Foodways of “The Wall People”: Organic Residue Analysis and Scanning Electron Microscopy of the Pottery Assemblages from the Long-Wall System in Mongolia

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Abstract

This research presents the first comprehensive analysis of medieval pottery (10th–13th centuries CE) from Mongolia, focusing on ceramics unearthed from the Medieval Border Systems. Lipid residue and archaeobotanical analyses revealed the presence of domesticated plants, particularly various types of millets, suggesting that millet was a primary staple in the diet alongside domesticated animals and wild resources through collection, hunting, and fishing. Miliacin, a biomarker specific to broomcorn millet (*Panicum miliaceum*) was identified in over 80% of the analyzed samples. Foxtail millet (*Setaria italica*) was identified in carbonized foodcrusts using Scanning Electron Microscopy, while barnyard millet (*Echinochloa esculenta*) was recovered from archaeobotanical assemblages. Isotope analysis of extracted palmitic and stearic acids is consistent with lipid residues derived primarily from C_3 based resources, with C_4-enriched signals interpreted as millet consumption and ruminant foddering practices. These findings demonstrate substantial millet use on the steppe, though the limited archaeobotanical evidence for on-site processing leaves the question of local cultivation versus external supply unresolved. The data reported here are significant not only for understanding dietary, culinary, and subsistence practices at Mongolian medieval frontier sites but also contributing to a baseline for the study of the medieval diet and economy across the sparsely populated Mongolian steppe. By integrating multi-proxy evidence, lipid residue analysis, carbonized foodcrust microscopy, stable isotope data, archaeobotanical and zooarchaeological remains, this study offers valuable insights into the foodways and economic foundations of these frontier communities while addressing the gap in our understanding of medieval border management in Mongolia.

Keywords: Foodways, Steppe Diet, Lipid Analysis, Medieval Mongolia, Scanning Electron Microscopy, Stable Carbon Isotope Analysis of $C_{16:0}$ and $C_{18:0}$

1. Introduction

Traditionally referred to as "Chinggis Khan's Wall" and the "Jin Border Trenches," the Medieval Wall System (MWS) represents one of the most extensive and least understood frontier infrastructures in Northeast Asia. Broadly dated to the 10th–13th centuries CE, it consists of three main parts: (1) the *Northern Line*, extending across northeast Mongolia, southeast Russia and northern China; (2) the *Central or Jin line*, located in northwestern China and eastern Mongolia, which itself comprises two main lines and smaller branches; and (3) the *Southern or Western Xia Line*, located in the Gobi Desert in southern Mongolia (Feng 2008; Li 2008; Kovalev and Erdenebaatar 2010; Kradin 2019; Sun 2010; Xie 2011; Dan 2013; Shelach-Lavi et al. 2020a, b; Storozum et al. 2021; Lotze et al. 2026).

Archaeological surveys and excavations have since been conducted by Russian, Mongolian, Japanese, and Chinese scholars (Shirokogorov 1919; Ponosov 1941; Kiselev 1958; Feng 2008; Li 2008; Yamaguchi et al. 2009; Sun 2010; Lunkov et al. 2011; Xie 2011; Dan 2013; Erdenbat et al. 2023). Nevertheless, many fundamental questions remained unresolved, including the exact chronology of construction and use across different segments, the dynastic attribution of individual sections, the purposes they served, the identity of the populations who operated them, and the strategies by which these communities survived in harsh frontier conditions.

Recently, ongoing systematic interdisciplinary surveys and excavations have been carried out by an international team from the Hebrew University of Jerusalem, the National University of Mongolia, Yale University, and the University of Pittsburgh. Between 2019 and 2025, extensive fieldwork focused on MWS segments, enclosures, and associated burial contexts in Dornod, Sukhbaatar, and Ömnögovi provinces (Shelach-Lavi et al. 2020a, b; Storozum et al. 2021; Fung et al. 2024; Hanks et al. 2024; Golan et al. 2025; Shelach-Lavi et al. 2025; Steiner et al. 2025, 2026, 2026). These surveys and excavations provide insights into the dates, functions, and makeup of the different components of the MWS and enable examination of frontier communities in the Mongolian Steppe, far from elite urban centers.

2. Historical and Archaeological Context

The Medieval period in Northeast Asia witnessed the rise of various nomadic and semi-nomadic polities, several of which established dynasties that integrated pastoralist tradition with Chinese cultural elements. Most relevant to present study are the Kitan which founded the Liao dynasty (901–1125) (predate Mongol Empire),, and the Jurchens, who established the Jin dynasty (1115–1234) (overlapping the early Mongol Empire and eventually conquered by the Mongols). Other groups including Huihu and Zubu (Wittfogel and Feng 1949, p 178), also featured prominently in interactions at the border zone. Historical sources such as the History of the Liao dynasty (遼史 Liaoshi), the History of the Jin dynasty (金史 Jinshi) and the Kitan Chronicles (契丹國志 Qidan guozhi) recorded various aspects of these populations, including their diet, agricultural and pastoral practices, fishing, hunting, trade networks, and pottery usage (Tuo 1344; Sun and Sun 2010; Kradin 2019; Lotze et al. 2026). According to these sources, the Kitan and Jurchen had access to wide variety of foods and ingredients acquired through hunting, pastoralism, and agriculture. However, direct archaeological evidence of the use of these resources and their relative importance in the diet of the Liao and Jin populations is scarce.

3. Research Questions and Objectives

Here we apply organic residue analysis (ORA) to Kitan and Jurchen pottery (encompassing both porcelain and earthenware) to obtain the direct molecular evidence of food processed in these vessels. ORA provides a means to address long-standing gaps in traditional archaeological and historical research on diet and subsistence by identifying lipids and other molecular biomarkers absorbed in ceramic fabrics, including dairy products, ruminant and non-ruminant animals, plant products, and marine or freshwater resources, which are not apparent through other analytical approaches. Historical records predominantly document the lives of elite and urban populations within the dynastic heartlands, leaving the subsistence practices of frontier communities, such as the “Wall People”, largely unknown. Many questions remain unaddressed and unanswered about these frontier communities, for example, what did the “Wall People” eat? How did they prepare food for consumption? Did they rely on primarily pastoral resources such as meat, dairy and animal fats? Did they consume agricultural products, and if so, were they locally produced or obtained through trade, taxation, or other exchange networks?

Current archaeological evidence provides only partial answers. Zooarchaeological remains from frontier sites indicate a predominance of livestock—sheep, goats, cattle, and horses, as well as wild animals and fish—supporting a pastoral economy, though the extent to which these animals supplied meat versus dairy or secondary products remains unclear (Steiner et al. 2025, 2026, 2026). Archaeobotanical data are sparse and uneven, leaving open the question of whether crops were cultivated locally or imported from agricultural centers of the Kitan and Jurchen states. Vessel typologies and site layouts alone cannot reveal what kinds of foods were prepared or consumed in daily life. This research therefore integrates ORA with current archaeobotanical, zooarchaeological, and historical studies to offer a more nuanced reconstruction of the diet, foodways and day-to-day subsistence practices in the Mongolian steppe.

4. Excavated Sites

With these research questions in mind, samples were collected from three sites (Clusters 23&24 and MA03) (Figure 1). Clusters 23 and 24 (Wall line with its enclosures) are located south of the *Northern Line*, in Dornod province. This line and the two enclosures were built during the Liao (Kitan) period (Shelach-Lavi et al. 2020a, b; Hanks et al. 2024). Another enclosure site (MA03) is located adjacent to the *Mongolian Arc* section of the eastern line in Sukhbaatar province (Fung et al. 2024; Shelach-Lavi et al. 2025). These enclosures and the line associated with them, were built during the Jin (Jurchen) period.

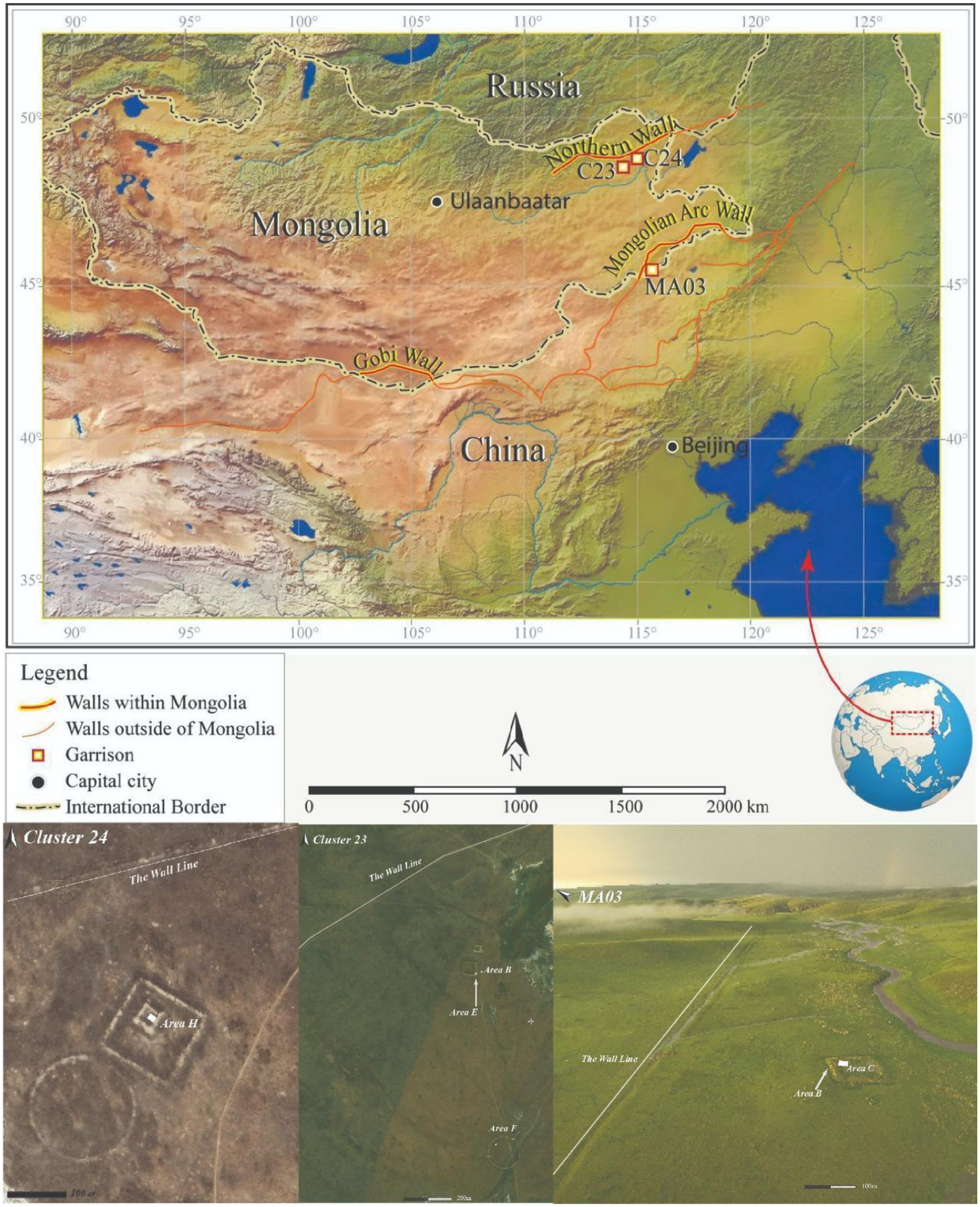

Figure 1. Excavated Areas of Clusters 24, 23 and MA03 with their Associated Structures (Squares and Circles)

At Cluster 24, pottery samples were taken from area H, located inside the smaller rectangular enclosure (Figure 1) which is believed to represent a habitational area. Pottery sherds were recovered from accumulation layers on the structure floor dating to its period of use.

At Cluster 23, sherds were sampled from four areas: Areas A, B and E, associated with the large rectangular earthen enclosure, and Area F, located inside the large circular earthen enclosure (Hanks et al. 2024) (2). Areas A and B have been interpreted as refuse pits or middens containing substantial quantities of animal bones, potsherds, and other artefact types (Steiner et al. 2025, 2026). Area E comprises a trench cut through the enclosure’s wall and ditch. Samples from the ditch context represent broken artifacts and refuse materials accumulated at the base of the feature. The function of Area F remains unclear, though it may represent some form of installation associated with a small number of artifacts, including animal bones, metal objects and pottery.

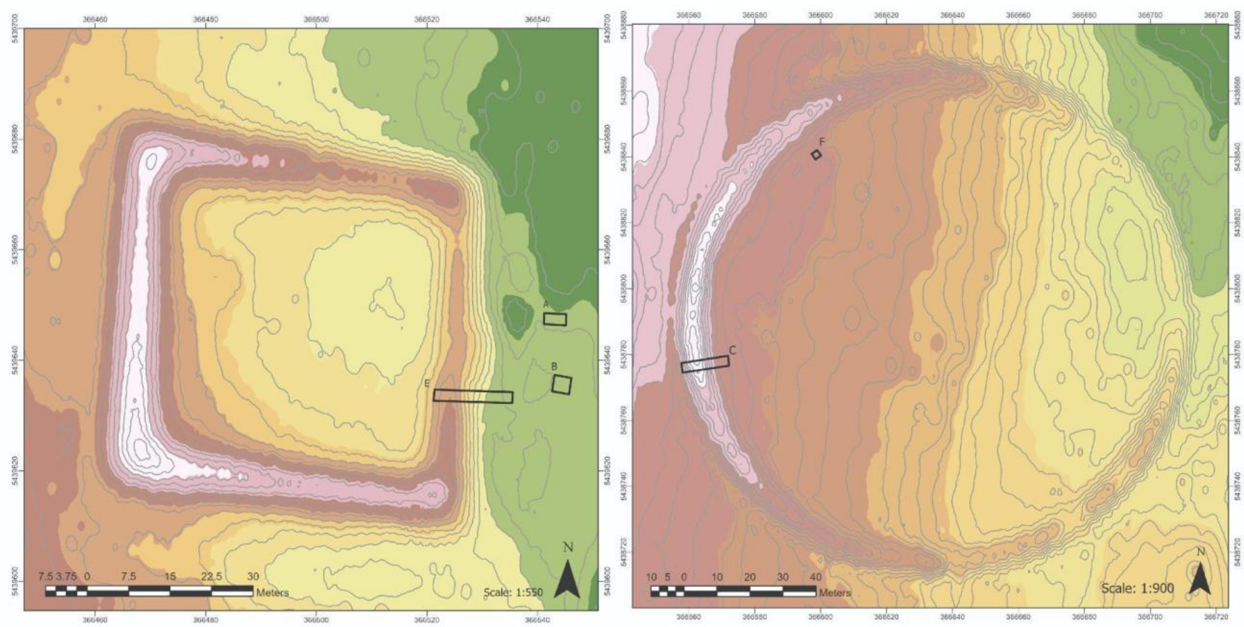

Figure 2. Digital Elevation Model Layout of Excavated Areas (A, B&E) of Cluster 23, where pottery sherds were sampled, Northern Line, Mongolia

At MA03, samples were taken from Areas B and C, located within the enclosure walls (Figure 3). The artifacts derive from two different contexts: two potsherds from Area B were part of the fort dated to the Jurchen period, while a birch basket and soil samples recovered from below and within it were part of a post-Mongol period burial (Shelach-Lavi et al. 2025).

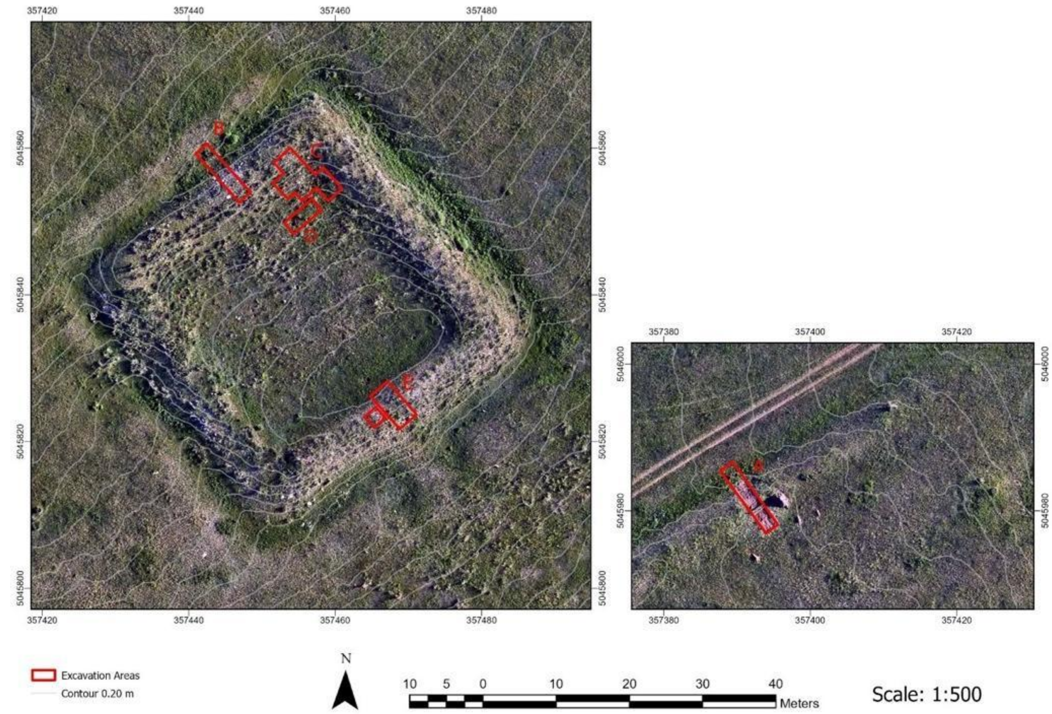

Figure 3. Excavated Areas (A, B, C, D&E) of MA03 with the Wall Line, the enclosure MA03

5. Materials and Methods

Residue analysis was done on 52 samples comprising 44 ceramic vessels and 8 soil samples and birch basket fragments from Clusters 23 and 24 (*Northern Line*), and Mongolian Arc 03 (MA03) (Figure 4). Samples were taken from different vessel parts, including rim, body, and base sherds. The majority were identified as earthenware (cooking bowls, storage jars etc.), characterized by distinct angular punctate decorations probably applied using a pronged fork implement or by roller stamp method attributable to the Kitan tradition, with some exhibiting burning marks and calcified deposits. The assemblage also included a green-glazed drumstick-shaped storage jar, a white-glazed plate or bowl, and a black matte vessel.

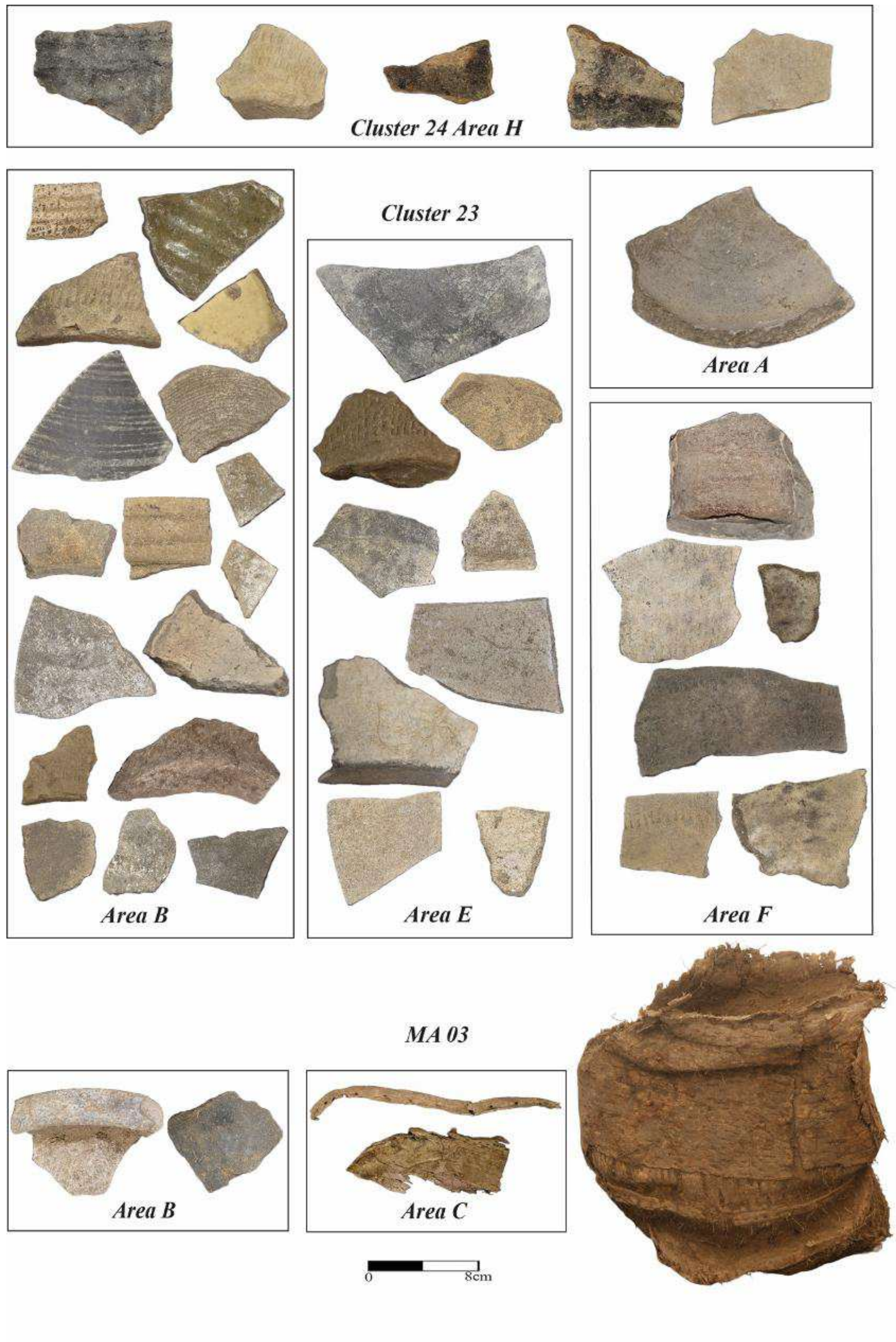

Figure 4. Analyzed Samples

Pottery was carefully collected, in situ from the ground during excavations. Sterile nitrile gloves were used to recover the sherds, and these were subsequently stored in sterilized aluminum foil before lab analysis. The sherds were photographed and drilled to collect 2 g ceramic powder (approximately 1 g for acid extraction and 1 g for solvent extraction) in a sterile lab hood environment at the BioArCh lab, the University of York. Ceramic powder underwent acidified methanol extraction (AE) and analyzed using Gas Chromatography–Flame Ionization Detector (GC-FID) and Gas Chromatography-Mass Spectrometry (GC-MS) with additional selected ion monitoring (SIM) to check heating markers (ω-(o-alkylphenyl) alkanoic acids, APAA), a common millet biomarker (milliacin) (Heron et al. 2016), and aquatic biomarker (isoprenoids) (Evershed et al. 2008b; Cramp and Evershed 2014; Lucquin et al. 2016b). APAAs (ω-(o-alkylphenyl)alkanoic acids) with 16 and 18 carbon atoms (APAA16 and APAA18) were identified in several samples using single ion monitoring, targeting compounds with carbon chain lengths ranging from C_{16} to C_{22} (*m/z* 74, 105, 262, 290, 318, 346). Peak integration was conducted using Agilent MassHunter Quantitative Analysis software to determine the E/H ratio APAA 18 and interpret the possible origin of the lipids (Bondetti et al. 2020, 2021). An additional set of samples (ceramic powder from the same sherds) was also prepared for solvent extraction to isolate the "unbound" lipids, which were subsequently analyzed by GC-FID and GC-MS to check dairy derivatives, alcohols, alkanes, resins, sterols, beeswax, etc. (Craig et al. 2013).

To further distinguish the lipid origins, carbon isotope values of the palmitic ($\delta^{13}C_{16:0}$) and stearic ($\delta^{13}C_{18:0}$) alkanoic acids were measured in acid extractions yielding more than 10 µg/g (of $C_{16:0}$ and $C_{18:0}$) by Gas Chromatography with Combustion and Isotope Ratio Mass Spectrometry (GC-c-IRMS). These values were then compared to archaeological reference values for marine, C_3, C_4 plants, ruminant and non-ruminant animals, and dairy from geological areas of Europe and Eurasia (Dudd 1999; Spangenberg et al. 2006; Gregg et al. 2009; Outram et al. 2009; Spiteri 2012; Craig et al. 2013; Horiuchi et al. 2015; Heron et al. 2016; Lucquin et al. 2016a; Taché et al. 2021; Lundy et al. 2024). It should be noted that these reference values are drawn predominantly from available European and Eurasian contexts and may not fully capture the isotopic baselines characteristic of Mongolian fauna.

Additionally, carbonized food deposit (foodcrust) from a cooking pot (TWP37) and storage jar base (TWP22) were subsampled with a sterilized scalpel and analyzed under high-resolution microscopy (Digital and Scanning Electron Microscope) to assess their composition. Foodcrust subsamples were first scanned under a stereomicroscope in order to identify the most suitable area for further analysis. From there, a small portion of the charred deposits was gently removed from the ceramic surface using a clean scalpel. It was analyzed following a three-step microscopy approach which involved: (1) initial observation of the food crusts using a low-powered binocular microscope at magnifications between 8x to 50x; (2) subsequent study of food crusts using a VHX-7000 Keyence digital microscope at magnifications from 20x to 200x to describe the foodcrusts' microstructural appearance and the physical attributes in more detail; (3) targeted SEM analysis (using a variable pressure Hitachi TM4000 Scanning Electron Microscope) was undertaken on sub-samples of the foodcrusts which were seen to contain organic inclusions including presumed plant remains such as cell-structures, plant tissues or seeds.

6. Results

6.1 High-resolution Scanning Electron Microscope (SEM)

Two pottery sherds with visible residues (TWP 22 and 37) were examined under SEM. Foxtail millet (*Setaria italica*) glume epidermis tissues, identified by morphometric comparison with reference material (Lu et al. 2009b), along with boiling cracks, were observed in the foodcrust adhering to the rim of a cooking pot from Cluster 24 (Figure 5). Degraded cell-tissues showing features consistent with foxtail millet were also observed on several sherds from Cluster 23 with Dino-lite digital microscope during fieldwork however further identification under SEM was not possible at the site. A possible fish scale was also identified in TWP 22 (bottom right of Figure 5) although this further analysis and comparison with reference collections is needed to corroborate this find.

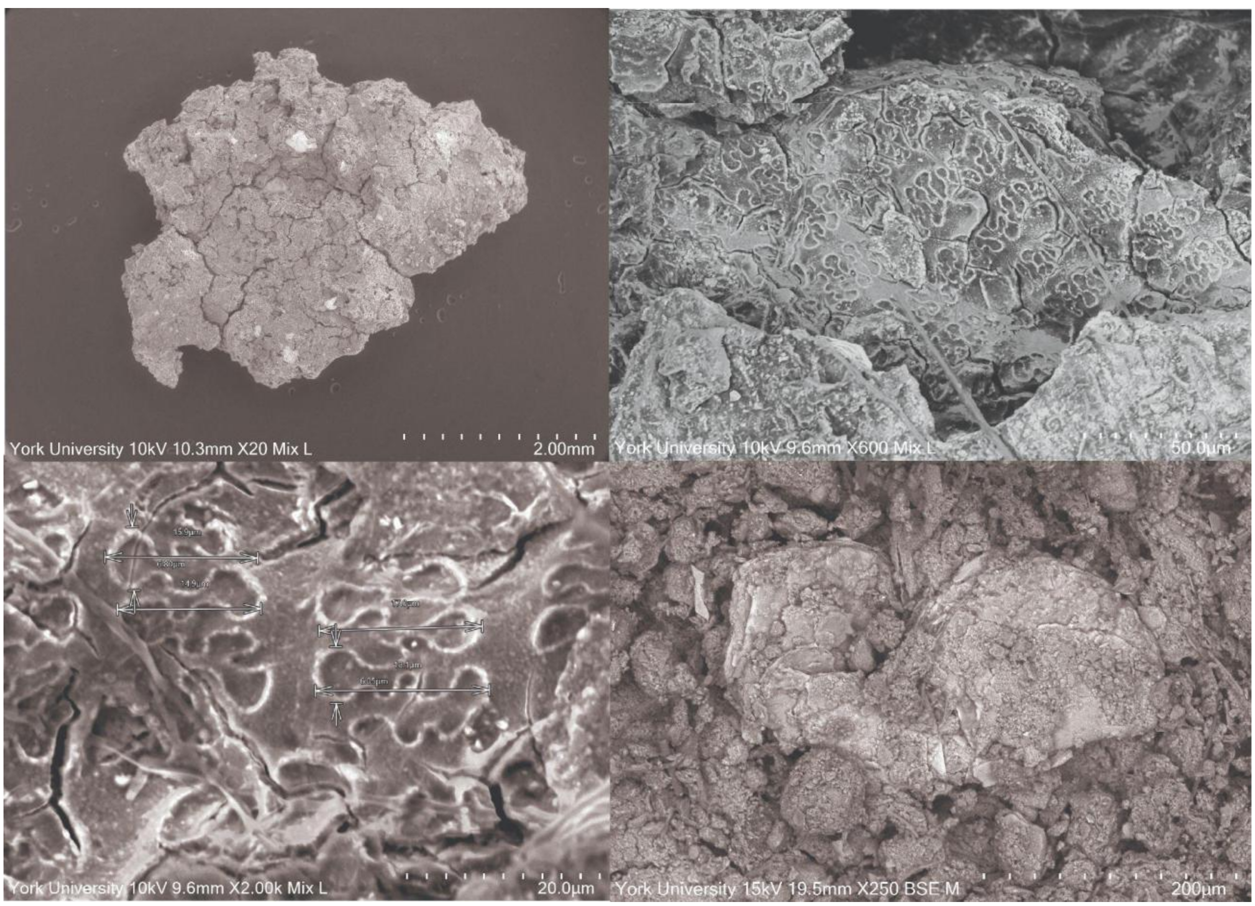

Figure 5. Domesticated foxtail millet (*Setaria italica*) glume epidermis in the foodcrust (top left and right) from the cooking pot (Cluster 24) with measurements (bottom left) as well as possible

fish scale (bottom right) (TWP22 from Area B, Cluster 23) from sample where freshwater catfish bones were found in the zooarchaeological record.

6.2 Lipid Residue Analysis of Medieval Potsherds from Mongolia

6.2.1 Molecular Identification by GC-MS Acid Extraction Results

All the samples from the Northern Line (Cluster 23 and Cluster 24) and the Mongolian Arc (MA03) yielded lipid concentration exceeding 5 $\mu g\ g^{-1}$, the threshold sufficient for archaeological interpretation (Evershed 2008a). Lipid concentration ranges from 10.5 to 16629 $\mu g\ g^{-1}$ based on acid extraction (see Appendix). More than half of the samples yield relatively high lipid (>50 $\mu g\ g^{-1}$); the highest value of 16629 $\mu g\ g^{-1}$ was obtained from a food crust recovered from a rim sherd from Cluster 24.

Lipid extracts revealed a complex mixture of fatty acids, including saturated fatty acids ranging from $C_{10:0}$ to $C_{32:0}$ (n = 51), with a strong predominance of palmitic ($C_{16:0}$) and stearic ($C_{18:0}$) acids, as well as monounsaturated fatty acids ($C_{14:1}$–$C_{32:1}$; n = 48), branched fatty acids (C_{12}–C_{29}; n = 48), and α,ω-dicarboxylic acids (C_6–C_{28}) were also identified. Saturated fatty acids were generally dominated by palmitic and stearic homologues. Long-chain saturated fatty acids (>C_{20}; n = 48) exhibiting an even-over-odd carbon number predominance were detected in 45 samples and are characteristic of plant epicuticular waxes (Evershed et al. 1991). The assemblage further included a series of unsaturated fatty acids, primarily unsaturated palmitic and stearic homologues, suggesting a possible plant oil origin, although an animal source cannot be excluded (Whelton et al. 2021). Short-chain dicarboxylic acids are likely oxidation products of unsaturated fatty acids. Even-numbered alcohols ranging from C_{16} until C_{30}, along with the alkanes ranging from C_{10} to C_{32}, were detected in the samples. Fatty alcohol 1-octacosanol was identified in samples TWP 2, 8, 18, 19, 20, 21, 22, 26 and 38.

ω-(o-alkylphenyl)alkanoic acids (APAAs) form when unsaturated fatty acids are heated at high temperatures, thus the carbon chain length and isomeric distribution have diagnostic value to indicate fat origin. APAAs with 16 and 18 carbon atoms (APAA16 and APAA18) were identified in several samples using single ion monitoring. APAA18 was detected in 14 samples. Calculation of the E/H ratio using the relative peak areas of the isomeric distribution (isomers A–I) of APAA 18 indicates different origin source inputs: leafy vegetables (TWP 2,13, 15, 18, 19, 20, 37 and 37fc), aligning with millet presence; animal-derived input (TWP1, 3, 7, 21, 22 and 38); and cereals, fruits, or non-leafy vegetables (TWP14) (E/H>4) (Bondetti et al. 2021) (see supplementary table AE). However, APAA20 (evidence for fish) was absent.

Miliacin (olean-18-en-3β-ol methyl ether), a biomarker specific to broomcorn millet (*Panicum miliaceum*) not found in other cultivated millets such as foxtail millet (*Setaria italica*), finger millet (*Eleusine coracana*), or barnyard millet (*Echinochloa esculenta*) (Heron et al. 2016), was detected in approximately 80% of the analyzed assemblage (primarily earthenware), suggesting a substantial broomcorn millet consumption (TWP 1–4, 6–10, 13–26, 28–29, 32–33, 35–36, and

40). Additionally, millets were found in five solvent extracted samples (TWP 5, 11, 12, MA03R, and MA03B) that yielded no signal in acid extraction, likely reflecting different absorption of lipids absorbed with different areas of the ceramic matrix, as the samples were drilled from separate areas.

Dehydroabietic acid was found in TWP 40 (Cluster 24, northern line), a compound typically interpreted as a marker for coniferous pine resin (Reber et al. 2019), suggesting that resin was applied to this vessel as a waterproofing or sealing agent.

Isoprenoid fatty acids, which are highly abundant in ruminant and aquatic organisms (Lucquin et al. 2016b), were detected in some samples, including 4,8,12-trimethyltridecanoic acid (TMTD) (n=11). However, no definitive aquatic biomarkers were identified in the lipid, and no APAA20 were found. The detected TMTDs could originate from ruminant fats rather than an aquatic source. Alternatively, this absence does not necessarily contradict the tentative fish scale observed via SEM and the fish bones recovered from the sites, as aquatic lipids are particularly susceptible to degradation and can be diluted or masked when co-processed with other food, or fish may have been processed in a way not absorbed in the pottery, or non-dietary usage such as glue.

6.2.2 Solvent Extraction Results

Both plant sterols (3β-stigmast-5-ene, β-sitosterol, lupeol, lanost-8-en-3-ol, stigmasterol and campesterol) and animal sterols (cholesterol), together with their degradation products were detected in the samples (e.g. 5-cholest-8-en-3-one in TWP 40), ruling out the possibility of introduced contamination (Hammann et al. 2020; Whelton et al. 2021) (see supplementary dataset SE).

Long-chain ketones (K_{31}, K_{33}, K_{35}) identified in several samples (TWP 2, 22, 35 and 37) are primarily associated with the heating of animal fats. In contrast, the presence of K_{31} alone in samples TWP 24, 31, 32, 33 is more consistent with an origin in epicuticular plant waxes, Allium (possibly leek), or from the thermal alteration of animal fats during cooking processes (Charters et al. 1995, 1997; Raven et al. 1997; Evershed et al. 1995; Drieu et al. 2020; Lundy et al. 2024) (see supplementary table SE). Triacylglycerols (TAGs) ranging from T_{40} to T_{54} were found in 7 samples (TWP2, 13, 15, 18, 20, 21&22) in the solvent extraction (see supplementary table SE and Figure 6) and are likely derived from ruminant animal fats. Samples characterized by shorter-chain triacylglycerols (n=7) were associated with ruminant dairy products.

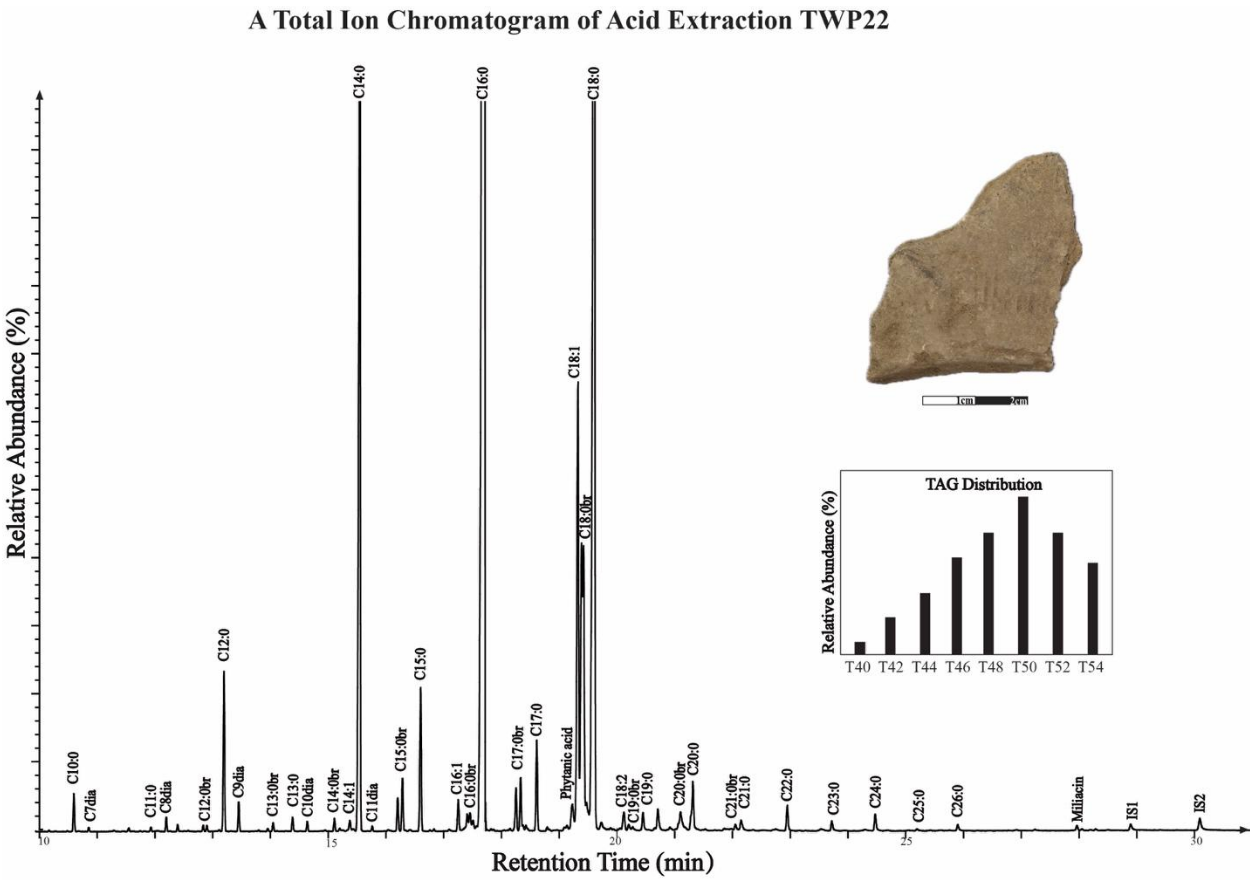

Figure 6. Total Ion Chromatogram of Acid Extraction TWP 22 plus (C $_{X:X}$: Saturated and unsaturated fatty acids; C $_{X:0}$ br: branched fatty acids; C_X dia: dicarboxylic acids; IS1: internal standard $C_{34:0}$, tetratriacontane in hexane; IS2: external standard $C_{36:0}$, *n*-hexatriacontane in hexane) T_x: Triacylglycerols (from SE)

The residue analysis reveals diverse dietary inputs encompassing plants, cereals/fruits, and animal fats with evidence for plant processing, possible freshwater resource exploitation, and resin usage (likely for waterproofing). Lipid profiles indicate both plant- and animal-derived products were utilized, with clear indications of food preparation and storage practices.

6.3 Stable Carbon Isotope Analysis of Fatty Acids by GC-c-IRMS

Carbon isotope values of the major fatty acids span a broad range ($-21.4‰ < \delta^{13}C_{16:0} < -31.6‰$; $-25.4‰ < \delta^{13}C_{18:0} < -31.2‰$), indicating inputs from a diverse suite of lipid sources (Figure 7). They include ruminant adipose and dairy fats, freshwater resources, wild non-ruminant animals, and terrestrial plant fats. Samples with intermediate isotopic signatures most likely reflect the mixing of multiple lipid sources rather than a single dominant input.

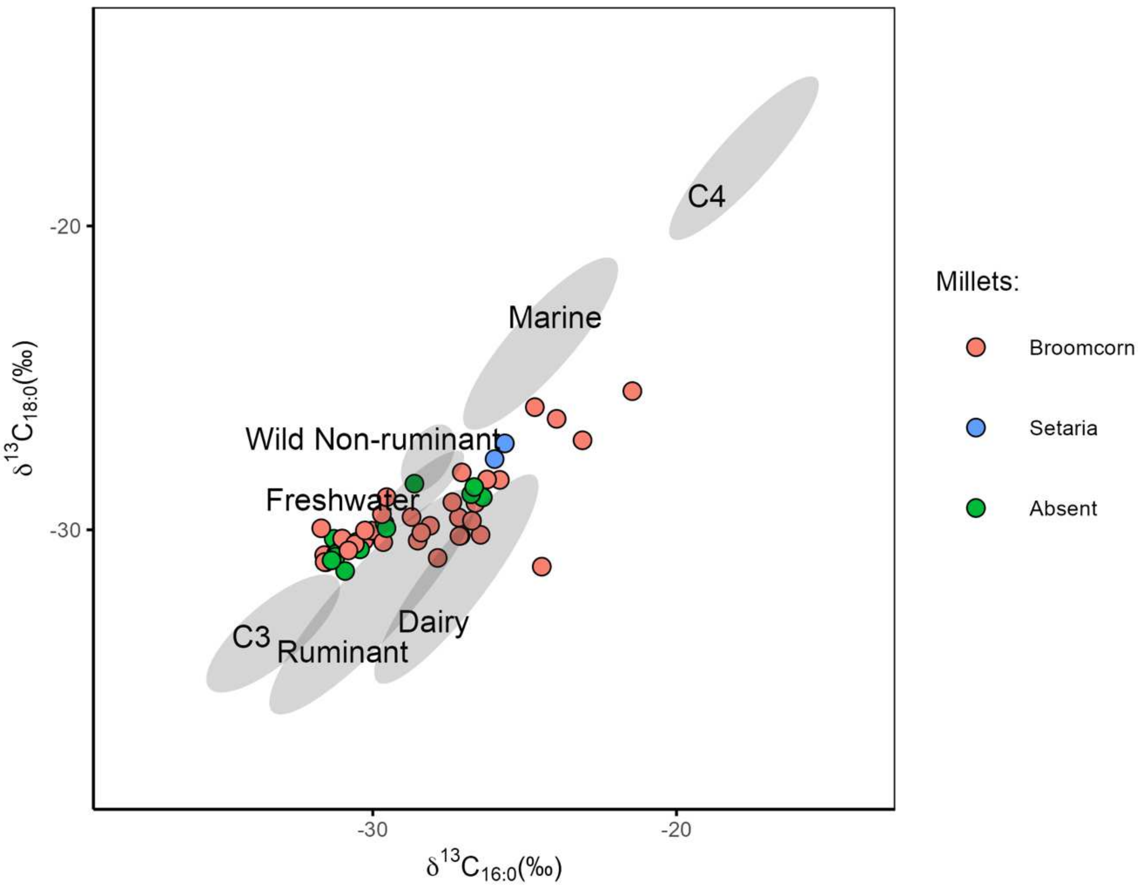

Figure 7. Fatty acid isotope values ($\delta^{13}C_{16:0}$ against $\delta\ ^{13}C_{18:0}$) from each potsherd. The presence/absence of millet is noted. Broomcorn millet is from the presence of milliacin in the lipid extracts, Setaria millet is based on the SEM Reference ellipses are shown at 68% confidence (Dudd 1999; Spangenberg et al. 2006; Gregg et al. 2009; Outram et al. 2009; Spiteri 2012; Craig et al. 2013; Horiuchi et al. 2015; Heron et al. 2016; Lucquin et al. 2016a; Taché et al. 2021; Lundy et al. 2024)

The reference isotope values used for comparison in this study are derived primarily from European and broader Eurasian contexts that are available (Dudd 1999; Spangenberg et al. 2006; Gregg et al. 2009; Outram et al. 2009; Spiteri 2012; Craig et al. 2013; Horiuchi et al. 2015; Heron et al. 2016; Lucquin et al. 2016a; Taché et al. 2021; Lundy et al. 2024). Direct isotopic data from Mongolian Steppe are limited, regional climate, soil geochemistry, and altitude, and the animals grazed on the local vegetation might result in its own distinctive C_3/ C_4 composition.

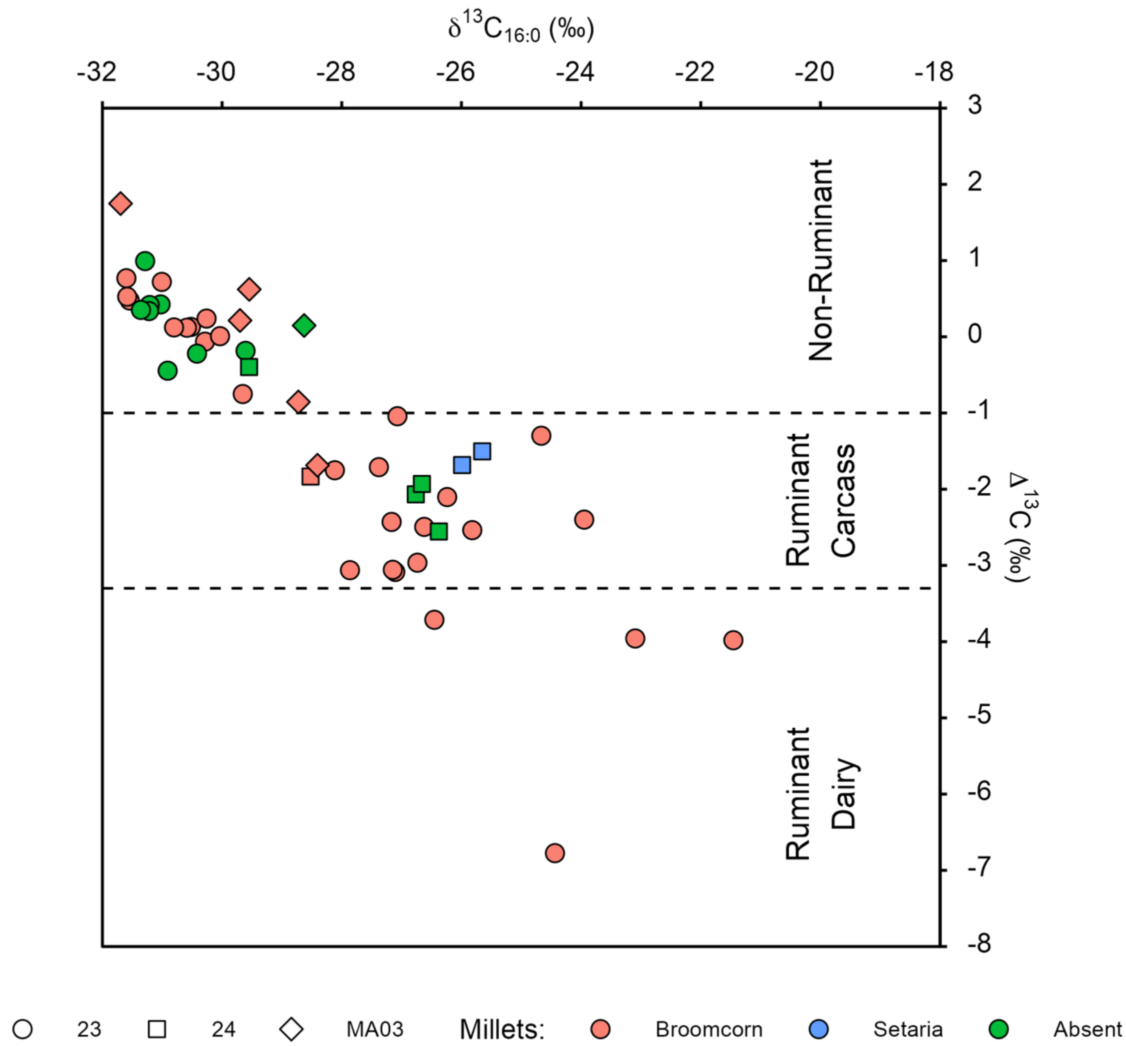

Figure 8. $\delta^{13}C_{16:0}$ against $\Delta^{13}C$ with different millet presence and sites (C23, C24 and MA03) with reference (non-ruminant, ruminant carcass and ruminant dairy) (Copley et al. 2003; Evershed et al. 2008b; Smyth et al. 2019) and the presence/absence of millet (Broomcorn or Seteria)

To further discriminate between lipid sources, the difference between the stable carbon isotope values of palmitic and stearic acids ($\Delta^{13}C = \delta^{13}C_{18:0} - \delta^{13}C_{16:0}$) were calculated (Evershed et al. 1997, 2002; Dudd and Evershed 1998; Copley et al. 2003; Steele et al. 2010). A number of samples plot within the non-ruminant range ($\Delta^{13}C > -1‰$), with $\delta^{13}C_{16:0}$ values clustering between -32 and -28‰, consistent with the processing of non-ruminant animals subsisting on a C3 plant-based diet (Figure 8). The strongly ^{13}C depleted carbon isotope values of both fatty acids are consistent with herbivores and omnivores feeding on C_3 vegetation characteristic of the Mongolian steppe. Although millet has a C_4 isotopic signature enriched in ^{13}C, its relatively low fatty acid content makes it unlikely to be identifiable when mixed with fat rich animal products. Consequently, the fatty acid isotopic signals observed in the vessels are more plausibly attributed to the diet of the animals, whose products were processed in the vessels.

Four samples plot within the dairy range, with $\Delta^{13}C$ values below -3.1‰ (Copley et al. 2003; Evershed et al. 2008b; Smyth et al. 2019); notably, all contained broomcorn millet. The relatively enriched ^{13}C observed in the fatty acids of these dairy residues may reflect C_4 plant consumption by the dairy animals, suggesting that livestock used for dairy production were foddered on C_4 plants. It is likely that millets were used as animal fodder, not just human food, possibly as seasonal feed in harsh wintertime.

Mixing of C_4 plant oils with ruminant fats could produce a similar $\Delta^{13}C$ shift. Analogous effects have been documented at pre-colonial South American sites where maize consumption produced similarly depleted $\Delta^{13}C$ values (Admiraal et al. 2023), and the influence of millet on $\Delta^{13}C$ interpretation in East Asian contexts has been addressed through simple and Bayesian mixing models (Taché et al. 2021; Craig et al. 2025).

Overall, the isotope data indicate substantial consumption of both non-ruminant and ruminant animal products, including dairy, by the communities inhabiting the enclosures. The predominant C_3-based isotopic signatures reflect a diet built primarily on animals and freshwater fish (based on faunal remains from the sites) (Steiner et al. 2025, 2026), while more enriched values in a subset of samples point to millet as an additional, C_4-based dietary input, likely introduced both through direct human consumption and as possible animal fodder. Together, the lipid and isotope datasets confirm a subsistence strategy centered on animal husbandry and the exploitation of C_3 resources, with millet playing a supplementary but significant C_4 component.

7. Discussion

The excellent preservation of absorbed organic residue in the sherds analyzed by this research allows, for the first time, direct molecular evidence of the foods processed in these vessels and culinary practices of the communities living on the frontiers of the Kitan and Jurchen empires. The inhabitants of Clusters 23 and 24 and MA03 consumed a diet centered on C_3-based resources, including non-ruminant animals, freshwater fish, and ruminant animals (characterized by C_4-depleted isotopic signatures) supplemented by other plant products, most notably millet.

7.1 Millet Consumption, Storage and Cultivation

Broomcorn and foxtail millets are staple crops originally domesticated during the Neolithic period in north China (Lu et al. 2009a; Diao and Jia 2017) and widely consumed across East and

Central Asia during both the Kitan and Jurchen periods (Sergusheva 2019). Alongside other cereals (i.e., wheat, buckwheat, sorghum) and legumes, they are frequently found at Kitan-Jurchen city sites and burials in more eastern areas of the dynasties (Inner Mongolia Archaeological Institute 1990; Sun and Zhao 2014), underscoring their socio-political and economic significance.

Miliacin was detected in 86.1% of the vessels from Cluster 23, 33.3% from Cluster 24, the latter also yielding evidence for foxtail millet, and 100% from MA03. The identification of Setaria cell-tissues under SEM from Cluster 24 provided direct evidence of Setaria consumption in the Northern Line. Additionally, barnyard millet seeds (*Echinochloa esculenta*) were recovered from flotation samples and soil samples from Cluster 23 and MA03. Together, these results indicate the consumption of diverse millet species by the communities residing near the MWS in both the Northern Line and the Mongolian Arc from both lipid analysis and archaeobotanical assemblages (Table 1).

Site	Millet Species Identified
Cluster 24 (Northern Line)	Foxtail millet (*Setaria italica*) (SEM); Broomcorn millet (*Panicum miliaceum*) (Lipid analysis)
Cluster 23 (Northern Line)	Foxtail millet (Archaeobotany); Broomcorn (all areas) millet (Lipid analysis and archaeobotany); Barnyard millet (Echinochloa esculenta) (Archaeobotany)
MA03 (Mongoian Arc)	Foxtail millet (Archaeobotany); Broomcorn millet (all areas) (Lipid analysis and archaeobotany); Barnyard millet (Archaeobotany)

Table 1. Summary of various millet species found in MWS

The presence of millet in both every day and funerary contexts — including the burial within fort MA03 — highlights its enduring importance in socio-political and economic systems of the steppe. The near-ubiquitous occurrence of broomcorn millet biomarkers in earthenware from Clusters 23 and MA03 stands in contrast to the limited recovery of broomcorn millet seeds in the archaeobotanical assemblage from these sites, raising intriguing questions: Where did the common millet come from? Were they locally grown? If not, were they transported from regions to the east with higher agricultural output?

The balance of current evidence points more toward external supply than local cultivation. The most diagnostic indicator of local processing — millet chaff, a byproduct of de-husking often recovered in flotation samples — is largely absent from current archaeobotanical assemblages from Cluster 23 and MA03. Its near absence here suggests that millet arrived at the sites already processed, consistent with redistribution from agricultural centers to the east rather than cultivation in the immediate steppe environment. This interpretation is further supported by iron cart-wheel fittings recovered from sites along both lines (Shelach-Lavi et al. 2025), and evidence for the provisioning of cattle to enclosures on the Northern Line (Steiner et al. 2025, 2026) suggesting a model of organized external supply. Regardless, the archaeobotanical diversity of millet species attests to substantial consumption and storage, whether supplied through long-distance exchange or local farming.

At the same time, the possibility of millet cultivation in Mongolia steppe cannot be excluded. Historical texts document military farming activities along the medieval frontier (Lotze et al. 2026), while archaeobotanical evidence demonstrates that millet cultivation was feasible in the region long before this period. Millet is attested in Mongolia as early as the Late Bronze Age (ca. 1000 BC) and is comprehensively documented in Xiongnu-period assemblages (Carolus 2025). For the Xiongnu period, evidence of local cultivation on the steppe comes from settlement contexts (Amartuvshin 2018; Honeychurch et al. 2023), while broomcorn millet has also been recovered from burial contexts in the Orkhon–Selenge Valley (Korolyuk and Polosmak 2010; Korolyuk et al. 2018). Chaff of foxtail and broomcorn millet has been identified at the Kitan settlements of Chintolgoy Balgas and Khermen Denzh (Sergusheva 2019). Furthermore, Jurchen period evidence from MA03, an iron plough head and flotation-recovered millet, further suggests that cultivation may have occurred at or near some sites during this period (Shelach-Lavi et al. 2025)

7.2 Animal Consumption

The fatty acid isotope data provide evidence for the processing of both ruminant and non-ruminant animal products within ceramic vessels. Ruminant fats, consistent with the exploitation of common steppe taxa including sheep, goat, cattle and gazelle, dominate the assemblage and were found at both Cluster 23 and MA03 (Steiner et al. 2025, 2026) (Table 2). A proportion of vessels additionally yielded non-ruminant lipid signatures, which may reflect the processing of non-ruminant animals such as hare, horse, badger, and marmot, all of which are attested in the faunal record (Steiner et al. 2025, 2026). Additionally, a total of 103 fish bones from Amur catfish and Cyprinid species were recovered at Cluster 23, likely deriving from nearby rivers and lakes (Steiner et al. 2025, 2026), though no definitive aquatic biomarkers were identified in the lipid assemblage. Several explanations are possible. The fish remains may represent incidental deposition rather than residues of cooking; fish may have been processed raw or dried, or cooked by methods not involving boiling or frying in ceramic vessels; or they may have been processed in vessels not included in this analysis. A further possibility is that fish were exploited for non-dietary purposes like glue (Bleicher et al. 2015). These all call for future study.

Category	Kitan Site (Area B, Cluster 23)	Jurchen Site (Area D, MA03)

Ruminant	sheep (*Ovis aries*) (51), goat (*Capra hircus*) (42), Sheep/goat (519), cattle (*Bos taurus*) (115), gazelle (*Procapra gutturosa*) (81)	sheep (*Ovis aries*) (12), sheep/goat (15), gazelle (*Procapra gutturosa)* (16)
Non-ruminant	hare (*Lepus* sp) (6), domestic dog (*Canid* sp) (36), horse (*Equus sp*) (342), badger (*Meles leucurus*) (5), marmot (*Marmota sibirica*) (4)	horse (*Equus sp*) (21), badger (*Meles leucurus*) (2), large dog (*Canid* sp) (3)
Freshwater Fish	fish (*Silurus asotus and Cyprinidae spp.*) (103)	NA

Table 2. Categories of faunal remains from Area B, Cluster 23, and Area D, MA03 (quantification of bones in parentheses) (Steiner et al. 2025, 2026)

Vessels containing ruminant dairy residues are frequently associated with broomcorn millet (present in most pots but more prevalent in those with dairy) as well as animal fat thermal alteration markers, suggesting that the inhabitants of the sites may have routinely prepared composite dishes combining ruminant dairy, animal products, and millet, a culinary tradition that finds a striking parallel in food practices still observed across the Mongolian steppe today. The ruminant animals represented in these residues also show isotopically enriched $\delta^{13}C$ values, suggesting these animals were fed on millet or other C_4 plants as fodder, an additional subsistence strategy that potentially helped maintain livestock condition and to sustain dairy productivity during seasons of limited pasture, reflecting a sophisticated and integrated agropastoral economy.

7.3 Vessel Usage

Clear differences in residue composition were observed between earthenware and glazed ceramics. Most earthenware vessels contained miliacin alongside animal and plant lipids, indicating use in food preparation or cooking involving mixed subsistence resources. In contrast, glazed vessels lacked millet biomarkers but yielded long-chain alkanes, long-chain alcohols, fatty acids, and non-ruminant animal fats, suggesting a functionally distinct pattern of use and implying that glazed wares were not employed for millet-based food processing, but may instead have served for the storage or processing of other substances, potentially liquids.

Two glazed vessels subjected to lipid analysis: TWP 30, a body sherd from a Kitan drumstick-shaped green-glazed jar, and TWP 34, the base of a white-glazed bowl or plate, both yield relatively high lipid concentrations of 300.76 and 439.25 $\mu g\ g^{-1}$, respectively, supporting previous observations that glazed ceramics can retain absorbed lipids (Pecci et al. 2016) probably through pores and microcracks within the glaze. No millet biomarkers were detected in either glazed vessel, in contrast to their widespread occurrence in earthenware (80.9%), instead, long-chain alkanes, alcohols, dicarboxylic acids (suberic, azelaic, and sebacic acids), plant sterols (3β-stigmast-5-ene and β-sitosterol), and a ketone (K31) indicate plant-derived inputs.

The carbon isotope values of palmitic ($\delta^{13}C_{16:0}$) and stearic ($\delta^{13}C_{18:0}$) acids in both pottery samples indicate a non-ruminant fat origin, with no evidence of dairy, consistent with either plant-derived sources or non-ruminant animal products, which aligns with faunal remains identified in Area B, Cluster 23, including horse, hare, dog, and badger. Comparable glazed ceramics from other places and later periods were associated with liquid storage in historical and archaeological contexts (Lu 2008, p 140; Institute of Cultural Relics and Archaeology, Inner Mongolia 2014, p 151; Qin et al. 2017); some were used to store grape wine, as attested by vessel inscriptions ("清香美酒" meaning "exquisite, clear, fragrant fine wine") (Adhyatman 1990; Xi'an Municipal Institute of Archaeology 2008; Anhui Provincial Museum 2009). The precise liquid contents of these vessels remain undetermined and require targeted analysis for organic acids associated with fermented or fruit-derived products to investigate further (Garnier and Valamoti 2016; Pecci et al. 2017; McGovern et al. 2017; Drieu et al. 2020, 2021).

Coniferous pine resin was identified in vessel TWP 40 (Cluster 24), consistent with its application as a waterproofing or sealing agent, indicating knowledge of resin exploitation to enable liquid containment. A repair hole observed in TWP 16 further suggests vessel reuse, reflecting the prolonged use-life and practical value of ceramic containers in these frontier communities. Fish may have been exploited for non-dietary purposes such as glue.

8. Conclusion

This study represents the first comprehensive application of organic residue analysis to medieval pottery from Mongolia, providing direct molecular evidence for the culinary practices of frontier communities on the border regions of the Kitan and Jurchen empires. The findings reveal a steppe diet integrating multiple millet species, animal products, and dairy, alongside a notable reliance on plant-based resources, especially millet.

The provenance of millet remains an important question. The limited presence of crop-processing byproducts, such as millet chaff, in the archaeobotanical record suggests that broomcorn and foxtail millets identified in pottery residues may have been transported from agricultural centers rather than cultivated locally. Evidence for the use of cattle to provision forts on the Northern Line (Steiner et al. 2025, 2026), together with iron cart-wheel fittings recovered from sites along both lines, may support this interpretation. The mixing of pastoral and agricultural products in the diet of the populations occupying both lines is noteworthy. One key issue related to our understanding of the operation of these lines concerns whether the people living in the forts and controlling the frontiers of the two empires were dispatched from imperial centers to serve on the borders, or whether they were locally recruited steppe people (Lotze et al. 2026). The intensive incorporation of agricultural products, combined with possible evidence for external supplies, could support the hypothesis that at least some of the inhabitants of these enclosures were not local pastoralists. While this idea should be further studied, it aligns with patterns of population movement from imperial centers to frontier outposts to serve administrative or military functions.

Traces of broomcorn millet were recovered from pottery (Jurchen period) and burial (post-Mongol period) at MA03, alongside an iron plough head (Jurchen period) (Shelach-Lavi et al. 2025), suggesting storage and possibly local cultivation of millets. Lipids extracted from these vessels including long-chain alcohols, long-chain alkanes, long-chain dicarboxylic acids, plant-derived sterols and plant waxes indicated plant inputs. However, compound-specific isotope value of $C_{16:0}$ and $C_{18:0}$ data plot slightly deviated from the current published reference data. This may be attributed to the dietary practice of consuming millet in combination with dairy and animal products, which overprint the plant-derived fatty acid signal, a culinary pattern consistent with both historical records and present-day Mongolian food culture.

The successful extraction of lipid residues from glazed wares is a noteworthy outcome of this study. These vessels yielded substantial amounts of lipid residues featuring non-ruminant animal fat and plant products, proposing future research should examine the use of high-status or technologically sophisticated ceramics beyond traditional typological approaches. The fact that glazed wares were found in those remote sites and their possible alcoholic content is another venue for discussion on contacts between those sites and the imperial centers. Bronze coins found at site MA03 (Shelach-Lavi et al. 2025), one interpretation suggest that people living at this site were paid for their work and could have purchased such expensive artifacts and products.

Taken together, these findings paint a rich picture of the Wall People's subsistence strategies. Previous reconstructions based largely on faunal remains and historical sources emphasized a predominantly pastoral economy, with limited insight into plant use and everyday culinary practices. By integrating organic residue analysis, stable carbon isotope data, and microbotanical observations, this study moves beyond broad subsistence categories to reconstruct how foods were processed, combined, and consumed in daily life. The results demonstrate extensive millet consumption alongside ruminant, non-ruminant, and freshwater resources, frequently prepared in combination with leafy vegetables and dairy products, reflecting diverse, flexible, and well-adapted foodways in a challenging frontier environment in the Mongolian Steppe.

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