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From green to white: The technological origins of early white porcelain in Northern China

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ABSTRACT

The appearance of white porcelain in Northern China during the Sui and Tang dynasties marks an important technological shift in the history of Chinese ceramics. How and why this development occurred from the established southern celadon tradition has been a long-standing question for researchers. In this study, samples of celadon, coarse white porcelain, and fine white porcelain excavated from a newly discovered Sui-Tang dynasty kiln site at Jinyang Ancient City, Shanxi, were analyzed for their composition. The results show that a local clay rich in calcium and magnesium was used for the ceramic body. A high-calcium lime glaze was commonly applied, and two distinct glaze formulations were identified based on the ware type. The glaze technology followed two distinct pathways: a common base of body material and plant ash was supplemented with either a silica- and iron-rich material to achieve the celadon glaze, or with a feldspathic mineral to develop the white porcelain glaze. These different technical choices indicate a progression from imitation to innovation. Celadon production followed southern techniques, but the low iron content of local clays required the addition of an iron-rich material to the glaze. This limitation, in turn, revealed the natural advantages of the local materials for making white porcelain, prompting a move from costly imitation toward more resource-efficient innovation. This change also drove improvements in paste refinement, glaze formulation, and the use of sealed saggers for firing. The case of Jinyang reveals a key process behind the origin of northern white porcelain: local, independent innovation was driven by a combination of resource constraints and the imitation of existing technologies. This work provides new physical evidence for understanding the technological origins and regional variations of white porcelain in Northern China.

1. Introduction

Northern China is recognized not only as home to numerous renowned porcelain production centers but also as the region where white porcelain first originated. North Chinese porcelains were the first true porcelains in the world (Wood, 1999, p. 91). As defined by modern ceramic science, the term "porcelain" refers specifically to high-fired wares characterized by a white, dense, and fully vitrified body, covered with either a white or a transparent glaze (China Building Industry Press [CBIP] and Chinese Ceramic Society [CCS], 1984, p. 765). Among early Chinese ceramics, only the wares produced in the north meet these criteria. These wares are characterized by a body composed primarily of kaolinitic clay, the application of lime or lime-alkali glazes, and firing temperatures that commonly exceeded 1200 °C. Archaeological evidence indicates that this technological breakthrough was first achieved in northern Chinese kilns during the Northern Dynasties to Sui-Tang period. The technology spread rapidly among multiple northern kiln sites, such as the Xing kilns in Hebei (Wang et al., 2004), and the Xiangzhou kilns (also known as the Anyang kiln; Kong, 2014) and Baihe kilns (also known as the Gongyi kiln; Sun et al., 2011) in Henan. The rise of white porcelain technology disrupted the existing ceramic production landscape, which had been dominated by celadon, laying a foundation for the prosperity of the Chinese ceramic industry in the later Song, Yuan, Ming, and Qing dynasties and exerting a profound influence on

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the global development of porcelain production.

The prevailing view posits a two-stage development for northern porcelain technology in the late Northern Dynasties: an initial phase of imitating southern celadon, followed by an autonomous innovation that resulted in the creation of white porcelain. Archaeological evidence from early production centers—such as the Anyang Kilns and Xing kilns in the border region of northern Henan and southern Hebei, and the Gongyi Baihe kilns in the Luoyang area of central Henan (Li, 2018)—appears to support this chronological sequence. These kilns initially produced celadon, which was gradually followed by the appearance of fine white porcelain. Particularly after the early Tang dynasty, these production centers progressively abandoned celadon in favor of white and black-glazed wares. However, scientific analyses have revealed significant compositional differences between northern white porcelain and southern celadon in their body and glaze formulas, as well as their firing temperatures (Zhou and Li, 1960). Therefore, the precise technological relationship between the two, and the extent to which southern celadon technology influenced the fabrication of northern white porcelain, have not been systematically investigated. Furthermore, recent scientific analyses of the Zhaill kiln, one of the earliest northern celadon sites, indicate that northern and southern celadon production technologies were themselves distinct (Huang et al., 2020; Geng et al., 2024). This finding suggests that northern potters may have begun actively modifying southern techniques from the initial stages of imitation. Whether these early technological modifications influenced the subsequent invention of white porcelain is a critical question that warrants further investigation. Therefore, a comprehensive study integrating southern celadon, northern celadon, and northern white porcelain is required to clarify this technological development chain and better understand the technical impetus behind the emergence of northern white porcelain.

Between 2012 and 2021, archaeological excavations in the northwestern area of the Jinyang Ancient City site in Shanxi Province (Fig. 1.1) uncovered three porcelain kiln sites, nine ash pits, and a large quantity of associated artifacts, including kiln furniture and ceramic sherds. The excavated ceramics can be divided into two main categories: celadon and white porcelain. The main operational period of the site is firmly placed within the Sui to early Tang dynasties, a conclusion supported by multiple lines of evidence. This chronology is based on two radiocarbon dates (650–676 CE and 605–642 CE at 68.3 % confidence), which are corroborated by stratigraphic data and extensive typological parallels (Han and Zhao, 2022). For instance, the excavated fine white porcelain stemmed cups resemble those from the dated tombs of Han Zunian, dated to 568 CE (Zhou et al., 2020), and Hulv Che, dated to 597 CE (Zhu and Chang, 1992). Furthermore, the kiln furniture is analogous to finds from contemporaneous northern kilns, including Gongyi (Sun et al., 2011), Ding (Huang, 2018), and Xing (Shi, 2006).

The Jinyang assemblage clearly demonstrates a developmental sequence from celadon to engobed white porcelain and finally to fine white porcelain. This provides an ideal case study for investigating the technological pathway from celadon to white porcelain in Northern China. By integrating the evidence from this site with the findings of previous research on northern ceramics, this study offers new insights into the technological trajectory that led to the origin of early white porcelain.

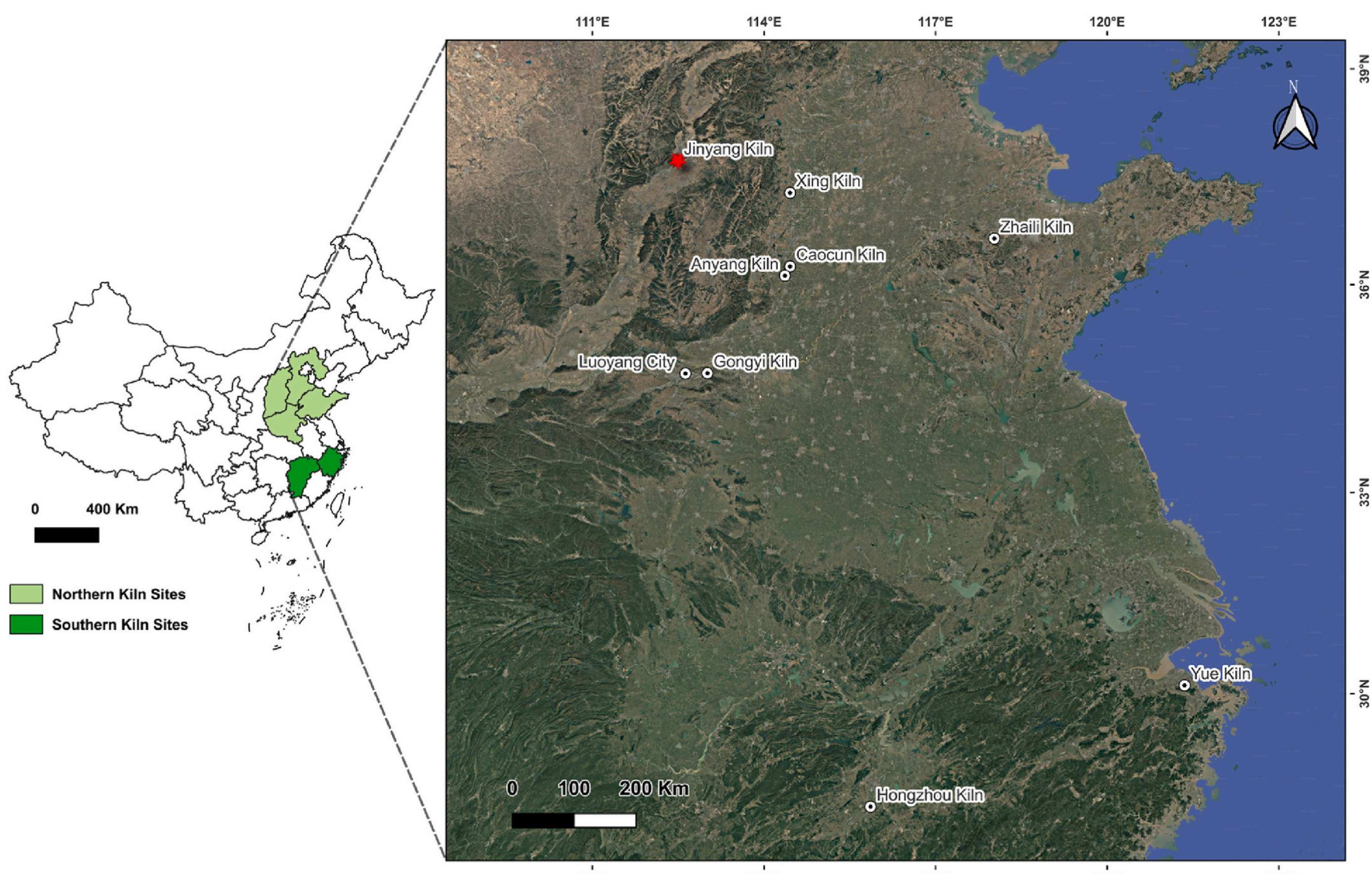

Fig. 1.1. Map of key archaeological sites related to early porcelain production in China. The inset map (left) delineates the general regions of the Northern (light green) and Southern (dark green) kiln traditions. The main map (right) indicates the location of the Jinyang kiln site (red star), which is the focus of this study, along with other significant celadon and white porcelain production sites mentioned in the text.

2. Materials and methods

The samples analyzed in this study were collected from the kiln site discovered in 2021 by the Jinyang Ancient City Archaeological Team in the northwestern area of the ancient city. For the purpose of this analysis, the samples were classified into three main groups. The first group is celadon, characterized by a ceramic body with a relatively high iron oxide content and glazes in greenish or yellowish hues. The second category is coarse white porcelain (engobed white porcelain), which has a body containing a certain amount of iron oxide and is typically coated with an engobe to enhance its whiteness; its glaze often has a greenish or yellowish tint. The final group consists of fine white porcelain (unengobed white porcelain), characterized by a body with a very low iron content, a high degree of vitrification, and a colorless, transparent glaze applied directly to the body without engobe.

Broadly defined, both the coarse and fine white wares from the Jinyang site are considered “porcelain”. They are easily distinguished by macroscopic observation, based not only on the application of an engobe but also on differences in body texture and glaze appearance. Although reliant on an engobe, the coarse white porcelain features a true high-temperature, vitrified glaze, distinguishing it from low-fired, lead-glazed earthenware. This study does not treat the relationship between the coarse and fine white wares as a simple evolutionary sequence; instead, it is proposed that they were likely in parallel production. Therefore, the term “coarse white porcelain” is used herein to specifically denote the early, not fully matured products from the Jinyang site, distinguishing them from wares of other periods and sites.

The excavation report mentions two fine white porcelain sherds, both from ash pit H36 (Fig. 2.1), with the respective registration numbers H36:32 (designated JX1 in this paper) and H36:6 (JX2). A total of seventeen coarse white porcelain samples (JC1–JC17) were recovered from ash pit H38 (Fig. 2.2). The ten celadon samples (JQ1–JQ10) were sourced from multiple contexts (Fig. 2.3), including kilns Y2 and Y3, and ash pits H36 and H38.

All analytical tests were conducted at the Laboratory for Scientific Archaeology, School of Archaeology and Museology, Peking University. Cross-sections of two samples from each group (fine white porcelain, coarse white porcelain, and celadon) were initially observed using a Keyence VHX-5000 3D digital microscope. For further analysis, and specifically to analyze the sub-glaze engobe layer which cannot be reached by surface techniques like ED-XRF, three coarse white porcelain samples (JC11, JC13, JC14) were selected, embedded in epoxy resin, and then ground and polished to expose their cross-sections. These polished sections were analyzed using a TESCAN VEGA3 scanning electron microscope (SEM) equipped with an EDAX ELEMENT energy-dispersive spectrometer (EDS). The analyses were performed in standardless mode using a backscattered electron (BSE) detector, with an accelerating voltage of 20 kV and an acquisition time exceeding 30 s per spot.

The major element composition of the ceramic bodies and glazes was determined using a HORIBA XGT-7000 X-ray fluorescence (XRF) spectrometer. Prior to analysis, the sample surfaces were cleaned with alcohol, and flat, fresh cross-sections were selected for measurement. It should be noted that a complete dataset could not be obtained for all specimens, as some were too small to meet the dimensional requirements for this analysis. The instrument was operated with a rhodium (Rh) X-ray tube at a voltage of 30 kV and a current of 0.062 mA. Data were collected for 100 s per spot with a beam diameter of 1.2 mm. All analyses were conducted in a vacuum environment to enhance sensitivity for light elements. Quantitative calculations were performed using a single-standard Fundamental Parameter (FP) method, with the Corning D glass standard (Corning Inc., USA) used to establish the instrument calibration. Subsequently, the Corning A glass standard was repeatedly analyzed as an unknown sample to evaluate the accuracy and precision of the procedure. The measured concentrations for the ten major elements relevant to this study are presented in Table S1 and compared with the accepted reference values reported by Adlington (2017).

Fig. 2. 1. Jinyang Ancient City’s fine white porcelain.

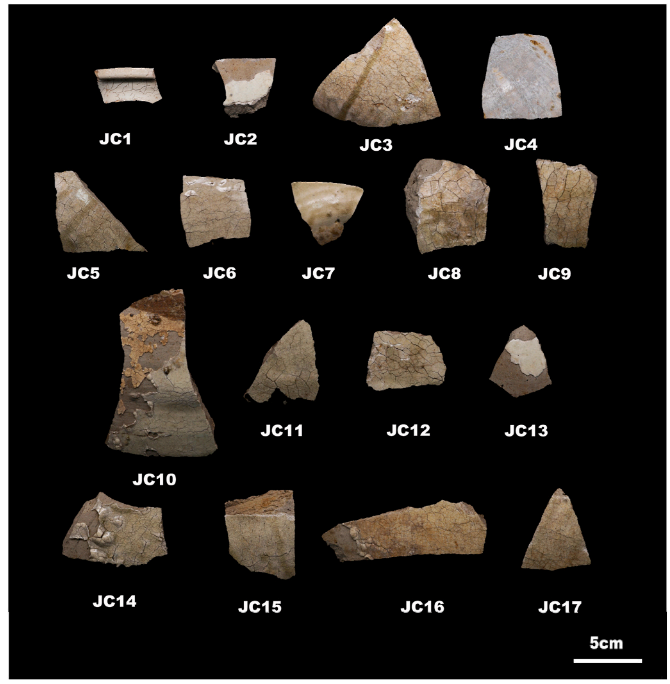

Fig. 2. 2. Jinyang Ancient City’s coarse white porcelain.

3. Results

3.1. Microstructure

Microstructural analysis revealed significant technological distinctions among the fine white porcelain, coarse white porcelain, and celadon samples (Fig. 3.1.1). Optical microscopy showed that the glaze layer of the fine white porcelain was approximately 170–290 μm thick with numerous bubbles, suggesting incomplete gas release during firing; their white appearance was achieved by applying a transparent glaze directly over a light-colored, low-impurity body. In contrast, the coarse white porcelain samples featured a substantially thicker glaze layer, typically exceeding 300 μm, with a smooth but often crazed surface. Critically, a distinct engobe layer was present on all such samples, varying considerably in thickness from 300 to 800 μm. In some instances, poor adhesion and cracking were observed at the interface between the engobe and the underlying body. The celadon samples exhibited a thinner glaze, ranging from 100 to 300 μm, which was uniform and largely free of defects such as bubbles or cracks. Further examination of the ceramic bodies via SEM (Fig. 3.1.2) indicated that

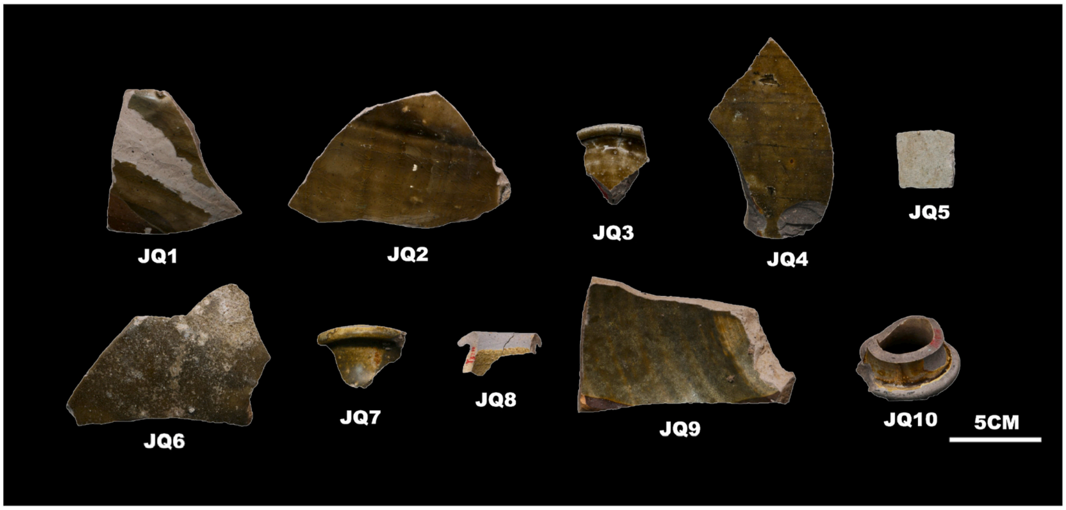

Fig. 2. 3. Jinyang Ancient City's celadon.

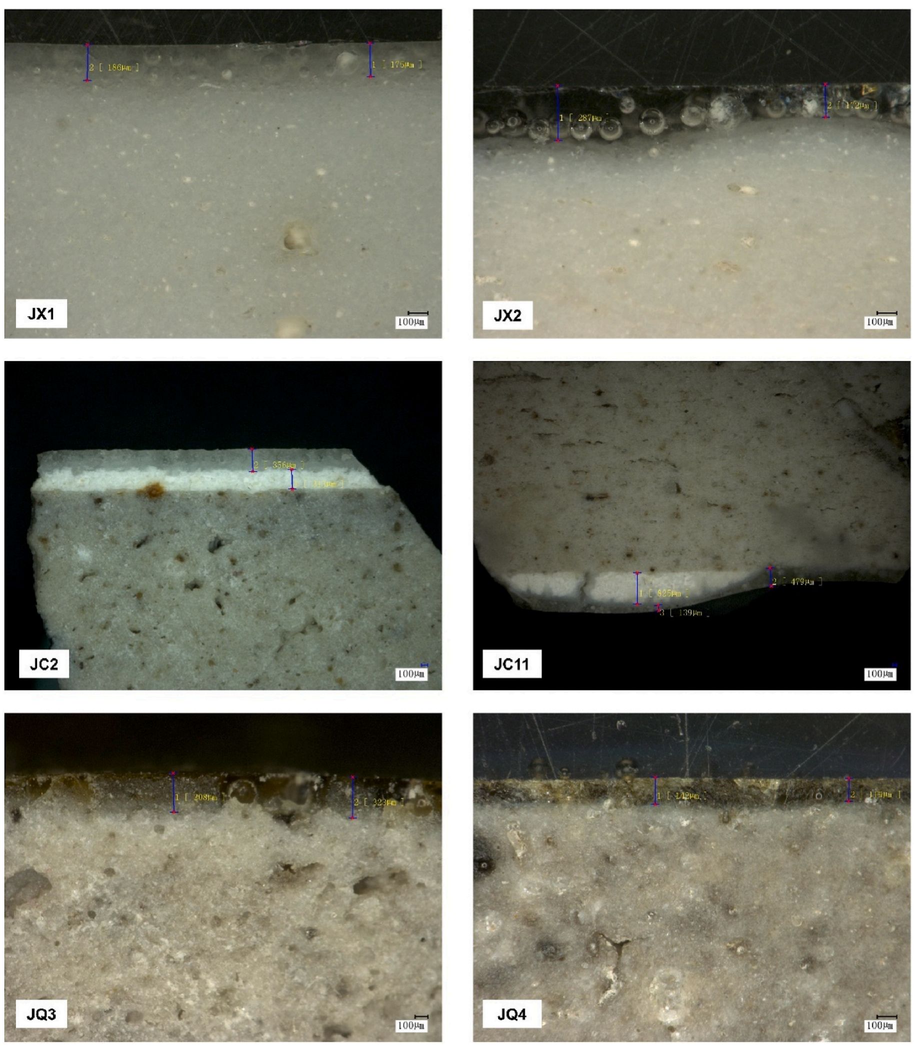

Fig. 3.1.1. Micrographs showing the microstructure of fine white porcelain (JX1, JX2), coarse white porcelain (JC2, JC11), and celadon (JQ3, JQ4) samples.

the body of the fine white porcelain was dense and well-vitrified with low porosity and no obvious unmelted mineral grains. The bodies of the coarse white porcelain, however, contained large quartz particles, generally between 50 μm and 100 μm in diameter; large quartz inclusions were also occasionally found in the celadon bodies. Compared to the well-bonded microstructure of the fine white porcelain, the bodies of both the coarse white porcelain and the celadon showed more heterogeneous sintering, likely resulting from differences in raw material

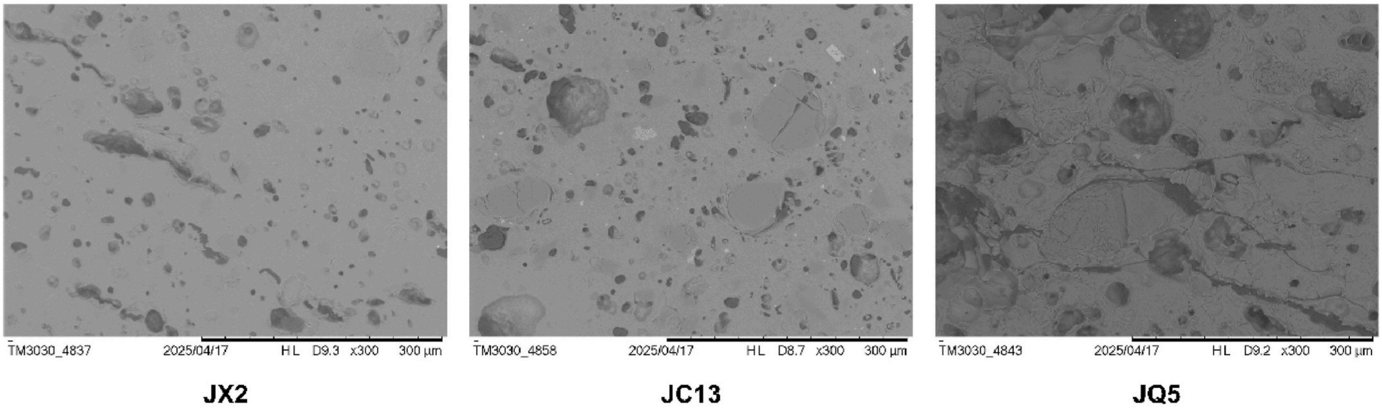

Fig. 3.1.2. Scanning electron micrographs (SEM) of the ceramic bodies of fine white porcelain (JX2), coarse white porcelain (JC13), and celadon (JQ5).

composition and less uniform temperature control during firing.

SEM-EDS analysis of the layered microstructure of the coarse white porcelain samples (Fig. 3.1.3) shows that the engobe is a high-alumina, low-silica clay (Table 1), with an average composition of 41.05 wt% Al_2O_3 and 52.24 wt% SiO_2. For context, published analyses of "hard kaolin" from several coal-measure deposits in Shanxi province show Al_2O_3 contents ranging from 38.7 % to 39.4 % (Wilson, 2004). The notably higher alumina content of the analyzed engobe strongly suggests that the Jinyang potters were not simply using a common local clay, but were deliberately selecting a higher-grade, more aluminum-rich material specifically for this application. Furthermore, this high alumina content, which exceeds the theoretical maximum for pure kaolinite (approx. 39.5 %), suggests the clay source was likely enriched with high-alumina minerals such as diaspore (α-AlO(OH)) or boehmite (γ-AlO(OH)) (Fang et al., 1990, p. 18). To further compare the raw materials of the body and engobe, the mass ratio of silicon oxide to aluminum oxide (SiO_2/Al_2O_3) was calculated from their respective compositions. The bodies of the three analyzed coarse white porcelain samples yielded an average SiO_2/Al_2O_3 ratio of 2.62 (2.81, 2.58, and 2.49 for JC11, JC13, and JC14, respectively). In stark contrast, the engobe layers on these same samples had a much lower average SiO_2/Al_2O_3 ratio of just 1.27 (1.19, 1.29, and 1.33, respectively). This significant compositional difference confirms that the engobe was formulated from a deliberately selected raw material, distinct from the body, and likely represents a higher-quality, kaolinitic clay.

3.2. Body compositions

The results of the ceramic bodies of the fine white porcelain, coarse white porcelain, and celadon specimens are presented in (Table 2). The concentration of P_2O_5 in the ceramic bodies was not determined to ensure overall data accuracy. This is because P_2O_5 levels in ceramic bodies are typically low, and its analytical reliability is limited due to methodological constraints. The strong signals from major elements in the body, such as SiO_2 and Al_2O_3, can suppress the P_2O_5 signal, leading to poor precision near the detection threshold.

Based on the compositional results, the ceramic bodies from the Jinyang kiln site exhibit several characteristic features. First, a scatter plot of the major elements Al_2O_3 and SiO_2 (Fig. 3.2.1a) shows that all samples have an Al_2O_3 content above 22 % and a SiO_2 content below 70 %. These elemental proportions indicate the utilization of high-alumina, low-silica clay materials, which is characteristic of typical northern kaolinitic bodies. A binary plot of Fe_2O_3 and TiO_2 (Fig. 3.2.1b) reveals that the coarse white porcelain and celadon bodies have similar iron and titanium oxide contents. The fine white porcelain bodies, however, have significantly lower levels of these oxides, with average values of approximately 0.77 % Fe_2O_3 and 0.52 % TiO_2, conforming to the general definition of a white porcelain body as having an iron content below 1 % (Zhang, 2005, p. 146).

Regarding the fluxing agents Na_2O, MgO, K_2O, and CaO, an initial look at the weight percentages might suggest K_2O is the primary flux, with an average content above 2 %, while Na_2O and MgO are below 1 % and CaO is around 1.62 %. However, a calculation of the molar concentrations reveals that Na_2O, MgO, and CaO are more significant than their weight percentages suggest due to their lower molecular weights, and all contribute to the sintering of the body. From a compositional perspective, it is therefore likely that these oxides had an equivalent fluxing effect and that no single element was dominant. This chemical signature is likely a natural feature of the local kaolin minerals. This interpretation is supported by the lack of obvious feldspar grains in the

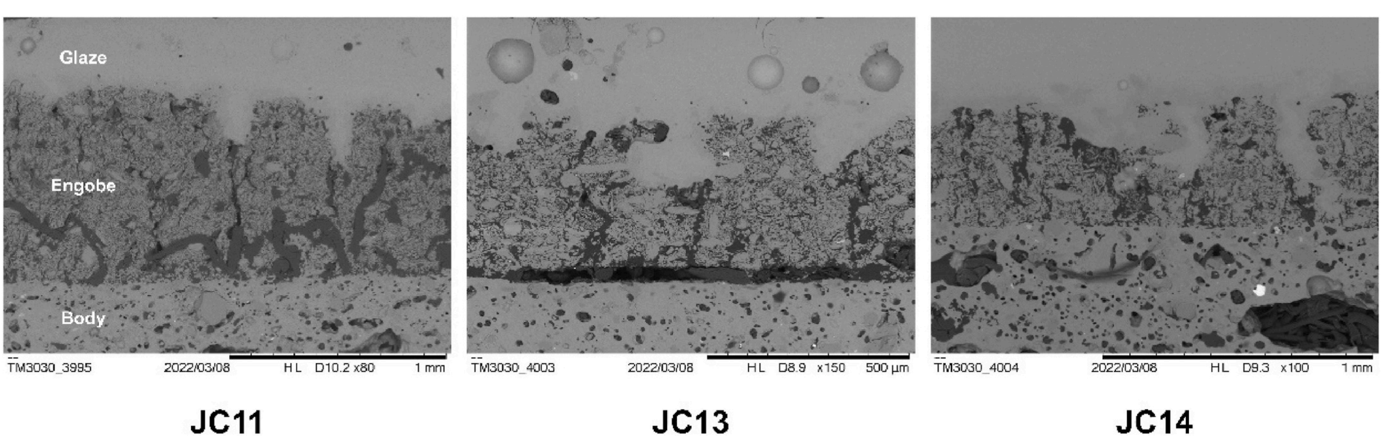

Fig. 3.1.3. SEM images showing the cross-sections of coarse white porcelain samples (JC11, JC13, JC14), illustrating the glaze, engobe, and body layers.

Table 1
SEM-EDS chemical analysis (wt%) for the engobe (E) and body (B) of coarse white porcelain samples.

No.	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO_2	Fe_2O_3
JC11-E	0.53	1.04	42.51	51.00	1.11	1.30	1.33	0.00	1.18
JC11-B	0.66	1.01	23.65	66.49	2.41	1.74	1.48	0.09	2.48
JC13-E	0.43	0.90	40.85	52.76	1.34	1.78	0.99	0.00	0.95
JC13-B	0.60	1.02	25.44	65.71	2.35	1.28	1.35	0.03	2.22
JC14-E	0.43	0.78	39.78	52.97	2.08	2.12	0.92	0.08	0.84
JC14-B	0.47	0.96	25.97	64.64	2.80	1.69	1.30	0.00	2.17

Table 2
ED-XRF analysis results of fine white porcelain, coarse white porcelain, and celadon bodies from the Jinyang ancient city (wt/%).

No.	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO	Fe_2O_3
JX1	0.65	1.63	26.53	64.71	2.19	3.12	0.40	0.00	0.75
JX2	1.15	0.71	30.42	64.06	1.4	0.83	0.66	0.00	0.77
JC1	0.30	0.70	31.22	61.33	1.80	1.44	1.10	0.09	2.02
JC2	0.31	0.67	22.68	68.60	2.63	1.83	1.26	0.03	2.00
JC3	0.61	0.97	24.04	66.28	2.72	1.89	1.33	0.00	2.16
JC4	0.36	0.79	30.88	61.32	1.72	1.51	1.41	0.00	2.00
JC5	0.78	1.11	24.96	65.41	2.54	1.84	1.18	0.00	2.18
JC6	0.78	0.95	24.43	65.81	2.68	1.87	1.25	0.00	2.23
JC7	0.21	1.63	30.06	63.48	1.14	2.13	0.50	0.01	0.83
JC8	0.64	0.97	25.10	65.09	2.66	1.94	1.28	0.08	2.24
JC9	0.52	0.83	23.19	67.67	2.43	1.74	1.37	0.01	2.23
JC10	0.50	0.84	24.81	66.16	2.58	1.63	1.36	0.00	2.13
JC11	0.38	0.82	23.94	67.26	2.51	1.68	1.16	0.00	2.25
JC12	0.52	0.85	24.14	66.65	2.44	1.73	1.41	0.02	2.25
JC13	0.27	0.77	24.39	67.03	2.58	1.60	1.35	0.00	2.01
JC14	0.36	0.75	24.54	66.55	2.72	1.85	1.10	0.00	2.12
JC15	0.37	0.76	24.99	65.89	2.53	1.58	1.63	0.17	2.09
JC16	0.38	0.74	23.67	66.97	2.68	1.87	1.33	0.00	2.37
JC17	0.44	0.83	24.50	66.15	2.65	1.69	1.43	0.03	2.26
JQ1	0.40	0.75	32.68	59.61	1.24	1.83	1.27	0.00	2.21
JQ2	0.49	0.78	30.53	62.40	1.50	1.14	1.02	0.00	2.15
JQ3	0.47	0.93	24.21	67.84	2.44	0.85	1.23	0.00	2.02
JQ4	0.37	0.75	26.40	64.29	3.06	1.44	1.62	0.03	2.03
JQ5	0.42	0.86	22.84	67.48	3.03	1.39	1.73	0.00	2.24
JQ6	0.48	0.84	34.86	58.37	1.88	0.52	1.33	0.03	1.69
JQ7	0.59	0.81	30.94	61.70	3.03	0.47	1.37	0.00	1.09
JQ8	0.41	0.75	32.06	59.57	1.37	1.91	1.34	0.07	2.51
JQ9	0.23	0.58	30.00	62.36	1.82	1.11	1.43	0.00	2.47
JQ10	0.21	0.62	28.35	63.23	1.65	2.32	1.35	0.00	2.27

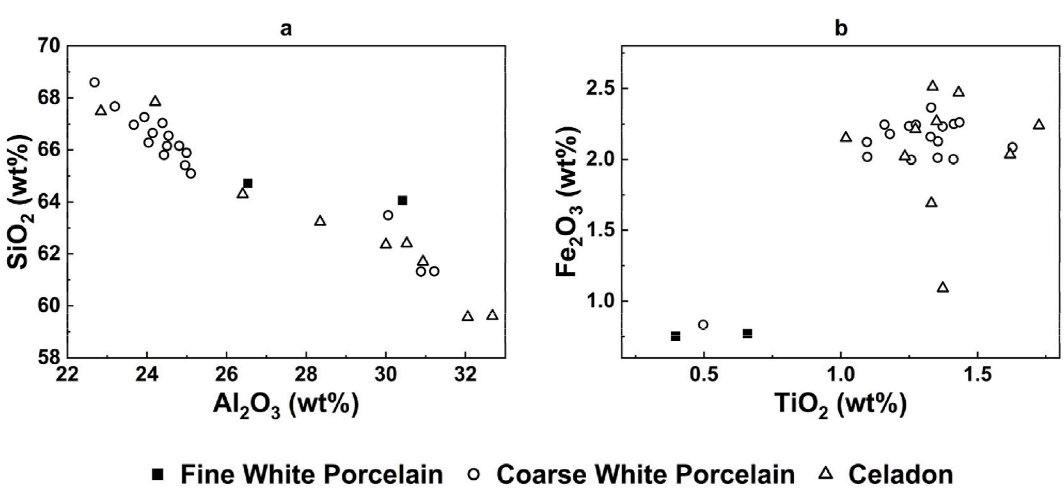

Fig. 3.2.1. A comparison of body compositions for the three ceramic types:(a) Al_2O_3 vs. SiO_2; (b) Fe_2O_3 vs. TiO_2.

SEM and microscopic analyses, suggesting the flux composition derives from the natural makeup of the local raw materials rather than the deliberate addition of feldspathic minerals. Even in samples that show a relatively high weight percentage of CaO, molar ratio calculations and microstructural observations show no clear evidence for the intentional addition of lime-based materials.

While coarse white porcelain and celadon bodies show general differences in their SiO_2 and Al_2O_3 concentrations, scatter plot analysis indicates some compositional overlap between the two groups. The Fe and Ti impurity levels in coarse white porcelain bodies are relatively high, approaching those of the celadon bodies. Some scholars have noted that for early white porcelain, individual samples may exceed this threshold, and a greenish or yellowish tint can occur due to variations in era, raw materials, and firing temperatures (Wang, 2009, p. 28). This suggests that coarse white porcelain was produced using a ceramic body similar to that of celadon, with the application of an engobe being the critical innovation that greatly improved the finished appearance. In summary, the compositional data show that while differences exist, there is a clear technological relationship between the bodies of coarse white porcelain and celadon.

3.3. Glaze compositions

The compositional analysis of the glazes from the fine white porcelain, coarse white porcelain, and celadon samples is presented in Table 3. For some samples, the suffixes "O" or "I" have been added to the sample number to denote two different datasets corresponding to the outer and inner surfaces of the same porcelain, respectively.

The glaze compositions are broadly similar in their major elements but show key distinctions in colorant oxides. The concentration of the fluxing agent CaO is widely distributed, ranging from approximately 7 %–20 %. In contrast, the major elemental compositions of Al_2O_3 and SiO_2 demonstrate similar patterns, with Al_2O_3 concentrations ranging from 10 to 20 % (average 14.63 %) and SiO_2 levels varying between 55 and 71 % (average 62.49 %). Other minor elements such as Na_2O, MgO, P_2O_5, and MnO show little variation. However, significant variations are observed in Fe_2O_3 and TiO_2 content among the three glaze types. The average Fe_2O_3 content in the fine white porcelain glaze (average 1.96 %) is slightly higher than that in the coarse white porcelain (1.15 %), but significantly lower than in the celadon (4.62 %). The highest TiO_2 content is found in the celadon (average 0.53 %), while the average TiO_2 content for both fine and coarse white porcelain glazes is approximately 0.1 % (Fig. 3.3.1a).

Furthermore, it is noteworthy that of the 13 coarse white porcelain samples large enough for glaze analysis, 9 exhibited compositional differences between the inner and outer glazes, particularly in CaO and SiO_2 content (Fig. 3.3.1 b). Calculations show that for this group of samples, the average CaO content in the outer glaze is 15.77 % with an average SiO_2 content of 60.72 %. In contrast, the inner glaze has an average CaO content of only 12.49 %, while its average SiO_2 content is as high as 66.9 %. The plot illustrates that the glazes of the celadon, and the inner and outer surfaces of the coarse white porcelain, occupy distinct compositional fields. The observed compositional variance between the inner and outer glazes could be attributed to differences in glaze thickness, varied interactions within the glaze during firing, or potential analytical bias caused by the XRF beam penetrating a thin inner glaze and reaching the underlying body. Although the traditional Chinese glazing method was immersion, which would typically coat the vessel completely, differences in glaze thickness and firing conditions can still lead to some compositional variation between the inner and outer surfaces. For those coarse white porcelain samples with similar inner and outer glaze compositions, it is possible that the glaze layer was thicker, or that the engobe layer acted as a barrier, significantly reducing body-glaze interactions and thus resulting in a more uniform glaze composition.

4. Discussion

4.1. Body material

The major element compositions of the celadon, coarse white porcelain, and fine white porcelain bodies indicate that all three types were produced using similar kaolinitic clay materials. The calculated SiO_2/Al_2O_3 ratios, ranging from 1.67 to 3.02, align with published data for contemporary northern Chinese wares from sites such as the Sui dynasty Anyang and Xing kilns, and the Sui to early Tang period Luoyang city (Zhu, 2007; Lu et al., 2012; Huang et al., 2023). However, northern ceramic technology during this period was not monolithic, and several

Table 3
ED-XRF Analysis Results of the three ceramic types from the Jinyang Ancient City (wt%).

No.	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3
JX1	0.43	2.07	16.15	60.71	0.45	1.18	15.47	0.20	0.07	1.88
JX2	1.11	1.67	14.57	70.71	0.29	1.80	7.12	0.05	0.15	2.03
JC1	0.25	3.91	14.69	61.64	0.29	2.47	14.88	0.10	0.13	1.41
JC3	0.26	2.71	15.34	56.28	0.74	1.74	20.33	0.28	0.16	1.61
JC5-O	0.35	2.63	16.64	63.03	0.34	2.87	12.66	0.16	0.11	0.95
JC5-I	0.25	1.87	14.71	67.07	0.46	1.55	12.64	0.07	0.10	0.65
JC6-O	0.34	2.40	16.26	60.91	0.52	2.02	15.42	0.24	0.13	1.51
JC6-I	0.29	1.97	15.53	65.27	0.39	1.45	13.58	0.13	0.11	0.85
JC7-O	0.26	2.69	13.82	54.83	0.83	4.29	18.92	0.31	0.30	3.04
JC7-I	0.26	1.73	13.36	67.19	0.98	0.98	11.09	0.20	0.16	2.22
JC8-O	0.37	1.93	16.50	60.14	0.53	2.59	15.68	0.33	0.12	1.38
JC8-I	0.31	1.83	14.68	66.77	0.42	1.70	12.86	0.19	0.10	0.66
JC9-O	0.38	2.31	14.19	62.19	0.41	2.57	16.25	0.12	0.14	0.92
JC9-I	0.26	1.64	14.29	67.42	0.34	1.53	13.35	0.09	0.10	0.69
JC11-O	0.39	2.27	14.49	61.37	0.49	3.00	16.04	0.14	0.14	1.16
JC11-I	0.29	1.92	15.25	67.86	0.33	1.40	11.71	0.08	0.11	0.77
JC12-O	0.32	2.08	15.47	65.31	0.45	2.58	11.70	0.16	0.12	1.04
JC12-I	0.26	1.99	14.90	66.98	0.48	1.59	12.34	0.08	0.12	0.74
JC13-O	0.30	1.79	13.68	65.46	0.46	2.10	14.17	0.09	0.10	1.39
JC13-I	0.34	1.74	14.69	66.93	0.40	1.71	12.47	0.13	0.11	1.03
JC14-O	0.27	2.22	14.24	62.65	0.45	1.84	16.54	0.13	0.13	0.90
JC14-I	0.25	1.90	14.97	66.51	0.46	1.54	12.92	0.08	0.11	0.66
JC15	0.32	2.08	14.30	62.63	0.37	2.77	16.19	0.10	0.12	0.82
JC17-O	0.37	2.08	20.81	55.90	0.53	1.94	16.29	0.41	0.12	1.18
JC17-I	0.28	1.84	14.52	67.14	0.49	2.10	11.87	0.21	0.10	0.94
JQ2	0.62	2.70	13.14	56.17	0.43	1.96	20.15	0.34	0.11	3.98
JQ3	0.87	1.59	14.12	55.42	0.64	3.73	18.01	0.73	0.15	4.27
JQ4	0.51	2.08	11.31	57.47	0.69	2.68	17.95	0.62	0.16	6.11
JQ5	0.54	2.29	13.13	66.18	0.28	4.07	11.43	0.08	0.11	1.62
JQ6	0.69	2.50	12.82	56.56	0.60	3.89	18.86	0.47	0.18	3.08
JQ8	1.03	2.91	10.81	58.34	0.35	2.87	16.71	0.51	0.12	6.06
JQ10	1.11	1.42	14.77	56.48	0.97	2.14	16.03	0.95	0.09	4.72

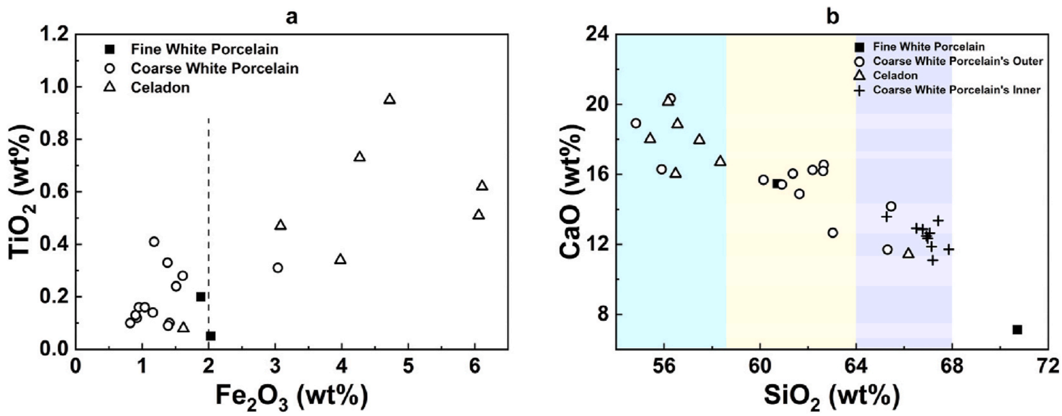

Fig. 3.3.1. A comparison of glaze compositions for the different ceramic types: (a) Fe_2O_3 vs. TiO_2 concentrations; (b) SiO_2 vs. CaO concentrations, distinguishing between the inner and outer glazes of coarse white porcelain.

distinct body recipes have been identified in previous research. The primary models include the addition of either ash-based materials or feldspathic minerals to the clay (Cui et al., 2012). For instance, the Xing kiln employed diverse recipes. Some Sui dynasty fine white porcelain incorporated potassium feldspar (Chen et al., 1990), while a small portion of Tang dynasty fine white porcelain utilized significant amounts of ash-based materials (Cui et al., 2012). The coarse white wares, in contrast, may have used calcareous clay or limestone (Li, 1998, p. 159). A third production model, identified at the Yiyongjie site in Luoyang, involved the deliberate addition of crushed quartz or milled sand to the clay paste. This practice is evidenced by the presence of much larger and more angular quartz grains up to 100 μm in size and a significantly higher SiO_2/Al_2O_3 ratio between 4.19 and 6.14 (Huang et al., 2023). In contrast, the Jinyang samples show no evidence of such deliberate additions. The few large quartz grains observed microscopically are therefore inferred to be residual primary minerals from the raw clay, not intentionally added temper.

Despite these general similarities to northern traditions, the body compositions of the Jinyang samples exhibit a distinct regional geochemical signature. A systematic comparison with published celadon data from contemporary northern kilns, including Zhaili (Huang et al., 2020; Geng et al., 2024) as well as Xing, Caocun, Anyang, and the Luoyang city sites (Huang et al., 2020), highlights this uniqueness. In an MgO-CaO scatter plot (Fig. 4.1.1a), samples from the other northern kilns cluster tightly in a low-calcium (CaO <1.0 %) and low-magnesium (MgO <0.6 %) field, showing remarkable consistency. The Jinyang samples, however—both celadon and white porcelain—form a distinct high-calcium (average 1.62 %) and high-magnesium (average 0.86 %) group that is clearly separate from the others. Conversely, on a K_2O-Na_2O scatter plot (Fig. 4.1.1b), the samples from all sites show significant overlap, suggesting that northern kaolin resources share a relatively consistent alkali content background. This raises a critical question: Were the elevated levels of Ca and Mg in the Jinyang bodies introduced as a separate additive?

The hypothesis that a flux, such as limestone or dolomite, was intentionally added is unlikely. The addition of limestone would have enriched the body only in CaO, failing to account for the corresponding increase in MgO. While dolomite contains both oxides, its typical CaO-to-MgO mass ratio of approximately 1.4:1 is not reflected in the Jinyang samples (Cui et al., 2012). Furthermore, the data form a tight cluster rather than a linear mixing trend on the scatter plot, which strongly suggests the use of a single, naturally composite raw material rather than the mechanical mixture of two separate components. This interpretation is further supported by microscopic observations, which reveal no clear evidence of intentionally added mineral phases. A more plausible explanation lies in the local geology. Ordovician limestones in North China underwent varying degrees of dolomitization, transforming them into dolomitic limestones or dolomite (Ma et al., 2021). The sedimentary kaolin used in the Shanxi region is known to have associated minerals including illite (Fang et al., 1990, p. 24), the presence of which also explains the relatively enriched K_2O content in the samples. We therefore propose that the Jinyang potters exploited a specific local kaolin resource that was naturally rich in dolomitic impurities, giving their porcelain a unique and identifiable geochemical fingerprint.

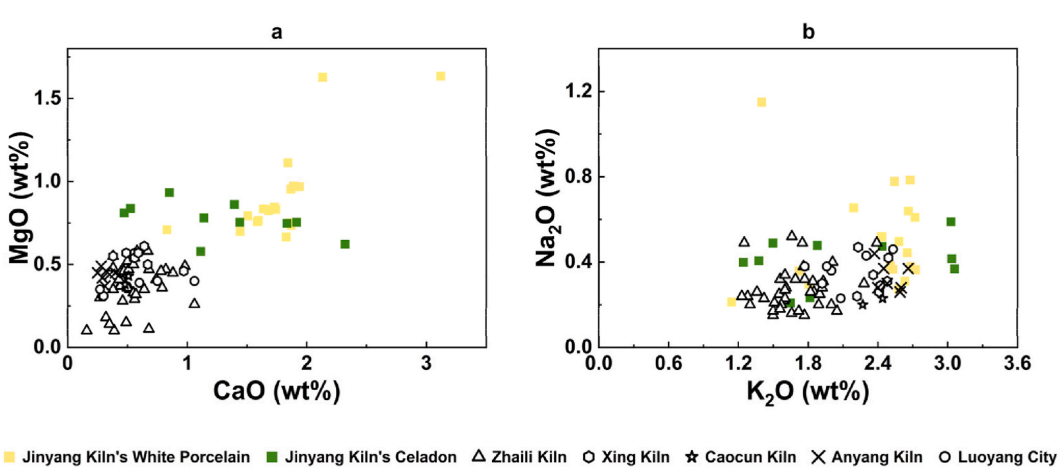

Fig. 4.1.1. A comparison of body compositions between Jinyang samples (both white porcelain and celadon) and celadons from other northern kilns: (a) CaO vs. MgO; (b) K_2O vs. Na_2O.

4.2. Glaze material

Analysis of the glaze compositions from the Jinyang kilns reveals that the majority of samples exhibit CaO contents exceeding 8 wt%. According to the definition provided in the Dictionary of Ceramics (CBIP and CCS 1984, p. 812), this threshold distinguishes lime glazes from lime-alkali glazes. The Jinyang glazes therefore belong to a typical lime glaze system.

To investigate the glaze formulation, we employed a methodology adapted by Huang et al. (2020) from the foundational work of Hurst and Freestone (1996) and Tite et al. (1998). This principle was initially developed for the analysis of lead glazes. According to this principle, if the glaze were formulated using a simple binary recipe of local clay paste and a fluxing agent containing negligible refractory components (such as Al_2O_3, SiO_2, Fe_2O_3 and TiO_2), then the ratio of these oxides should remain consistent between the ceramic body and the glaze. However, a plot of the Al_2O_3/SiO_2 ratios in the bodies versus the glazes shows that most Jinyang samples deviate significantly from the 1:1 diagonal line (Fig. 4.2.1a). This indicates that Jinyang potters added a silica-rich component to their glaze slurry, a strategy consistent with other northern kilns where specific materials were chosen to address high-alumina, low-silica clays: loess was used at Zhaili and Zibo (Huang et al., 2020; Geng et al., 2024), while “a silica-rich loess or similar quartz-rich material” was used at Anyang and Luoyang City (Huang et al., 2020). Further calculation of the mass ratio of SiO_2/Al_2O_3 in the glazes reveals a stable value consistently above 4. This is significant, as a SiO_2/Al_2O_3 ratio of 4–5 is necessary to readily form an amorphous glass phase in the SiO_2–Al_2O_3–CaO–MgO–Na_2O–K_2O system (Partyka et al., 2015). It can therefore be inferred that the local high-alumina, low-silica kaolinitic clay mandated the addition of a third component, leading to a ternary recipe for the Jinyang glazes consisting of clay, flux, and a silica-rich material.

Having established a general ternary framework, the next step is to deconstruct the specific glaze recipe of the Jinyang celadons. Previous research has suggested that the Xing kilns were among the first to use limestone as a flux during the Sui to mid-Tang period, possibly mixed with plant ash (Ma et al., 2021), while some samples from Luoyang City suggest the use of mineral fluxes like dolomite or talc (Huang et al., 2023). The Jinyang celadons, for their part, exhibit glaze recipes consistent with the mainstream technological tradition of northern celadon production. Comparative analysis (Fig. 4.2.2) demonstrates a significant overlap between Jinyang celadon glazes and those from other major northern celadon kilns, such as Anyang, Zhaili (Huang et al., 2020; Geng et al., 2024), and Gongyi (Ma et al., 2018), in terms of both their fluxing systems (K_2O, Na_2O, CaO) and P_2O_5 contents. The consistent presence of detectable P_2O_5 (average 0.57 wt%) indicates that the flux was primarily based on plant ash. Furthermore, the mass ratio of iron (III) oxide to aluminum oxide (Fe_2O_3/Al_2O_3) is markedly higher in the glazes than in the bodies (Fig. 4.2.1 b), suggesting that in an effort to imitate the desirable glaze colors of southern celadons, the Jinyang potters intentionally incorporated an iron- and silica-rich material as the third component in their celadon glaze recipe.

The white porcelain from Jinyang, however, showcases a distinct local innovation. A compositional comparison of white porcelain glazes (Fig. 4.2.3) shows that the Jinyang glazes occupy a unique “medium-calcium” compositional space, distinguishing them from both the “high-calcium” technological pathway of Luoyang (Huang et al., 2023) and the “high-alkali ($K_2O + Na_2O$)” tradition of the Xing kilns (Lu et al., 2012), thereby reflecting a degree of recipe independence. Sample JX2 is particularly noteworthy. Its “low-calcium, high-alkali” characteristics are analogous to samples from Group 3 found at the Luoyang City and to Sui-dynasty fine white porcelain from the Xing kilns (Huang et al., 2023; Lu et al., 2012). Although its profile is broadly analogous to these other groups, subtle differences in the total alkali content are still apparent. This may point to the possible introduction of a feldspathic flux, with the observed variations potentially reflecting differences in the type of feldspar used or in the proportion added. This rare recipe is therefore a significant compositional outlier. However, with so few examples, it is difficult to determine whether this represents a deliberate technological experiment or simply an occasional, non-standardized variation in the production process.

4.3. Technological shifts in the emergence of white porcelain

The emergence of northern white porcelain was not an isolated technological event but a result of the complex interplay between imitation and innovation, framed by the aesthetic standards of southern celadons. It is widely accepted that northern potters, aiming to compete with southern celadon production, initially sought to replicate the appearance of Yue celadons. However, these attempts were largely unsuccessful, failing to achieve the aesthetically prized “thousand peaks of green” (千峰翠色) and typically resulting in a more yellowish-green coloration. Not until the Five Dynasties and early Song periods did kilns such as Yaozhou kiln succeed in producing celadons comparable to those from the Yue kilns. Material analysis of the ceramics from the Jinyang kilns provides new evidence to reconstruct this technological trajectory.

The initial phase of imitation is evident in the glaze chemistry. From the perspective of glaze fluxes (Fig. 4.3.1 a), the CaO content in Jinyang celadons is comparable to that of products from the Yue Kiln (Li, 1998, p. 120) and Hongzhou kilns (Xiong, 2018), indicating that northern potters had successfully mastered and replicated the “lime glaze”

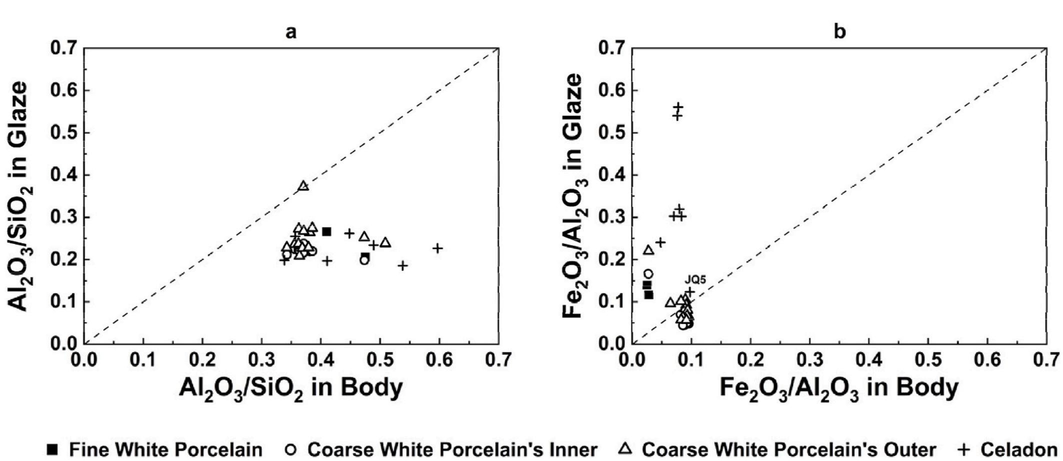

Fig. 4.2.1. A comparison of chemical ratios in the bodies versus the glazes for the Jinyang samples. (a) Al_2O_3/SiO_2 ratio; (b) Fe_2O_3/Al_2O_3 ratio. The dashed 1:1 line is for reference.

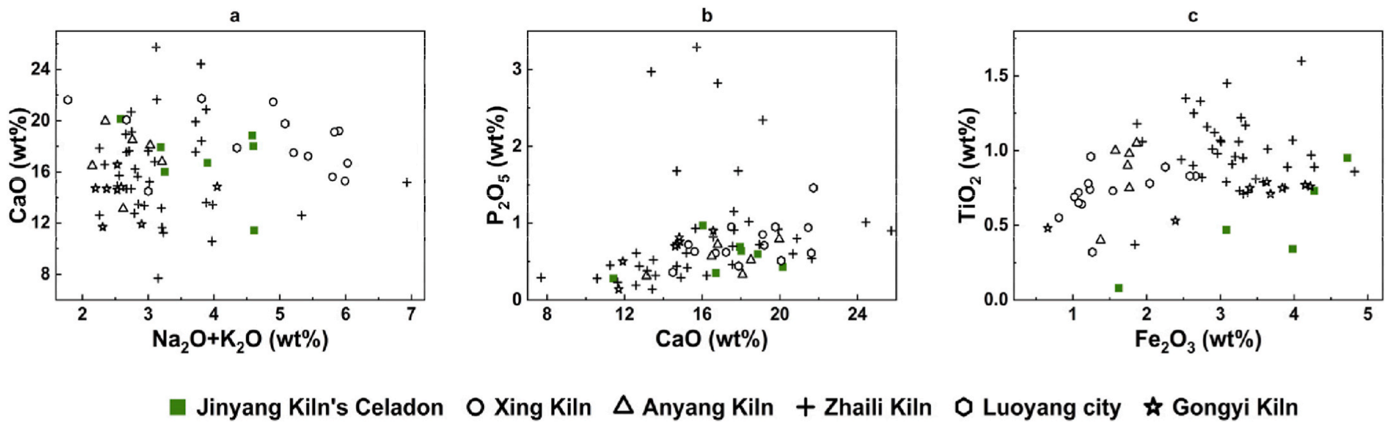

Fig. 4.2.2. A comparison of celadon glaze compositions from Jinyang and other northern kilns: (a) CaO vs. $Na_2O + K_2O$; (b) P_2O_5 vs. CaO; (c) TiO_2 vs. Fe_2O_3.

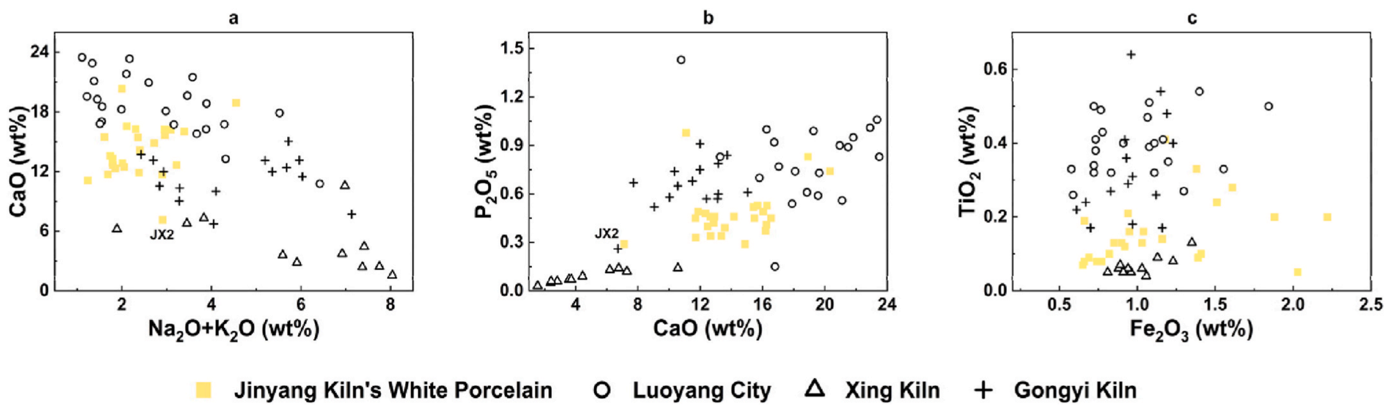

Fig. 4.2.3. A comparison of white porcelain glaze compositions from Jinyang and other northern sites:(a) CaO vs. $Na_2O + K_2O$; (b) P_2O_5 vs. CaO; (c) TiO_2 vs. Fe_2O_3.

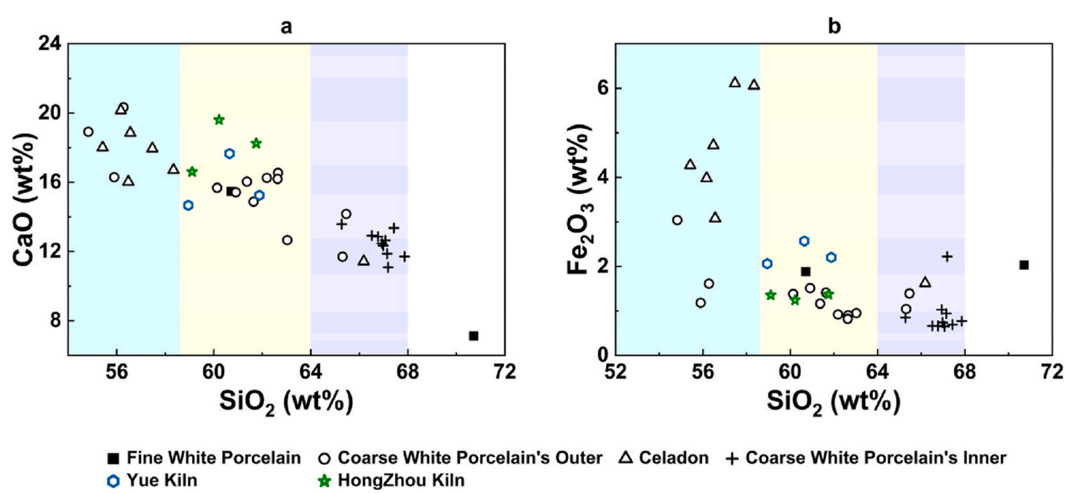

Fig. 4.3.1. Comparison of glaze compositions from Jinyang and southern celadon kilns, plotting: (a) CaO vs. SiO_2 and (b) Fe_2O_3 vs. SiO_2.

formulation system of southern celadons. However, a comparison of colorant content reveals a significant divergence (Fig. 4.3.1b). The Fe_2O_3 content in Jinyang celadon glazes is considerably higher than in their southern counterparts. In contrast, the content in the coarse white porcelain glazes is far more comparable, closely resembling that of the southern celadons. This points to a fundamental difference in raw material bases. Southern celadons were typically made using a binary recipe of porcelain stone and plant ash, whereas the glaze materials available at Jinyang were inherently low in iron. A simple transplantation of the southern recipe would have resulted in a whitish-yellow glaze. Consequently, to achieve the desired green hue, Jinyang potters had to intentionally add a third, silica- and iron-rich component, such as loess. This additive not only compensated for the narrow vitrification range of the local high-alumina clays but, more importantly, introduced the necessary iron to act as a colorant. This demonstrates that Jinyang potters did not simply copy southern celadon technology but actively adapted it to the properties of local materials.

It is plausible that the material constraints encountered in imitating celadon prompted a divergence in production towards white porcelain. This change was likely not a simple linear evolution but rather a strategy of parallel production. The first stage of this innovation is embodied in the refinement from celadon to coarse white porcelain. Both wares from Jinyang used the identical paste for the body, with the key differences being the presence or absence of an engobe and the amount of the iron-rich additive in the glaze recipe. The use of engobe to improve ceramic quality first appeared and became widespread in southern China during the Southern Dynasties. In the north, kilns began applying engobe to celadons no later than the Northern Qi dynasty, and sites producing engobed white porcelain during the Northern Dynasties to the Sui period include the Gongyi kilns, certain areas within the Xing kiln complex, and the Anyang kilns (Qin, 2018). As a production center operating from the Sui to the early Tang, the Jinyang kiln was among the earliest northern producers to adopt this technique, specifically using a low-iron, high--alumina engobe to conceal the coarse body and brighten the glaze color. Furthermore, by reducing or eliminating the iron-rich clay from the glaze recipe, the purity of the glaze color could be maximized. Sample JQ5 visually captures this transition; it was intended as a celadon (lacking an engobe), but its glaze is extremely pale and nearly transparent. In Fig. 4.2.1b, this sample plots close to the 1:1 line, clustering clearly with the coarse white porcelain, marking it as a product of this technological transition.

The subsequent leap from coarse to fine white porcelain was driven by comprehensive improvements in body, glaze, and firing technology. From a macroscopic perspective, a comparison of the average major oxides in the glazes of Jinyang's white porcelain and celadons from the Yue kilns reveals an apparent compositional proximity, hinting that the white porcelain glaze recipe may have conceptually evolved from the southern celadon tradition (Fig. 4.3.2). However, this was not a matter of direct technological transplantation but rather served as a baseline for complex and experimental local innovations. One of the key innovations occurred in the body formulation. Potters appear to have achieved a significant upgrade by repurposing the high-quality, low-iron engobe material as a foundation for the fine white porcelain body. The chemical compositions of the engobe and the fine porcelain body are indeed very similar, aside from their silica and alumina content. Compositional modeling suggests that adding approximately 40 % quartz to the engobe material yields a body composition closely resembling that of the fine white porcelain sample JX2 (Table 4).

The glaze formulation was also a site of significant experimentation. When plotted on the CaO-Al_2O_3-SiO_2 ternary phase diagram—where

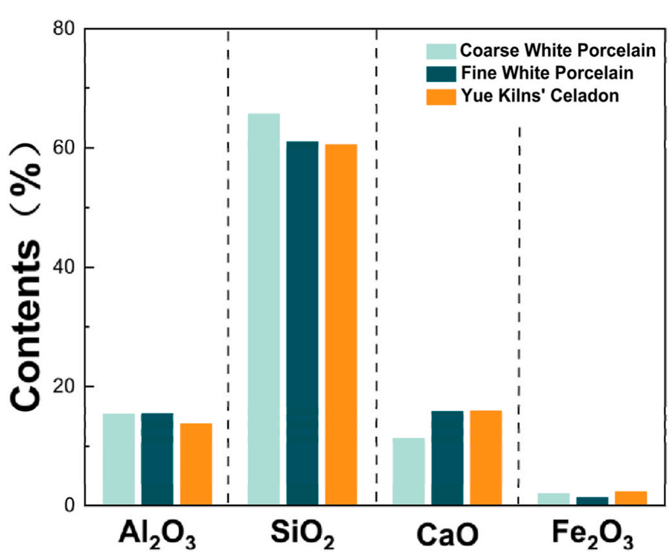

Fig. 4.3.2. Comparison of the average major oxide contents in the glazes of Jinyang's white porcelains (coarse and fine) and Yue Kilns' Celadon.

CaO represents the molar sum of all fluxing oxides (CaO, Na_2O, K_2O, MgO, MnO, and Fe_2O_3)*—the majority of the Jinyang samples, including the celadon, the coarse white porcelain glazes, and one of the fine white porcelain samples (JX1), cluster together around the low-melting-point eutectic of pseudowollastonite-anorthite-tridymite (Fig. 4.3.3). This group represents the mainstream northern technological system of the period. In stark contrast, the other fine white porcelain sample, JX2, departs significantly from this baseline, shifting decisively into a region richer in silica and alumina and plotting within the tridymite primary phase field. The existence of this single, high-performance outlier suggests that Jinyang potters were likely experimenting with higher-performance recipes. The scientific principles behind such a shift are well-established: the increase in silica would have reduced the fluidity of the glaze at its maturing point, preventing it from running during firing, while the concurrent addition of alumina would have inhibited unwanted crystallization, ensuring a purely vitreous texture (Taylor and Bull, 1986, pp. 16, 18). Although this represents a necessary step towards achieving a superior finish, with only one such example, it points towards an incipient, experimental phase rather than a mature and widely adopted new technology.

The firing technology for fine white porcelain also differed significantly from that of celadon and coarse white porcelain, particularly in the utilization of kiln atmosphere and innovations in kiln furniture. Archaeological excavations have revealed that the Jinyang kilns were of the horseshoe-shaped mantou type, which, due to their updraught structure, naturally produce a predominantly oxidizing atmosphere (Qin, 2018). While detrimental to achieving the characteristic bluish-green or grey-green colors of southern wares, this atmosphere was highly advantageous for producing white porcelain. It ensured that iron remained primarily in its weakly coloring ferric state (Fe^{3+}) rather than being reduced to the intensely coloring ferrous state (Fe^{2+}). This explains the seeming paradox of why the Fe_2O_3 content in Jinyang fine white porcelain glazes is comparable to that in the Yue kilns (c. 2 wt% (Li, 1998, p. 116), yet the final appearance is a translucent white rather than green. This stands in contrast to the Yue kilns, which typically used dragon kilns where a reducing atmosphere could be achieved in specific sections (Li, 1998, p. 130). This reduction of iron to its divalent state (Fe^{2+}) was essential for producing the classic green coloration. Furthermore, Jinyang potters employed more advanced saggars for firing fine white porcelain. The discovery of saggar remnants with fine white porcelain rims still attached provides direct evidence for the use of enclosed firing (Han and Zhao, 2022). Compared to open-stacking methods, saggars not only shielded the wares from falling ash and uncontrolled atmospheric changes but also ensured a stable and effective oxidizing environment for the porcelain within.

In summary, the complete production sequence revealed at the Jinyang kilns illuminates the technological foundations and evolutionary pathway for the origin of northern white porcelain. This process transitioned from an initial phase of imitating southern celadon to a subsequent phase of independent, local innovation. In the early stage, northern potters were constrained by local raw materials and kiln conditions, forcing them to make technological adjustments that still could not fully overcome the inherent limitations of their materials. The birth of white porcelain, by contrast, represented a technological breakthrough achieved by capitalizing on local advantages, namely the availability of low-iron materials and the prevailing oxidizing atmosphere of their kilns. The technical upgrades seen in fine white porcelain, such as body optimization and the adoption of saggars, reflect a process of continuous refinement adapted to local resources. This study thus clarifies the technological evolution at the Jinyang kilns and provides an empirical foundation for understanding the critical relationship between technological change and resource adaptation in the genesis of northern white porcelain.

Table 4
Chemical compositions (wt%) of fine white porcelain bodies (JX1, JX2) and simulated bodies, as determined by SEM-EDS. The simulated compositions are calculated by adding 40 % silica to the measured composition of base engobe samples (JC11, JC13, JC14).

No.	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO	Fe_2O_3
JX1	0.70	1.64	26.58	65.11	2.01	2.86	0.28	0.07	0.68
JX2	1.01	0.73	30.70	63.53	1.44	1.15	0.64	0.00	0.79
JC11 + 40 % silica	0.38	0.74	30.36	65.00	0.79	0.93	0.95	0.00	0.84
JC13 + 40 % silica	0.31	0.64	29.18	66.26	0.96	1.27	0.71	0.00	0.68
JC14 + 40 % silica	0.31	0.56	28.41	66.41	1.49	1.51	0.66	0.06	0.60

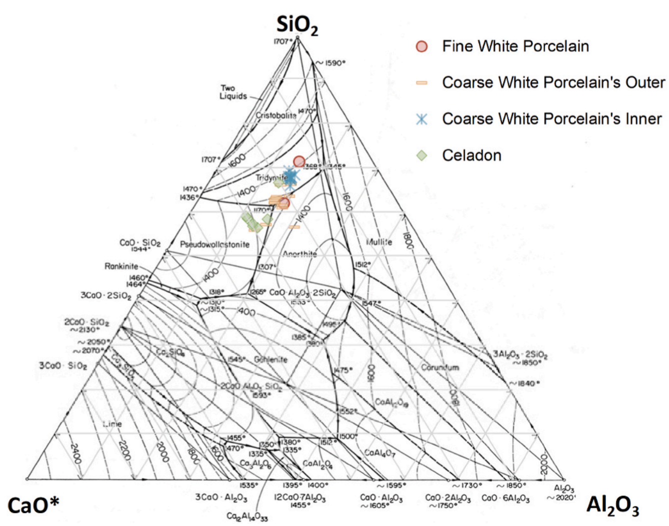

Fig. 4.3.3. Composition of Jinyang kiln glazes plotted on the CaO*-Al_2O_3-SiO_2 ternary phase diagram. (Modified from Rehren and Yin, 2012).

5. Conclusions

Systematic analysis of ceramics from the Jinyang ancient city site reveals a complex technological landscape during the Sui and Tang dynasties, characterized by a dynamic interplay of established northern traditions and localized innovation. Rather than simply replicating a single technological package, potters at Jinyang developed multiple adaptive strategies, consistently utilizing local kaolinitic clays rich in dolomitic impurities to produce a diverse repertoire, including celadon, coarse white porcelain, and fine white porcelain. This study demonstrates that Jinyang was a center of significant technological diversity and adaptation.

Our analysis identifies two primary technological strategies at Jinyang. The first involves the transition from celadon to coarse white porcelain; this was achieved by reducing the addition of iron-rich materials to the glaze and applying a low-iron white engobe, which effectively shifted the glaze color from bluish-green to white. The second strategy is characterized by the parallel development of coarse and fine white porcelain. The creation of fine white porcelain involved innovations in body formulation, likely by combining high-quality engobe clay with a siliceous material, and was supported by the crucial adoption of saggars for firing. These developments drastically improved the final product's quality. Archaeological evidence, which shows both coarse and fine white porcelain co-occurring in the same strata from the same period, confirms that their development was concurrent rather than a linear evolution, indicating the coexistence of multiple technical routes within the Jinyang kiln's repertoire.

The identification of the Jinyang kiln complex as an early northern white porcelain production center is a major contribution, placing it alongside the well-known manufacturing centers in the Luoyang region (e.g., the Gongyi Baihe and Beiguanzhuang kilns) and the historical Yecheng region (e.g., the Anyang and Xing kilns). This study provides a new perspective on the diverse pathways to fine white porcelain. The findings from Jinyang suggest that early production was not monolithic; instead, it involved varied and localized experiments. The subtle yet deliberate adjustments in both body composition and glaze formulation, combined with critical innovations in firing technology, collectively demonstrate a sophisticated, practice-based approach to ceramic refinement in medieval China. This discovery not only enriches the material database for the study of northern white porcelain but also provides a vital new case study for investigating the mechanisms of technological diversity and innovation.

CRediT authorship contribution statement

Yujie Wu: Writing – original draft. **Jianfeng Cui:** Writing – review & editing. **Binghua Han:** Resources.

Data availability statement

The data that support the findings of this study are available within the article.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2025.106334.

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