL communities is the intersection of the last two characteristics.

VL settlements, even those which are contemporaneous or in close proximity, are otherwise highly diverse in terms of landscape location, size and subsistence economy. The VL settlement system is an attempt to explain and unify these diverse sites. It classifies VL sites into three categories based on their

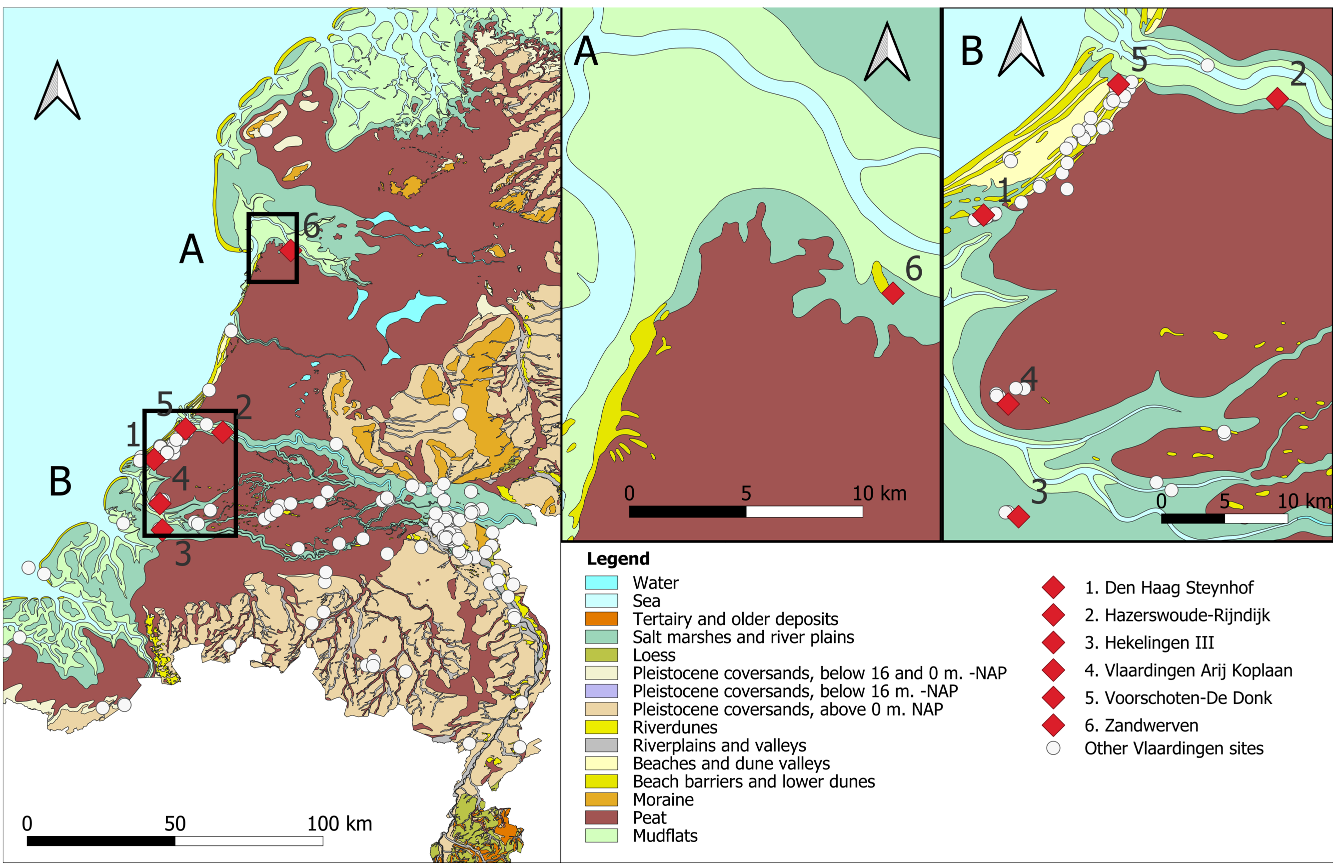

FIGURE 1 | Palaeogeographical map of the Netherlands with all sampled and known VL sites. (A) Detail of the location of Zandwerven; (B) detail of the locations of Den Haag Steynhof, Hazerswoude Rijndijk; Hekelingen III; Vlaardingen Arij Koplaan, and Voorschoten-De Donk (Van den Dikkenberg and Brandsen 2025; Vos et al. 2020).

environmental setting: coastal sites, levee sites and river dune sites. Each category would play a different role in an overarching settlement system (Louwe Kooijmans 1993; Raemaekers 2003). We focus here on the two best known categories: coastal sites and levee sites.

The first settlement type, coastal sites, is located on coastal dunes. VL sites in salt marshes are sometimes also included in this category (Raemaekers 2003). These sites often feature substantial residential architecture, evidence for hide-working and a subsistence economy centred on domestic animals and crops (Louwe Kooijmans 1993; Petrogiannaki and Van Gijn 2024; Raemaekers 2003). Consequently, coastal sites would be permanent settlements for multiple VL households.

The second category of sites is located on levees. Subsistence activities at these sites are focussed on hunting, fishing and gathering (Louwe Kooijmans 1987; Raemaekers 2003). Cereals are systematically found at levee sites but are thought to have been imported rather than locally cultivated (Out and Dörfler 2017). Levee sites do not yield traces of substantial structures, but small huts have been attested (e.g., Louwe Kooijmans 1987, 245). Therefore, levee sites are interpreted as seasonal camps which were occupied by small communities, potentially individual households from nearby coastal sites, who travelled back and forth to these coastal sites carrying harvested resources (Louwe Kooijmans 1993; Raemaekers 2003).

The last settlement type is river dune sites. River dune sites are often little more than sparse artefact scatters. A role as temporary hunting camps for nearby coastal and levee sites has been suggested, but these settlements remain ill-understood (Louwe Kooijmans 1993; Raemaekers 2003). Hence, river dune sites have been excluded here.

Thus, the VL settlement system explains the diversity of VL settlements by arguing these settlements form a broader, interconnected system. This interpretation has been challenged over the past decade. In particular, the singular focus on environmental conditions to explain human behaviour has been criticised (see Amkreutz 2013). This criticism is in part borne out by use-wear analyses of lithic artefacts at VL sites. These studies systematically demonstrate a more diverse set of activities than those envisioned in the classification of these sites (Van den Dikkenberg and Van Gijn 2024; Van den Dikkenberg et al. 2024). These problems raise the need for new approaches which can assess the relations between VL settlements and test whether these relations conform to the VL settlement system.

We argue that a systematic analysis of paste preparation processes in VL vessels meets these requirements. Ethnographic studies show that households or local groups play a prominent role in the transmission of knowledge about ceramic paste preparation in small-scale, domestic ceramic production, leading to a correlation between technical choices and households or local communities (Arnold 2018; Wallaert 2012; Roux et al. 2017). Moreover, knowledge about raw materials, such as their behaviour during firing and source locations in the landscape, is often tied to local communities of potters (Arnold 2018; Gosselain and Livingstone Smith 2005). Assuming that these patterns apply to VL ceramic production, testable hypotheses can be formulated for the VL settlement system.

Specifically, we can hypothesise that the different composition of inhabitants at VL settlements in coastal and levee sites would lead to differences in the diversity of paste recipes. For example, coastal dune settlements would be inhabited by multiple households, whereas levee sites might be inhabited by subcommunities from coastal sites (Raemaekers 2003, 744). As such, we expect a higher diversity of paste recipes at coastal sites than at levee sites since these paste recipes are shared within households. These hypotheses can be tested through a study of paste recipes at VL settlements.

To detect paste recipes at VL settlements, we prepared thin sections from 90 vessels from four VL sites (Table 1 and Figure 1) and incorporated 15 previously published thin sections (Kroon et al. 2019; Table 1). The following coastal sites were sampled: Den Haag Steynhof (Van Zoolingen and Bulten 2021), Voorschoten De Donk (Van Veen 1989) and Zandwerven (Van Regteren Altena and Bakker 1961). The sampled levee sites are Hazerswoude Rijndijk (Diependaele and Drenth 2010),

TABLE 1 | Overview of sites, site types, date range, source of radiocarbon dates, number of thin sections and source thereof.

Site	Site type	Date range (in years cal. BCE)	Source 14C-dates	Thin sections	Source thin sections
Den Haag Steynhof	Coastal	3100–2340	Van Zoolingen (2021)	24	This study
Hazerswoude Rijndijk	Levee	2871–2350	Kleijne and Huisman (2023)	5	Kroon et al. (2019)
Hekelingen III	Levee	3011–2468	Louwe Kooijmans (1985, 100)	32	This study
Vlaardingen Arij Koplaan	Levee	3499–1978	Lanting and Van der Plicht (1999/2000, 69–82)	20	This study
Voorschoten De Donk	Coastal	2852–2031	Van Veen (1989)	5	This study
Zandwerven	Coastal	2905–2299	Van Heeringen and Theunissen (2001, 56)	19	This study; Kroon et al. (2019)

Note: For the date range of Hazerswoude Rijndijk, see Kleijne and Huisman 2023; for Den Haag Steynhof, see Van Zoolingen 2021; date ranges for the other sites are based on available 14C-dates, recalibrated in OxCal v4.4.4 with the Intcal20 calibration curve (Bronk Ramsey 2009, 2021; Reimer et al. 2020).

Hekelingen III (Louwe Kooijmans 1987) and Vlaardingen Arij Koplaan (Van Beek 1990).

The sample design specifically included ceramics from these sites with cooking residue to ensure that all studied vessels were integrated into the domestic activities. The vessels may still have been imported to the sites (see Kroon et al. 2019) but their integration into domestic activities implies that the paste recipes still reflect the diversity in available technical knowledge at these sites. Moreover, this sample design allows for follow-up analyses on extracted lipids and food crusts to study vessel use (Van Gijn et al. 2025).

We also include a number of thin sections from contemporaneous Funnel Beaker West (FBW) and Corded Ware (CW) vessels to examine VL paste recipes in a broader context. These samples include 15 thin sections from CW vessels found at VL settlements in the coastal area (see Kroon et al. 2019), 42 thin sections from FBW vessels found in funerary contexts further inland (see Kroon 2024) and 19 thin sections from CW vessels found in funerary contexts further inland (see Kroon 2024). FBW and CW ceramics from settlement contexts would have been preferable for the last two datasets. However, FBW and CW settlements are rare in the Netherlands (Mennenga 2017; Bakker 1982, 88–90). Moreover, FBW vessels in funerary contexts are argued to stem from domestic contexts (Brindley 2022, 140; Brindley and Lanting 1992, 137), although this may not apply to CW (Wentink 2020). As such, these thin sections serve as an indication of the paste recipes in use among contemporaneous inland communities.

3 | Methodology

All thin sections were studied at the Laboratory for Material Culture Studies in Leiden, with a Leica DM 750P microscope with a HC plan s10x/22 mm eye piece and three lenses: Hi plan 4x/0.10, Hi plan 10x/0.25 and Hi plan 40x/063. The description of the thin sections followed the scheme from Whitbread (1989) with modifications from Quinn 2013 (see Kroon et al. 2019).

Documenting paste recipes requires variables which relate to artisanal choices rather than strict geological classifications (Arnold 2000). We constructed 10 binary variables to capture categories of materials and choices which we believe would have been distinct to prehistoric potters (see Arnold 2000) and which can be detected with optical microscopy. These variables are the use of (1) calcareous or (2) ferruginous clay (Quinn 2013); the presence of (3) abundant ($\geq 20\%$ surface area) or (4) sparse ($< 20\%$ surface area) silt in the clay matrix; the addition of tempers including: (5) crushed rock, (6) grog, (7) plant matter, (8) sand and (9) bone; and lastly homogenisation of the clay paste in a (10) dry or (11) wet state (Ho and Quinn 2021). Thin sections are grouped by unique combinations of these 10 variables for choices in clays, tempers and paste preparation. We refer to these unique combinations as paste recipes.

To calculate the diversity in paste recipes at VL settlements, we first determine the relative frequency of each paste recipe at all settlements. We then compute the Gini-Simpson diversity index with the simpson library in Python (Chorley 2014) over these data. This index provides a quantitative estimate of the diversity in paste recipes (Simpson 1949).

Next, we test whether diversity in paste recipes corresponds to settlement type. To perform this test, we formulate two rankings for the sampled VL settlements. The first ranking encodes the relative height of the Gini-Simpson index for each site. The second ranking is based on the expected diversity of paste recipes at each settlement. In this ranking, coastal sites receive rank 1, whereas levee sites receive rank 2 (see *Materials selection*). Subsequently, we test whether a monotonic relation exists between these two rankings by calculating Kendall's Tau-b in SciPy (v1.16.2; Virtanen et al. 2020). Kendall's Tau-b is preferred in this context due to the comparatively small number of observations (Hollander et al. 2015; Kendall 1938, 1945). As such, this test enables us to test the hypothesis that coastal sites are more diverse in terms of paste recipes than levee sites.

To also determine the similarity in paste recipes between VL settlements, we construct a probability distribution for each site by interpreting the relative frequency of a given technical choice as the odds of that choice occurring in a paste recipe. We apply the same operation to the thin sections from CW vessels from coastal sites, CW vessels from inland sites and FBW vessels (see *Materials selection*).

We perform a pairwise comparison of these empirical probability distributions with the Wasserstein distance in SciPy (v1.16.2; Virtanen et al. 2020). The Wasserstein distance is a nonparametric measure which calculates the optimal number of changes necessary to transform one probability distribution into another. The more changes required for the transformation, the larger the Wasserstein distance (Villani 2009; Ramdas et al. 2017). Given that the empirical probability distributions reflect both the relative frequency and presence/absence of technical choices of potters at a given site, the Wasserstein distance between two sites is an indicator for the amount of shared technical knowledge (see Kroon 2024).

We then apply a permutation test to determine whether the Wasserstein distance between two empirical probability distributions indicates a significant number of shared technical choices. For this evaluation, we generate 1000 random probability distributions. The random generation process builds a distribution by picking either a random percentage of vessels with a specific technical choice (in the case of tempers) or two random percentages such that these add up to 100% (for compound variables such as the use of calcareous or ferruginous clay). We then calculate the Wasserstein distances from the first of the paired, empirical distributions to each of these randomly generated distributions. This creates a new probability distribution of the likelihood that a given Wasserstein distance is found given that one set of choices is made at random. We then calculate the percentile rank (p) of the Wasserstein distance between the two empirical distributions relative to this new distribution with SciPy (v1.16.2; Virtanen et al. 2020). As such, p *is* the likelihood that the similarity between the two empirical distributions would result from a random process in which no technical knowledge is shared. The lower the value of *p*, the likelier that technical knowledge about these choices was shared. Consequently, this procedure enables us to evaluate the likelihood that technical knowledge was shared between two VL settlements.

Finally, we perform a Mantel test to determine whether shared knowledge about paste recipes predominantly occurred between adjacent, local communities. In this test, we compare the lower triangular matrix of the significant Wasserstein distances between VL settlements against a distance matrix with the geographic distances between these sites. The latter matrix is calculated using the geo_distance function from the geopy v. 2.4.1 library in Python (Tygart et al. 2018; Karney 2013). The Mantel test returns the linear correlation between the two distance matrices in the form of the Pearson's correlation coefficient (ρ) as well as a *p*-value (p) and a *Z*-score (z) to assess the significance of the outcome (Carr 2015; Mantel 1967). For performing the Mantel test, we use the mantel v2.2.2 library in Python (Carr 2015).

4 | Results

Eighteen petrofabrics were identified in the sampled VL ceramics through optical microscopy (see Figure 2, Table 2 and Supporting Information for full detailed thin section descriptions). These petrofabrics relate to both technological and compositional characteristics. For the purposes of this study, we discuss the technological choices in these fabrics in more detail below.

4.1 | Choice of Clays

All sampled thin sections feature calcareous clays. These clays are recognisable through golden brown (Figure 2, e.g., petrofabric 3) to pale brown (Figure 2, e.g., petrofabric 18) interference colours (Quinn 2013; see Figure 2). These interference colours were observed either throughout the entire thin section or in the oxidised margins. The cores and/or margins on various thin sections also feature dark brown or dark grey interference colours due to the presence of organic materials which were added (see below) or present naturally (see Figure 2, e.g., petrofabric 14 and 16, respectively).

The thin sections feature various textural concentration features (TCFs) with red brown to orange interference colours, which are indicative of ferruginous clays (Quinn 2013; see Figure 2, e.g., petrofabric 7). TCFs with brown or yellow brown interference colours also occur (e.g., Figure 2, petrofabric 18). The shapes and boundaries of these TCFs were used to determine detection of clay mixing (Ho and Quinn 2021; see below).

The samples exhibit considerable variation in the abundance of the fine fraction of the inclusions. The most common mineral in the fine fraction is angular quartz, which fits the sedimentary nature of Dutch clay deposits (see Berendsen 2011). However, samples in petrofabrics 1, 5, 7, 12 and 13 feature abundant fine inclusions, up to and over 20% of the surface area of the sample (see Figure 2). By contrast, the fine fraction is far less abundant in petrofabrics 2, 9, 10 and 18 (see Figure 2). Fabrics with and without abundant inclusions in the fine fractions occur on all VL settlements. However, Zandwerven stands out for having relatively many fabrics with a sparse fine fraction (64%), whereas fabrics with an abundant fine fraction are more common at Hekelingen III (63%), Den Haag Steynhof (50%) and Vlaardingen Arij de Koplaan (45%).

4.2 | Selection of Nonplastic Inclusions

For the choice in raw materials, we rely on the observations about the coarse fraction of the inclusions. In general, the sampled fabrics are bimodal or multimodal. In the latter case, rounded quartz fragments in the size range of medium to fine sand were likely added to the matrix (see Figure 2, e.g., group 6).

Three materials commonly occur in the coarse fraction of the inclusions. Angular rock fragments are the most common element (73% of thin sections, e.g., Figure 2, petrofabric 2), and these chiefly encompass mono- and polycrystalline quartz as well as plutonic rocks (granite and diorite). Grog is the second most common inclusion, occurring in 45.6% of the fabrics (e.g., Figure 2, petrofabric 12), followed by plant matter (10%; e.g., Figure 2, petrofabric 2). No absolute differences in choice of nonplastic inclusions exists between sites. However, two sites stand out. At Zandwerven, a relatively high percentage of fabrics was enriched with large fragments of plutonic rock (92%), whereas at Hekelingen III, Den Haag Steynhof and Vlaardingen Arij de Koplaan, around 60% of the fabrics feature tempering with grog (see Supporting Information).

These differences in the preference of inclusions and temper may relate to the natural availability of these materials. Zandwerven is relatively close to glacial deposits which are the only source of plutonic rock fragments in the Netherlands. Den Haag Steynhof, Vlaardingen Arij de Koplaan and Hekelingen III, on the other hand, are at the end of the Rhine-Meuse delta in which silicate gravel (primarily quartz and quartzite) is the primary available rock (Berendsen 2011, 112; Zandstra 1978, Tab. A).

4.3 | Paste Homogenisation

We distinguished between wet and dry paste preparation on the basis of the shape and boundaries of TCFs in the fabrics. We took the presence of clay lumps and lenses with clear boundaries as an indication for dry paste preparation,and the presence of streaks and laminations as an indicator for wet paste preparation (Ho and Quinn 2021).

Wet paste preparation is more common (60%) than dry paste preparation (40%) in the fabrics. However, this overall balance hides an important distinction. At Vlaardingen Arij de Koplaan, Den Haag Steynhof and Hekelingen III, the percentage of thin sections with traces of wet paste preparation varies between 45% and 58%. However, approximately 86% of the thin section from Zandwerven features signs of wet paste preparation. Therefore, it appears that the potters at Zandwerven took a different approach to paste homogenisation than those at the other VL settlements.

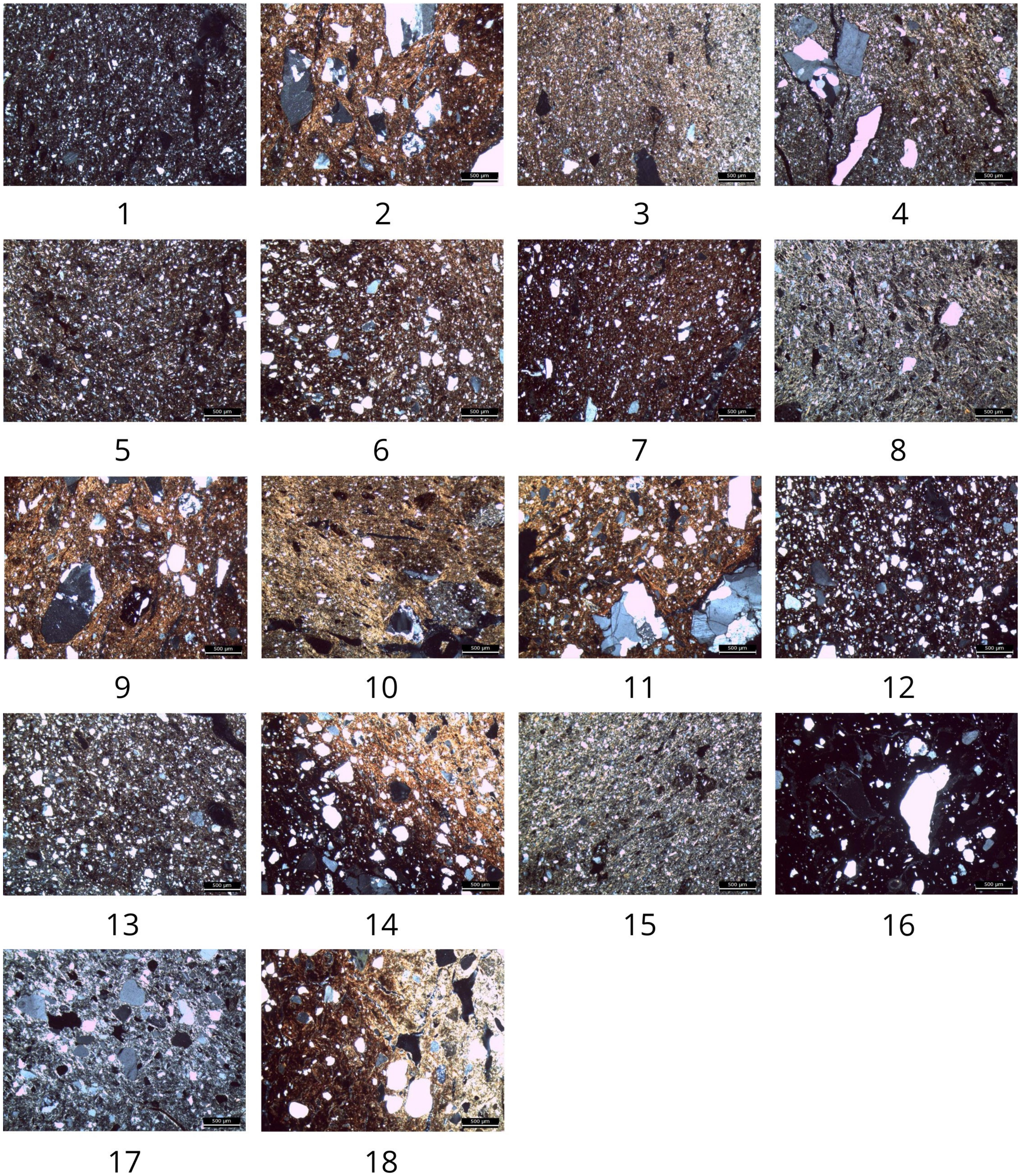

FIGURE 2 | Photomicrographs of the 18 petrofabrics (in XP).

4.4 | Analysis of Diversity in Paste Recipes

After conversion of these petrographic observations into distinct paste recipes (see Section 3), we calculated the Gini-Simpson diversity index for each site and tested for a correspondence between the site type and the diversity in paste recipes (see Table 3).

We observe that the test statistic (p) of Kendall's Tau-b far exceeds $\alpha = 0.05$ (Table 3), indicating that the zero hypothesis of the test cannot be rejected. In other words, the test indicates that the two rankings are not correlated. Irrespective of the test statistic, the correspondence between both rankings (τ) is negligible (see Table 3). These outcomes likely result from the relatively high diversity values observed in all VL settlements sampled here. Only

TABLE 2 | Summary of the petrographic groups (see Supporting Information for full details).

Petrofabric	Sites	Matrix (xp)	Max. inclusion size	Porosity	Void size	% paste	Inclusions	TCF presence in group	% (sub) rounded versus % (sub) angular
1	Steynhof Hekelingen III Vlaardingen	Dark brown–almost black	2.4 mm	Irregular long pores	Macro	55–65	Quartz, granite, grog, diorite, biotite muscovite, pyroxene, mica (biotite and muscovite)	No (50%) and yes (angular/rounded) (50%)	40–60
2	Steynhof Vlaardingen	Brown–dark brown	2.6 mm	Irregular long pores around inclusions	Macro	45–55	Quartz, granite, grog, diorite, biotite, muscovite, Micriet, pyroxene, organic material, mica (biotite and muscovite)	No (80%) and yes (angular/rounded) (20%)	25–75
3	Steynhof Zandwerven	Light brown–darkish brown	2.8 mm	Small and mostly rounded	Macro	65–75	Quartz, granite, grog, diorite, biotite, mica (biotite and muscovite)	No (90%) and yes (rounded) (10%)	10–90
4	Steynhof	Grey–Brown	2.7 mm	Few long pores	Meso	60–70	Quartz, granite, grog, diorite, biotite, mica (biotite and muscovite)	No (50%) and yes (angular/rounded) (50%)	0–100
5	Steynhof Vlaardingen Zandwerven	dark brown–almost black	2 mm	Elongated and cracked	Meso	50–60	quartz, granite, grog, diorite, biotite, mica (biotite and muscovite)	no (90%) and yes (rounded) (10%)	10–90
6	Steynhof Zandwerven	Light brown–brown	2.7 mm	Cracked and rounded	Meso	45–55	Quartz, granite, grog, diorite, biotite, chert, mica (biotite and Muscovite)	No (90%) and yes (rounded) (10%)	10–90
7	Hekelingen III Vlaardingen	Dark brown–almost black	2.8 mm	Irregular long pores around inclusions	Meso	60–70	Quartz, granite, grog, diorite, biotite, muscovite, mica (biotite and muscovite)	No (100%)	25–75
8	Hekelingen III Vlaardingen	Grey–light brown	2.3 mm	Small and mostly rounded	Meso	60–70	Quartz, granite, grog, diorite, biotite, organic material, mica (biotite and muscovite)	No (80%) and yes (angular/rounded) (20%)	25–75

(Continues)

TABLE 2 | (Continued)

Petrofabric	Sites	Matrix (xp)	Max. inclusion size	Porosity	Void size	% paste	Inclusions	TCF presence in group	% (sub) rounded versus % (sub) angular
9	Hekelingen III	Light brown–dark brown	2.1 mm	Elongated and cracks	Macro	50–60	Quartz, granite, grog, diorite, biotite, mica (biotite and muscovite)	No (90%) and yes (rounded) (10%)	40–60
10	Vlaardingen	Light brown–brown	2.7 mm	Elongated and cracks	Macro	70–80	Quartz, granite, grog, diorite,mica (biotite and muscovite)	No (100%)	45–55
11	Zandwerven	Brown–Reddish brown	3.8 mm	Irregular rounded around inclusions	Meso	50–60	Quartz, granite, grog, diorite, biotite, amphibole, mica (biotite and muscovite)	No (100%)	25–75
12	Hekelingen III	Dark brown–almost black	2.1 mm	Small and mostly rounded	Meso	50–60	Quartz, granite, grog, diorite,mica (biotite and muscovite)	No (70%) and yes (angular/rounded) (30%)	30–70
13	Hekelingen III	Grey–black	1.9 mm	Irregular long pores	Macro	60–70	Quartz, granite, grog, diorite, biotite, mica (biotite and muscovite)	No (100%)	40–60
14	Hekelingen III	Light grey–greyish brown	2.3 mm	Small and mostly stretched	Macro	75–85	Quartz, granite, grog, diorite, mica (biotite and muscovite)	No (60%) and yes (angular) (40%)	40–60
15	Zandwerven	Black	3 mm	Irregular rounded around inclusions	Meso	55–65	Quartz, granite, diorite, biotite, mica (biotite and muscovite)	Yes (angular/rounded) (100%)	25–75
16	Zandwerven	Grey	5 mm	Small and irregular	Meso	70–80	Quartz, granite, diorite, biotite,	No (100%)	50–50
17	Zandwerven	Light brown–dark brown	2.9 mm	Irregular cracked rounded around inclusions	Macro	50–60	Quartz, granite, grog, diorite, biotite, muscovite, organic material, mica (biotite and muscovite)	No (20%) and yes (angular/rounded) (80%)	40–60
18	Hekelingen III	Light brown–dark brown	2.4 mm	Elongated and cracks	Macro	50–60	Quartz, granite, grog, diorite, biotite, mica (biotite and muscovite)	No (25%) and yes (angular/rounded) (75%)	20–80

TABLE 3 | Diversity indices (real and ranked) and ranks for expected diversity for all sampled VL settlements.

Site	Observed diversity		Expected diversity
Name	Gini–Simpson index	Ranked	Rank
Den Haag Steynhof	0.9132	2	1
Hazerswoude Rijndijk	0.7999	5	2
Hekelingen III	0.9434	1	2
Vlaardingen	0.89	4	2
Voorschoten De Donk	0.48	6	1
Zandwerven	0.8975	3	1
Kendall's Tau-b	τ	**p**	
Outcomes	0.0861	0.8272	

Note: The outcomes of the Kendall's Tau-b test are reported at the bottom. Table entries in bold emphasis present a statistic test rather than a site as the lines above. This is to make clear that this is a test of the table/outcomes above.

Voorschoten De Donk has a relatively low Gini-Simpson diversity index and also happens to be a coastal settlement for which high diversity is expected (see *Materials selection*). Therefore, we conclude that no relation exists between the diversity of paste recipes at VL settlements and their environmental setting. This outcome contradicts the hypothesised signature of the VL settlement system in the diversity of paste recipes.

Three alternative explanations can be offered for this outcome. Firstly, the transmission of knowledge about paste recipes may not be strictly tied to household contexts in VL communities. Such a scenario could explain the high diversity in paste recipes irrespective of settlement type, since paste recipes could occur irrespective of the households present at a site. An alternative explanation could be that habitation of (or vessel deposition at) these settlements is not structured along households. This would also result in a higher diversity in paste recipes than strictly expected, since paste recipes from multiple households would end up at the same site. The final explanation, once the previous two alternatives have been excluded, is that the VL settlement system as hypothesised in previous studies (Louwe Kooijmans 1993; Raemaekers 2003) does not exist as such.

Exclusion of the first two alternative explanations is difficult without further information on two factors: population structure and vessel provenance. Specifically, information on homozygosity or biological relatedness among individuals at VL settlements could help to shed light on whether or not multiple households are present at these sites (Ringbauer et al. 2024). However, the sparsity of human skeletal remains at VL settlements and of VL funerary contexts may complicate such an approach (Olalde et al. 2026). Similarly, systematic provenance analysis of VL ceramics remains absent (Kroon et al. 2019) and must be preceded by identification of geochemical markers for the various marine, fluvial and glacial clay deposits in the Netherlands (Griffioen et al. 2016). In the absence of information on VL population structures and vessel provenance, we modify the analysis to account for a more complex relation between paste recipes and settlement communities by implementing a probabilistic comparison.

4.5 | Knowledge Transmission Between VL Settlements

For the second part of this test, we calculate the similarities in paste recipes between sites directly with the Wasserstein distance (see Section 3). This approach does not assume a strict relation between local communities and paste recipes but does allow us to detect the impact of the VL settlement system. To detect this impact, we first assume that knowledge about paste recipes is acquired during direct interactions between potters (e.g., through apprenticeships, see Wallaert 2012; Roux et al. 2017; Arnold 2018). Secondly, we assume that the VL settlement system structures such interactions along geographic proximity. In other words, the coastal sites are the primary loci of knowledge transmission, but adjacent communities may meet at satellite levee (and river dune) sites. This spatially embedded nature of knowledge exchange on paste recipes should lead to a correlation between the Wasserstein distance and geographic distance between two sites. In turn, this correlation can be detected with a Mantel test (see Section 3).

The Wasserstein distances between the VL settlements are shown in Figure 3. In addition, we also compared the choices of VL potters against those of potters who made CW vessels in the coastal area (Kroon et al. 2019) and those of potters who fashioned CW and FBW vessels further inland (Kroon 2024). We represented these Wasserstein distances as a spatial network to aid interpretation (see Figure 4). Three observations stand out from these results.

Firstly, shared knowledge about paste recipes occurs independent from spatial proximity, contrary to the hypothesised impact of the VL settlement system. The Wasserstein distances between VL settlement sites are not strongest to adjacent sites, but on occasion, skip these adjacent sites and instead run to distant sites (see Figures 3 and 4). For example, the paste recipes employed at Hekelingen bear the most resemblance to those at Steynhof, rather than those at the closer settlement VL. Similarly, Voorschoten-De Donk does not feature shared knowledge about paste recipes to Steynhof and Hazerswoude-Rijndijk, despite being in relatively close proximity to both settlements. This is borne out by a Mantel test for the masked similarity matrix (Figure 3) and a distance matrix for the geographic distances between the sites (see Section 3). The two-tailed Mantel test returns $\rho = 0.2$, with $p = 0.74$ and $z = 0.41$. The low veridical correlation and poor significance values indicate no linear correlation exists between the spatial distances and Wasserstein distances between these settlements. Therefore, it appears that these communities share knowledge about paste recipes independent of geographic distance.

Secondly, two VL settlements are outliers in terms of paste recipes. These outliers are Zandwerven and Voorschoten De Donk. Neither settlement features significant similarities to the other VL settlements. Instead, the paste recipes at these sites best resemble those observed in FBW vessels found further inland (see Figures 3 and 4). Looking at the thin sections

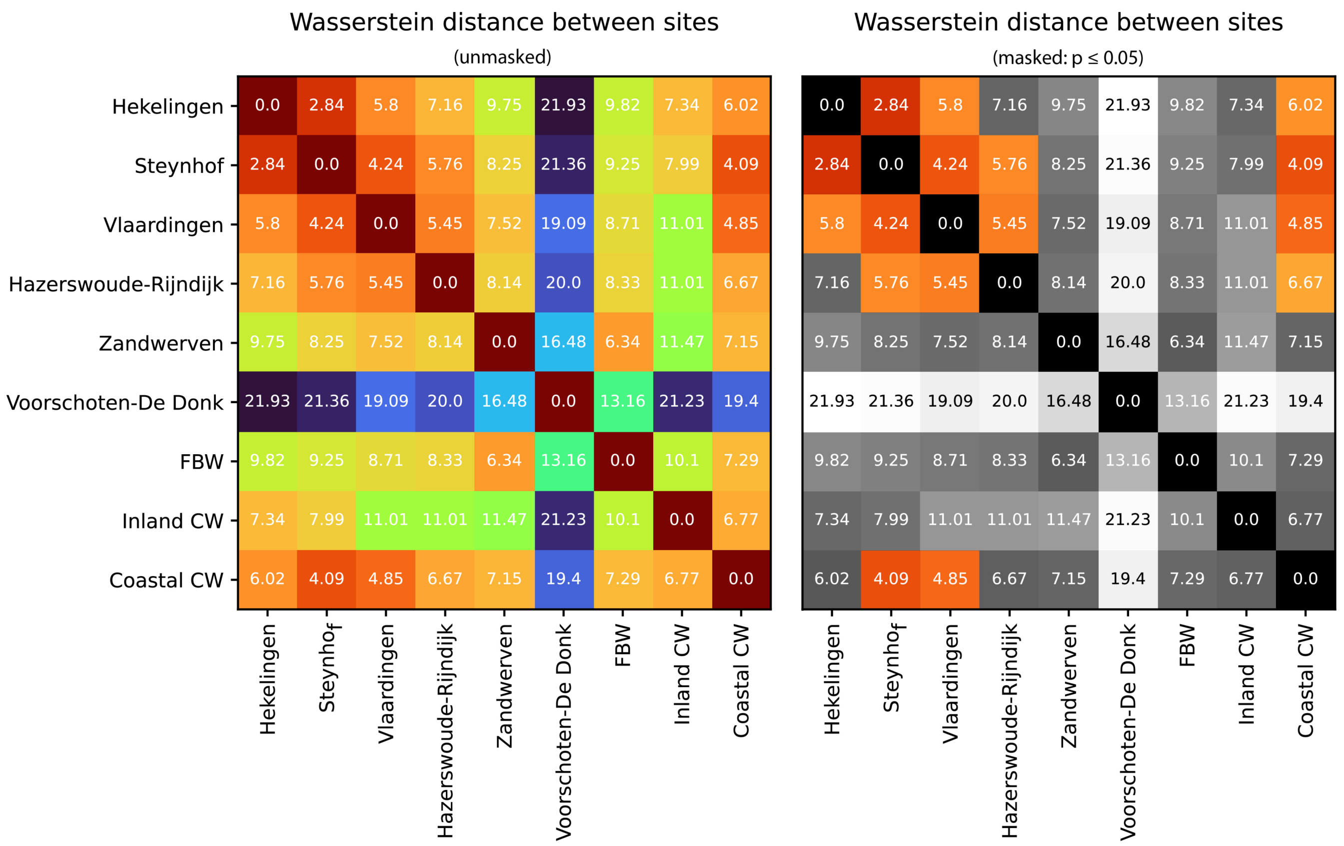

FIGURE 3 | Heat map of the Wasserstein distances between paste recipes at VL settlements, as well as those in CW vessels from coastal settlements, and CW and FBW vessels from inland communities. Left: heatmap masked for $p \leq 0.05$.

(see Supporting Information S1), these short Wasserstein distances are likely caused by technical choices while adding temper and homogenising the paste. At both VL settlements, potters opted to add crushed rock and perform paste homogenisation on a wet paste relatively often compared to the other VL settlements. Both choices are characteristic for FBW paste recipes (see Kroon 2024). However, neither of the Wasserstein distances to FBW paste recipes is significant (see Figures 3 and 4), indicating that VL potters at these sites either adopted only some elements of FBW paste recipes or used additional paste recipes. Therefore, these potters learned and experimented with paste recipes from FBW communities rather than outright adopting them.

The last observation pertains to CW vessels from the coastal area. Strikingly, the paste recipes of these vessels do not feature significant similarities to paste recipes from CW vessels found further inland. Instead, the paste recipes in these vessels feature relatively short Wasserstein distances to those used at multiple VL settlement sites (see Figures 3 and 4). These paste recipes in CW vessels from coastal settlements indeed deviate from those of inland vessels in terms of tempers and paste preparation (see Supporting Information S1; Kroon et al. 2019; Kroon 2024). Compared to paste recipes in inland CW vessels, the potters who fashioned these vessels from coastal contexts less often opted to add grog to the paste and more often opted for sand and crushed rock. Moreover, wet paste homogenisation is more prevalent in vessels from coastal sites than those in inland sites. Both factors contribute to the match with VL ceramic technology. As such, it appears that these vessels, despite being CW vessels in terms of typology, were made from clay pastes which follow the paste recipes found at VL sites on the Dutch West coast.

5 | Knowledge Transmission in the Wetlands

In this paper, we study the VL settlement system through a petrographic study of paste recipes in VL ceramics. Knowledge about these recipes is passed on within households or local communities (Arnold 2018; Wallaert 2012; Roux et al. 2017). Therefore, diversity and similarities in paste recipes at VL sites can be used to test the population structures at, and relations between, VL sites which are proposed within the VL settlement system (see Raemaekers 2003; Louwe Kooijmans 1993).

Our analyses show that the diversity of paste recipes at VL settlements does not correspond to the hypothesised role of these sites in the VL settlement system. We find that diversity in paste recipes is systematically high regardless of the proposed differences in numbers of households at coastal and levee sites (Table 3). Moreover, knowledge sharing about these paste recipes is not limited to local communities but appears to be independent of spatial proximity (Figures 3 and 4). These two observations point to the existence of complex intersite relations in which people, vessels and/or technical knowledge moved between settlements independent of spatial proximity. Further work on population structures and vessel provenance at VL settlements could shed new light on these relations.

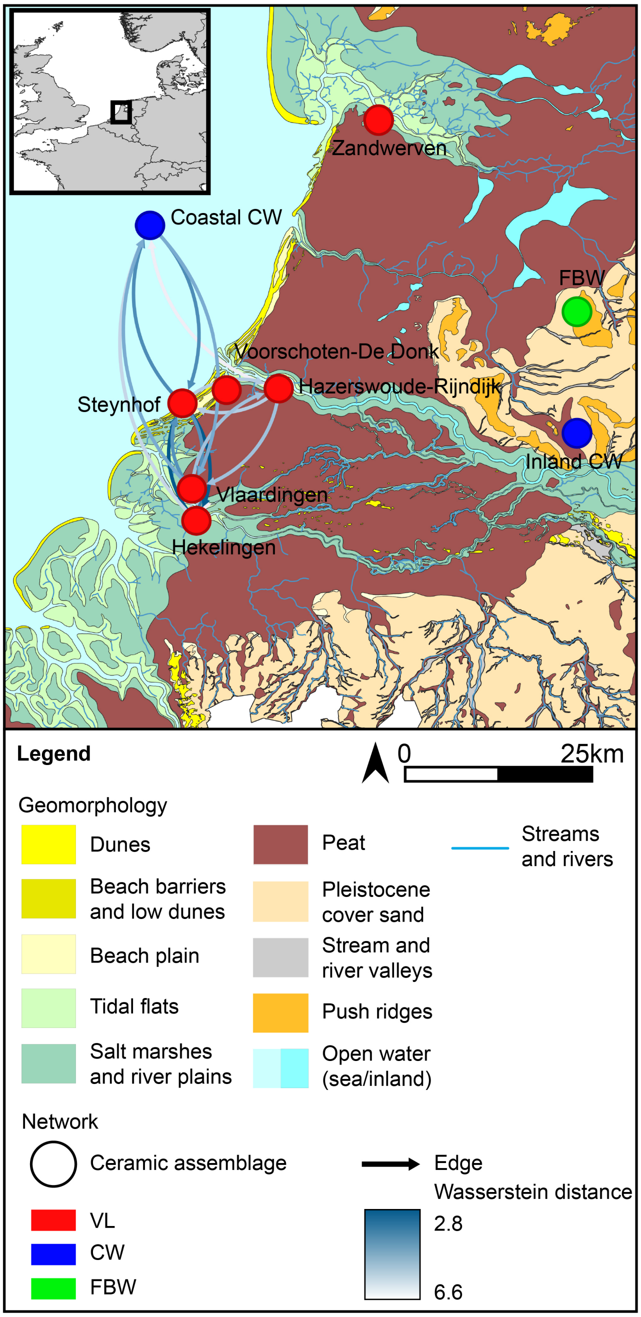

FIGURE 4 | Network representation of the Wasserstein distances between paste recipes found in VL vessels, FBW vessels, CW vessels found inland and CW vessels from the coastal area (see Figure 3). The network contains only edges for which $p \leq 0.05$. Network visualisation with Gephi's Geo Layout algorithm (Bastian et al. 2009; for background maps, see Vos et al. 2020; Eurostat: EuroGeographics for the administrative boundaries).

An interesting goal for follow-up studies would be to perform a diachronic comparison of VL paste recipes. Based on the currently available radiocarbon dates (Table 1), all sampled sites are considered broadly contemporaneous. However, some of these sites exhibit multiphase stratigraphies (see Louwe Kooijmans 1985; Van Regteren Altena et al. 1962) which could be used to refine their absolute chronology through Bayesian chronological modelling (Bronk Ramsey 2009). Indeed, this method has already been applied successfully to some recently excavated VL settlements (e.g., Kleijne and Huisman 2023). Unfortunately, many of the key VL settlements were excavated decades ago and the legacy radiocarbon dates from these excavations do not lend themselves for in-depth Bayesian chronological modelling (Bayliss 2015). A renewed radiocarbon dating program for VL settlements is beyond the scope of this study but would be a major contribution to our understanding of the VL settlement system.

Our findings also shed new light on the relations between the Middle and Late Neolithic VL, FBW and CW communities in the Netherlands. Contacts between FBW and VL communities have long been surmised based on the presence of FBW vessels at VL sites and VL vessels at FBW sites (Beckerman and Raemaekers 2009, 79; Amkreutz 2013, 342; Drenth 2019), but the impact of these connections on both communities was thought to be superficial (Drenth 2019, 832; Louwe Kooijmans 1983, 58–60; Bakker 1982, 95–6). However, recent studies of ceramic *chaînes opératoires* have demonstrated knowledge transmission about ceramic production between FBW and VL communities (Kroon 2024). Here we show that specific VL communities also learned and experimented with FBW paste recipes. The transmission of paste recipes and *chaînes opératoires* often requires apprenticeships (Wallaert 2012; Arnold 2018). Therefore, our results indicate close, formative interactions between VL and FBW communities.

The interpretation of CW vessels at VL settlements has recently been debated in light of broader genomic evidence for migration (see Allentoft et al. 2024; Olalde et al. 2026). On the one hand, the presence of these CW vessels has been interpreted as an indication for the adoption of CW identities by VL communities (Beckerman 2015) or even the presence of migrant communities in the coastal area (Hogestijn 1997). On the other hand, the characteristic CW burial rites are absent in the coastal area (Wentink 2020, 340–5; see Furholt 2019), and continuities in ceramic technology, subsistence economy and settlement location at VL sites indicate continuity of VL groups in the area (Kroon et al. 2019). Our results shed new light on this debate. We show that the paste recipes of CW vessels from the coastal area bear closer resemblance to paste recipes in local VL vessels than to those of CW vessels found further inland. This further indicates continuity of VL communities and their practices in the third millennium BCE (see Olalde et al. 2026; Amkreutz 2013; Kroon 2024), as well as the willingness of VL communities to experiment with and adopt practices from neighbouring communities.

6 | Conclusion

The VL settlement system emerged as an attempt to explain both the persistence of populations in the Dutch wetlands and the diversity of VL settlements in terms of built-up architecture, landscape zones, subsistence economy, and crafting activities. This model proposes that VL settlements in specific environments are specialised sites which are part of a broader system in which people and resources move. Despite the central role of the VL settlement system in explaining the resilience of these populations and our understanding of VL communities, the veracity of this model continues to be debated.

Here, we apply a novel approach to shed light on the VL settlement system. We use ceramic petrography to detect the paste recipes used in ceramic production at various settlement sites. Ethnographic studies show that these paste recipes are transmitted within local communities or households. Therefore, the diversity and similarity in paste recipes enable us to retrace community structures and learning events on and between VL settlements.

We demonstrate that the diversity in and spread of knowledge about paste recipes in VL communities does not match the expected signatures of the VL settlement system. Paste recipes at VL settlements are systematically more diverse than expected, and this diversity does not correlate with the environments in which the settlements are located. Moreover, the similarities in these paste recipes appear to be independent from geographic distance, contradicting the idea of local communities. In addition, we show that VL communities were willing to adopt and experiment with practices from neighbouring CW and FBW communities.

Thus, we argue that this willingness to engage and experiment with novel practices is a key factor to understanding VL communities. These communities occupied an ever-shifting wetland landscape for over a millennium alongside inland FBW and CW communities. The pluriformity of VL settlements as well as the resilience of VL communities may well result from this property.

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Data Availability Statement

The data that support the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Detailed petrographic descriptions of samples.