DEVELOPMENT, PREPARATIONS AND COLORATION MECHANISM FOR JUN PORCELAIN CU-SERIES GLAZE AT YUZHOU, HENAN CHINA

LAI HUASHENG

UNIVERSITI SAINS MALAYSIA

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by

LAI HUASHENG

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

Page

LIST OF SYMBOLS

a	Lattice parameter (nm)
b	Body density (g/cm^3)
C	Colorimetric parameter (e.g., chromaticity)
d	Crystal interplanar spacing (nm)
D	Average particle size (μm or nm)
E	Energy level or binding energy (eV)
F	Firing temperature (°C)
G	Gloss (GU, gloss units)
H	Hardness (Mohs or GPa)
I	Intensity of XRD peak or signal
L*	Lightness in the CIELAB color space
a*	Red-green color axis in CIELAB color space
b*	Yellow-blue color axis in CIELAB color space
P	Porosity (%)
R	Reflectance (%)
T	Thermal shock resistance (cycles)
W	Water absorption (%)
α	Thermal expansion coefficient ($\times 10^{-6}/°C$)
λ	Wavelength (nm)
ρ	Density (g/cm^3)

LIST OF ABBREVIATIONS

XRD	X-ray diffraction
SEM	Scanning Electron Microscopy
EDS	Energy Dispersive Spectroscopy
XPS	X-ray Photoelectron Spectroscopy
USM	Universiti Sains Malaysia
USA	United States
Al	Aluminum
Fe	Ferrum
K	Kalium
Na	Sodium
Si	Silicon
CuO	Copper(II) oxide
$BaCO_3$	Barium carbonate
ZnO	Zinc oxide
SnO_2	Tin(IV) oxide
Al_2O_3	Aluminum oxide
TiO_2	Titanium dioxide
CeO_2	Cerium(IV) oxide
ZrO_2	Zirconium dioxide
GB/T	China Recommended National Standard
QB/T	Recommended standards for China's light industry

LIST OF APPENDICES

PEMBANGUNAN, PENYEDIAAN DAN MEKANISME PEWARNAAN BAGI LICAU SIRI-CU JUN DI YUZHOU, HENAN CHINA

ABSTRAK

Jun porcelain, terkenal dengan warna transformasi kiln yang unik, memiliki reputasi tinggi dalam seni seramik antarabangsa dan berperanan sebagai wakil cemerlang seni seramik Cina kontemporari. Namun, penghasilan tradisional Jun porcelain menghadapi cabaran seperti inovasi terbatas dalam formulasi gerlis, kadar kecacatan yang tinggi, serta reka bentuk yang kurang mesra alam, yang menjejaskan kelestariannya. Walaupun kajian terdahulu telah mengkaji Jun porcelain dari pelbagai sudut seperti pemilihan bahan mentah, rejim pembakaran, dan analisis struktur mikro, kajian sistematik mengenai mekanisme pewarnaan gerlis berasaskan kuprum (siri Cu) bagi warna merah, hijau, dan biru masih terhad. Kajian ini menumpukan kepada gerlis berasaskan kuprum dalam Jun porcelain dengan fokus pada proses penyediaan dan mekanisme pewarnaannya. Hubungan antara formulasi gerlis, parameter penyediaan utama, dan persembahan warna diberi penekanan. Melalui reka bentuk eksperimen faktor tunggal dan ortogonal, beberapa formulasi gerlis baharu telah dibangunkan. Teknik pencirian lanjutan seperti SEM, EDS, XRD, dan XPS digunakan untuk menjelaskan mekanisme pewarnaan dari pelbagai aspek, termasuk struktur kristal, keadaan valens unsur, mikromorfologi, dan struktur pemisahan fasa. Hasil kajian menunjukkan gerlis merah memperoleh warna daripada zarah koloid Cu^{+} yang digabungkan dengan struktur pemisahan fasa berbentuk cacing, menghasilkan warna merah yang khas. Gerlis hijau pula menampilkan warna hijau zamrud hasil sinergi antara ion Cu^{2+} dan struktur pemisahan fasa berbentuk bulat bersaiz kira-kira 100 nm. Manakala, gerlis biru mencapai warna biru yang lebih jelas akibat kepekatan tinggi

ion Cu^{2+} bersama struktur pemisahan fasa bersaiz lebih besar (kira-kira 313 nm). Ciri fisikokimia ketiga-tiga formulasi gerlis baharu ini mematuhi piawaian kebangsaan untuk porselin guna harian dan keselamatan makanan, disahkan melalui laporan ujian dari Pusat Pemeriksaan dan Ujian Produk Seramik Kebangsaan China. Kajian ini menyediakan bukti eksperimental dan sokongan teori untuk penyelidikan dan inovasi dalam gerlis berwarna berasaskan kuprum dalam Jun porcelain. Ia memberi impak penting terhadap inovasi bahan, pemodenan teknik tradisional, dan pembangunan lestari dalam bidang seramik. Dengan menggabungkan sains, teknologi, dan kemahiran warisan budaya tidak ketara, penyelidikan ini menyumbang kepada pemeliharaan dan inovasi budaya Jun porcelain dalam era baharu.

DEVELOPMENT, PREPARATIONS AND COLORATION MECHANISM FOR JUN PORCELAIN CU-SERIES GLAZE AT YUZHOU, HENAN CHINA

ABSTRACT

Jun porcelain, renowned for its unique kiln color transformations, holds a prestigious reputation in international ceramic art and serves as an exemplary representation of contemporary Chinese ceramic art. However, traditional production of Jun porcelain faces several challenges, including limited innovation in glaze formulations, high defect rates, and less environmentally friendly designs, all of which hinder its sustainable development. While previous studies have examined Jun porcelain from various perspectives such as raw material selection, firing regimes, and microstructural analysis, systematic investigations into the coloration mechanisms of copper-based (Cu-series) glazes in red, green, and blue hues remain limited. This study focuses on copper-based glazes in Jun porcelain, systematically investigating their preparation processes and coloration mechanisms. Emphasis is placed on the relationship between glaze formulation, key preparation parameters, and color expression. Through single-factor and orthogonal experimental designs, several new glaze formulations were developed. Advanced characterization techniques, including SEM, EDS, XRD, and XPS, were employed to elucidate the coloration mechanisms from multiple aspects, including crystal structure, elemental valence states, micromorphology, and phase separation structures. Results indicate that the red glaze obtains its color primarily from colloidal Cu^{+} particles combined with worm-like phase separation structures, producing a distinctive red hue. The green glaze exhibits an emerald green color resulting from the synergistic effect of Cu^{2+} ions and roughly 100 nm spherical phase separation structures. Meanwhile, the blue glaze achieves a

more intense blue expression due to the high concentration of Cu^{2+} ions combined with larger phase separation structures (~313 nm). The physicochemical properties of these three novel glaze formulations comply with national standards for daily-use porcelain and food safety, as confirmed by certified test reports from the National Ceramic Product Inspection and Testing Center of China. This study provides experimental evidence and theoretical support for research and innovation in copper-based colored glazes within Jun porcelain. It has significant implications for material innovation, modernization of traditional techniques, and sustainable ceramic development. By integrating science and technology with intangible cultural heritage skills, this research contributes to the preservation and innovation of Jun porcelain culture in the contemporary era.

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter briefly introduces the main research content of the research topic, Jun porcelain Cu-series color glaze, and in particular, the various issues involved in developing contemporary Jun porcelain colored glaze. Jun porcelain Cu-series color glaze is essential and unique in Jun porcelain and has high historical and cultural value. What are the issues with Jun porcelain color glaze products during the ceramic production? What challenges does the development of Jun porcelain Cu-series color glaze face? Research into the preparation process and color mechanism of Jun porcelain Cu-series color glaze will be a significant scientific research endeavor. Through the lens of ceramic materials science, we understand the charm and exquisite technology of Jun porcelain and delve into the preparation process, materials, and artistic expression possibilities of Jun porcelain Cu-series color glazes. By studying the preparation process and color mechanism of Jun porcelain Cu-series color glazes, we can better understand and master the technology and craftsmanship of Jun porcelain and better promote the innovation and development of the Jun porcelain industry. This chapter also describes the motivation for the research objectives of this study. The main content of this chapter is outlined, including the introduction, literature review, methods, development and preparation of new glazes, glaze testing, data analysis, and conclusions.

The preparation process of the Cu-series color glaze for Jun porcelain involves multiple steps, such as the selection of raw materials, the mixing ratio of raw materials, the optimization of the process flow, and the control of the firing process. Among these, raw materials selection and mixing ratio are critical steps in the preparation process. The color effect of the ceramic is affected by the content and mixing ratio of copper. In contrast, the mixing ratio of other raw materials determines the effect of the glaze surface. In addition, the control of the processing and firing processes will affect the quality and stability of the ceramic. This requires in-depth discussion. Through this research, we can solve many technical problems for ceramic companies, improve product quality, and better understand the preparation technology and color development principle of the Cu-series color glaze of Jun porcelain, thereby promoting the innovative development of the Jun porcelain industry. At the same time, this research can also provide experience and reference for the preparation and color development of other similar ceramic materials.

1.2 Background of the Study

Chinese ceramic art boasts a long and storied history, with Jun porcelain, one of the "Five Great Kilns of the Song Dynasty," holding a distinguished place in global ceramic art due to its unique kiln-transformation colors and copper-based glazes. In particular, the red, green, and blue copper-based colored glazes, with their rich tonal variations and inimitable visual effects, hold significant research value in both artistic creation and materials science. However, the stable preparation of Cu-series glazes presents numerous challenges, which have long hindered technological innovation and industrial transformation in Jun porcelain.

Figure 1.1 The destruction of the natural environment caused by the massive deforestation for fuel for wood-burning stoves. (Source: Henan Provincial Timber Trading Market, Zhengzhou City, China).

Traditional Jun porcelain firing predominantly relies on wood and coal kilns, creating unique atmospheric conditions that facilitate valence state transitions of copper ions at high temperatures, resulting in diverse glaze color variations (Liu, Ren, & Li, 2021). However, as illustrated in Figure 1.1, the dependence of traditional kilns on wood resources has led to extensive deforestation, severely damaging ecosystems. This practice conflicts with national energy conservation and emission reduction policies (Wen, 2023). As further demonstrated in Figure 1.2, wood firing not only consumes large quantities of saggars and energy but also generates smoke and dust pollution, exacerbating environmental burdens. Consequently, transitioning to more environmentally friendly and controllable gas kiln technologies has become an imperative trend in contemporary Jun porcelain production. As shown in Figure 1.2, the unsustainable use of wood-firing techniques underscores the need to explore cleaner firing methods to promote the green transformation of the ceramic industry.

Figure 1.2 Wood burning is wasteful of energy, saggers, etc., and pollutes the environment. (Source: Henan Jun Porcelain Industry Research Center, Yuzhou City, China).

Concurrently, the Jun porcelain cultural industry holds significant economic potential. To promote the high-quality development of the Jun porcelain industry, this study conducts a comparative analysis of major ceramic production regions in China. In 2023, the ceramic industry output value in Jingdezhen, Jiangxi, reached 86 billion CNY; Dehua, Fujian, 57.7 billion CNY; Chaozhou, Guangdong, 60 billion CNY; and Foshan, Guangdong, 98.8 billion CNY. In contrast, Yuzhou, the core production hub of Jun porcelain, recorded an industry output value of 20 billion CNY (as shown in Figure 1.3) (Lu, 2023). Based on Yuzhou's GDP data for 2023 (90.4 billion CNY), it is estimated that with systematic upgrades in digitalization, eco-friendly practices, and financialization, the Jun porcelain industry's output value could potentially surpass 40–50 billion CNY, injecting new momentum into economic growth in the Central Plains region. This context not only underscores the significant cultural and market value of the Jun porcelain industry but also highlights the pivotal role of technological innovation in driving industrial advancement. To meet market demands, it is essential to integrate advanced materials science and technology with contemporary aesthetics, continuously developing innovative Jun porcelain glazes and products that enhance design appeal and functionality, thereby strengthening the industry's core competitiveness.

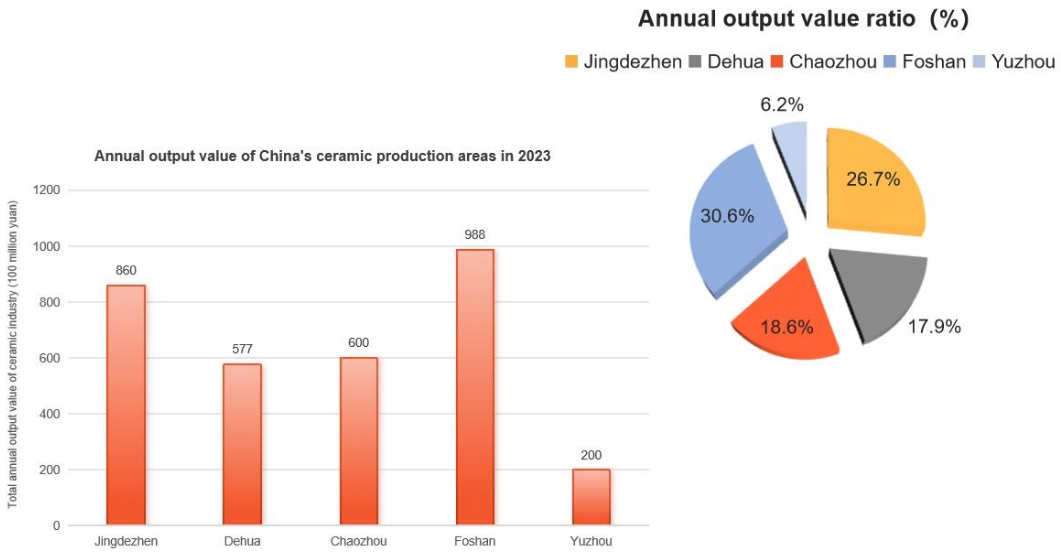

Figure 1.3 Total output value and proportion of each ceramic production area in China in 2023. (Source: China National Bureau of Statistics, 2023).

The scientific challenges in researching copper-based colored glazes for Jun porcelain stem from the complexity of their structural and coloration mechanisms. Multiple factors, including firing atmosphere, temperature regimes, and formulation components, influence the valence state transitions of copper in glazes. In a strongly reducing atmosphere, Cu^{2+} can be reduced to Cu^{+}, forming colloidal particles or nanoscale clusters that produce red hues through Mie scattering or surface plasmon resonance phenomena (Zhou, 2022). Conversely, in an oxidizing atmosphere, Cu^{2+} exists in ionic form, combining with phase separation structures to yield green or blue tones (Tao & Peng, 2024). These subtle valence transitions are highly sensitive to parameters such as firing curves, glaze layer thickness, and body composition, making it difficult to achieve stable and reproducible glaze colors.

Furthermore, phase separation structures in copper-based glazes play a critical role in color presentation. Research indicates that when phase separation structures are on the nanoscale (<100 nm), Rayleigh scattering enhances green hues. In contrast, larger structures (>300 nm) can produce opalescent structural colors, intensifying blue tones (Xie et al., 2023). The formation of these structural colors depends on the fluidity of the glass phase and nucleation kinetics at high temperatures, requiring precise control over formulation design, including component ratios, flux systems, and crystal phase regulation.

Currently, Jun porcelain glazes face issues such as the lack of standardized protocols, reliance on empirical formulations, and low reproducibility. Particularly in modern gas kiln firing of copper-based glazes, achieving stable valence states and microstructures poses significant challenges. Therefore, this study focuses on the composition-process-structure-color chain of copper-based red, green, and blue glazes, aiming to optimize formulations through systematic experimental design. By employing advanced characterization techniques such as SEM, EDS, XRD, and XPS, the study aims to elucidate the microscopic coloration mechanisms, address issues of color instability and low yield rates, and provide scientific support for the development of green and high-quality Jun porcelain.

In the context of China's "Rural Revitalization" and the preservation of intangible cultural heritage (Zheng, Yu, & Xu, 2021), Jun porcelain, a vital component of Henan's intangible cultural heritage, holds immense potential for industrial development. However, the traditional Jun porcelain industry has long been hindered by insufficient innovation, product homogenization, and the absence of standardized processes (Lu, 2023). To overcome these challenges, modern scientific methods must be integrated into glaze research systems, establishing an innovation pathway centered on data-driven formulation optimization, structural visualization analysis, and industrial validation. This approach will drive the fusion of technology and art in Jun porcelain, promoting its internationalization and cultural expression.

1.3 Problem Statement

Cu-series color glazes of Jun porcelain, a significant component of traditional Chinese ceramic art, are renowned for their rich visual expressiveness and complex chemical reaction mechanisms. However, the development and production of copper-based red, green, and blue glazes currently face two prominent core challenges: first, the lack of a scientifically optimized glaze formulation system, and second, the absence of systematic analysis of the coloration mechanisms of Cu-series color glazes. These critical technical bottlenecks severely limit the quality stability, yield rate, and innovative expressiveness of Jun porcelain glazes.

Although previous studies have explored the coloration mechanisms of copper red or copper blue glazes (Zhu et al., 2020; Wang et al., 2021), most have focused on single color systems or the restoration of ancient techniques, lacking systematic research on copper-based red, green, and blue glazes under modern process conditions (e.g., gas kilns and eco-friendly formulations) (Li et al., 2024). Particularly under high-temperature firing conditions, copper elements are highly susceptible to factors such as temperature, atmosphere, and the thickness of the glaze layer. The complex interplay among valence state distribution (Cu^{+}/Cu^{2+}), dispersion morphology (colloidal/ionic states), and microstructures (phase separation, crystalline phases) remain poorly understood, with no unified explanation for their formation mechanisms (Jia et al., 2021; Sang et al., 2020). Moreover, the transformation patterns between different glaze colors have not been clearly defined, restricting the targeted design and control of glaze colors.

Based on field investigations, the authors collected Cu-series glaze samples from representative kilns in Yuzhou, Henan. As shown in Figure 1.4, these samples commonly exhibit issues such as significant color variations, excessive bubbles, and severe cracking, which adversely affect yield rates and aesthetic quality (Li et al., 2024). Both literature and survey findings indicate that imprecise control of firing atmospheres, imbalanced flux ratios, and uneven glaze layer thickness are primary causes of these defects (Wang et al., 2022; Guo et al., 2012). These challenges not only hinder the high-quality development of the Jun porcelain industry but also limit its broader application in contemporary daily-use ceramics and high-end artistic ceramics.

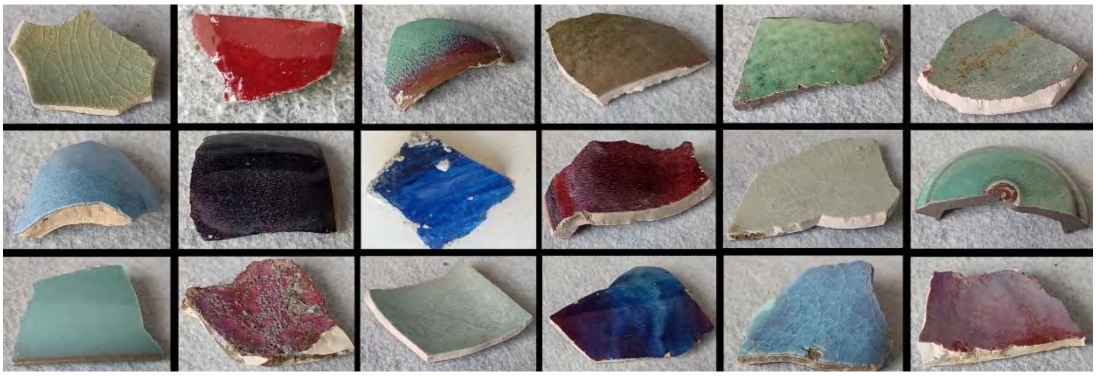

Figure 1.4 Representative color glaze samples from each kiln of contemporary Jun porcelain from Yuzhou, Henan Province. (Source: Henan Jun Porcelain Industry Research Center, Yuzhou City, China).

Current literature on the compositional behavior of copper glazes predominantly relies on macroscopic descriptions, lacking in-depth analysis from the perspectives of microstructure and material physics behavior. For instance, critical issues such as the binding state of Cu^{2+} with the glass phase, the contribution of phase separation size to coloration, and the impact of crystalline-to-amorphous phase transitions on color stability remain in the exploratory stage (Zhou, 2022; Yang et al., 2021).

To address these technical challenges and research gaps, this study focuses on three key aspects. The lack of a systematic formulation optimization pathway for copper-based colored glazes in Jun porcelain based on modern ceramic science. The absence of microscopic mechanistic explanations for the relationships among copper valence state transitions, structural morphology, and coloration at high temperatures. There is a lack of reproducible modeling studies on the formulation-structure-color response mechanisms across different Cu-series glaze color systems.

This study employs single-factor and orthogonal experimental design methods, integrating systematic firing variable control strategies based on scientifically optimized formulations. By utilizing material characterization techniques such as SEM, EDS, XRD, and XPS, the study analyzes the microstructure and chemical reaction behavior of red, green, and blue color glazes. The findings provide theoretical foundations and technical support for addressing issues such as poor stability, low yield rates, and uncontrolled coloration in traditional Cu-series color glazes. The research outcomes not only offer actionable technical improvement recommendations for the Jun porcelain industry but also provide new insights and practical guidance for ceramic education in higher institutions, the preservation of local ceramic craftsmanship, and innovation in ceramic art. For example, establishing a standardized system for colored glaze preparation can enhance artisans' skills while facilitating the transformation of Jun porcelain, as intangible cultural heritage, toward modern design, cultural creativity, and international ceramic art. This, in turn, strengthens its cultural influence within the global ceramic art system (Chen et al., 2024; Li & Wei, 2023).

1.4 Research Questions

Research has found that the porcelain-making process for Jun porcelain's color glaze has a long history. The unique kiln-fired glaze color is formed naturally, and each piece of Jun porcelain has a unique color. This unique glaze color is created by firing various chemical compositions in a reduced atmosphere at high temperatures. New glaze colors appear in each era, thanks to the research and exploration of ceramic artisans. The porcelain-making process has been continuously developed and improved, and it has become increasingly mature with the progress of various technologies over the years. The coloring mechanism of Jun porcelain involves the state of metallic elements in the glaze. The coloring effect is also affected by changes in factors such as firing temperature and firing atmosphere. It is these changes in factors that create the colorful, unique texture and profound artistic conception of the kiln-fired effect of Jun porcelain. The development of Jun porcelain color glaze to the present day has resulted in a wide range of colorful glazes. However, Jun porcelain color glaze ceramic products still have many problems that must be solved through innovation and research into new glazes. This paper will conduct experimental research around the following four research questions(Table 1.1).

Research Question 1: What is the composition, preparation technology and development status of contemporary Jun porcelain Cu-series color glaze?

Research Question 2: What new preparation technology are used to carry out a series of experiments on red, green and blue Jun porcelain color glaze of Cu-series?

Research Question 3: what is the coloration mechanism of Cu-series red, green and blue Jun porcelain color glaze?

Research Question 4: How to validate the research finding on new glazes?

1.5 Research Objectives

The overall aim of this study is to develop new formulas and preparation processes for Jun porcelain Cu-series red, green, and blue glazes using new contemporary materials and methods and to study and analyze the coloration mechanism of Jun porcelain Cu-series color glazes using testing methods such as

XRD, EDS, SEM, and XPS. Experimental research was used to improve the quality of contemporary Jun porcelain products, enhance the commercial and artistic value of Jun porcelain products, provide a theoretical basis and practical guidance for the development and innovation of the Jun porcelain industry, and fill the gap in theoretical knowledge of the coloration mechanism of Cu-series color glazes red, green and blue. For this reason, more specific objectives(Table 1.1) are:

Table 1.1 Research questions and objectives.

Research Questions	Research Objectives
Research Question 1: What is the composition, preparation technology and development status of contemporary Jun porcelain Cu-series color glaze?	Research Objective 1: To study the development status, composition and preparation technology of contemporary Jun porcelain Cu-series glaze.
Research Question 2: What new preparation technology are used to carry out a series of experiments on red, green and blue Jun porcelain color glaze of Cu-series?	Research Objective 2: To conduct a series of experiment on Cu-series Jun porcelain color glaze by using new preparation technology.
Research Question 3: what is the coloration mechanism of Cu-series red, green and blue Jun porcelain color glaze?	Research Objective 3: To analyse the color mechanism of Cu-series red, green and blue Jun porcelain glaze.
Research Question 4: How to validate the research finding on new glazes?	Research Objective 4: To validate the research finding by ceramic industry institution.

1.5.1 Research Objective 1

To study the development status, composition and preparation technology of contemporary Jun porcelain Cu-series glaze. The main objective of this research is to analyze the development status, formula composition, and preparation process of the Cu-series color glaze in contemporary Jun porcelain. By consulting literature and data, the development process and current status of Jun porcelain color glaze are understood, and the concept, types, and colors of Jun porcelain color glaze are summarized to provide background and support for this research topic. Research the inheritance and development of the Cu-series color glaze in contemporary Jun porcelain. Explore the various porcelain-making processes and techniques in the production of contemporary Jun porcelain. Through evaluating and testing the physical and chemical properties of contemporary Jun porcelain color glaze samples, study the formula composition of contemporary Jun porcelain color glaze and the related problems that exist. Research the production process system of Jun porcelain from past dynasties, including the exploration of critical techniques such as firing temperature and atmosphere control, which is conducive to improving the yield and artistic quality of the finished product. The research of the Cu-series color glaze of contemporary Jun porcelain is a comprehensive field that covers history and culture, material science, and modern technology. Achieving this research goal will not only enable a better understanding and protection of this traditional craft but also promote its innovative development and make the art of Jun porcelain more colorful.

1.5.2 Research Objective 2

To conduct a series of experiment on Cu-series Jun porcelain color glaze by using new preparation technology. The main objective of this research was to carry out a series of experiments on the Cu-series color glaze of Jun porcelain using new methods, formulas, materials, and processes in order to explore new glaze formulas and preparation processes and provide new technical means for the innovation and development of the Jun porcelain industry. With the changing times, the traditional Jun porcelain color glaze can no longer meet people's needs for the quality and aesthetics of Jun porcelain. Specific analyses were carried out to address the research objectives. New materials and methods were used to study the effects of glaze composition on the color development and stability of Jun porcelain Cu-series color glaze. In order to explore the application of new materials in Jun porcelain Cu-series color glaze, the performance characteristics of new materials and their effects on the application of Cu-series Jun porcelain color glaze were studied. A new preparation process was used to test the Jun porcelain Cu-series color glaze and the effects of factors such as the formula composition, firing temperature, glaze thickness, ball milling time, and different bodies on the color rendering effect and physical properties of the Jun porcelain Cu-series color glaze were studied. Finally, the experimental results were obtained, a new glaze formula and preparation process were found, and the production technology and properties of the Jun porcelain Cu-series color glaze were optimized.

1.5.3 Research Objective 3

To analyse the color mechanism of Cu-series red, green and blue Jun porcelain glaze. The main objective of this study is to analyze the coloration mechanism of red, green, and blue Jun porcelain colors made from the Cu-series. Through experimental testing and analysis, the coloration mechanism and influencing factors of different colored Cu-series Jun porcelain color glazes are explored. The specific analysis for the research objectives is as follows. The coloring principles of the red, green, and blue glazes of the Cu-series Jun porcelain, as well as the state and content of the copper under different firing conditions, were studied using experimental testing methods such as XRD, EDS, SEM, and XPS. The influence of process parameters such as the formula composition, firing temperature, glaze thickness, ball milling time, and different bodies on the coloring effect of the Cu-series Jun porcelain color glaze was studied, and the relationship between the coloration mechanism and the process parameters was explored. The color rendering effects and influencing factors of the red, green, and blue glazes of the Cu-series Jun porcelain were compared, and the color rendering rules were summarized to provide a theoretical basis for optimizing the preparation process of the Cu-series color glaze of Jun porcelain. This study systematically explores the relationship between the coloration mechanism, formula composition, and preparation process and puts forward suggestions for optimizing the preparation process of Cu-series color glaze for Jun porcelain so as to improve the color effect and stability of Jun porcelain products.

1.5.4 Research Objective 4

To validate the research finding by ceramic industry institution. The primary objective of this study is to validate the performance of newly developed copper-based red, green, and blue glazes for Jun porcelain using the Chinese national standards for testing daily-use ceramics. The physicochemical properties of these glazes were evaluated to verify their performance. Through testing, the authors obtained a report from the China National Ceramic Product Quality Inspection and Testing Center. The new glazes were assessed against Chinese national standards for daily-use ceramics to determine compliance with national ceramic standards. The testing parameters included chromaticity, porosity, density, flexural strength, glaze surface hardness, gloss, water absorption, and other performance metrics. The evaluation also confirmed whether the glazes exhibit superior qualities such as wear resistance, corrosion resistance, non-radioactivity, and absence of lead and cadmium leaching, meeting the requirements for Grade A product classification. The objective of this study is to validate the performance of new materials for Cu-series Jun porcelain glazes. Quantitative testing methods were primarily employed for industrial standard validation, while qualitative aspects such as artistic feedback and community evaluation were not included. These dimensions will be further explored in subsequent studies.

1.6 Research Significance

Scientific Significance. At the materials science level, this study employs systematic experiments and advanced characterization techniques (e.g., XRD, SEM, EDS, XPS) to elucidate the valence state transition mechanisms of copper under varying redox atmospheres and its physicochemical coupling with glaze matrices. For the first time, it achieves microscopic modeling of the structure-composition-color relationships for copper-based red, green, and blue glazes. This exploration not only addresses the gap in prior literature regarding the coordinated regulation of multiple color systems but also provides experimental evidence with controllable structures and precise mechanisms for ceramic glaze design. Furthermore, this study offers a systematic explanation of the coloration mechanisms driven by phase separation structures within glaze layers. The experimental validation of the synergistic effects between structural and chemical coloration will advance research on amorphous coloration mechanisms in ceramics, providing critical theoretical references for inorganic non-metallic materials science and the development of visually functional ceramics. These findings will directly benefit researchers in ceramic materials, new materials engineering laboratories, and glaze formulation development teams.

Industrial Significance. In industrial practice, this study validates the controllability of multiple Cu-series Jun porcelain glazes under modern gas kiln conditions, as demonstrated by experimental data, thereby significantly improving yield rates and color stability. It offers scalable, low-emission production solutions for existing ceramic factories. Additionally, the newly developed glaze formulations exclude toxic raw materials such as lead and cadmium, thereby meeting the requirements of the National Food Safety Standards and facilitating the green transformation and sustainable development of the ceramic industry. The study proposes a data-driven evaluation system that integrates performance, cost, and art, providing a technical template for product iteration and new product development in Jun porcelain factories. This enhances the traditional industry chain's ability to respond rapidly to market demands. The results will directly empower ceramic manufacturing enterprises, arts and crafts companies, and cultural and creative industry parks.

Cultural Significance. As a Chinese national intangible cultural heritage, Jun porcelain embodies historical cultural memory, and the ingenuity of its glazes reflects the wisdom and aesthetic ideals of ancient Chinese artisans. By reconstructing and innovating the preparation system for Cu-series Jun glazes through modern scientific methods, this study establishes a data-driven, reproducible process framework. This approach mitigates the risks of intergenerational loss and empirical reliance on traditional techniques, offering a systematic model for the educational dissemination of ceramic intangible heritage, as well as for museum exhibitions and university curricula. Moreover, by integrating contemporary expressive forms and structural coloration concepts, the study opens new creative pathways for ceramic art, achieving modern visual expressions while respecting tradition. This fosters the renewed recognition and dissemination of Jun porcelain in global art design, cultural tourism, and educational creation. The research outcomes provide sustainable guidance for intangible heritage artisans, ceramic artists, and design educators.

1.7 Conceptual Framework

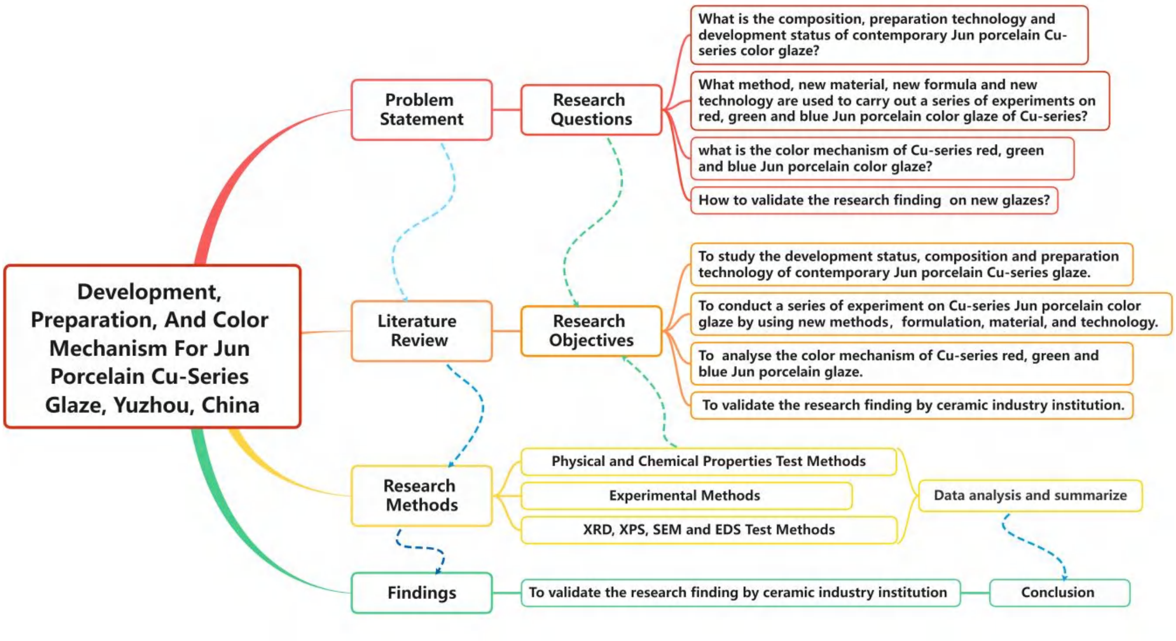

Plate 1.1 Conceptual framework for the research on Jun porcelain Cu-series color glazes. (Source: Shi et al., 2020).

Plate 1.1 illustrates the fundamental rationale behind this study, forming a conceptual framework that serves as the origin and process of the research. The development of this conceptual framework is the focal point of the study, encapsulating the exploration of the formulation, preparation processes, and coloration mechanisms of Cu-series red, green, and blue glazes for Jun porcelain. It also provides a preliminary reflection on the research process of new glazes and their novel coloration mechanisms.

The conceptual framework revolves around a closed-loop system that encompasses the optimization of preparation processes, the analysis of coloration mechanisms, and the performance validation of copper-based colored glazes in Jun porcelain. This framework strikes a balance between scientific rigor and practical applicability. Drawing on Professor Shi's research on iron-based glazes, the study employs single-factor and orthogonal experimental methods to select optimal formulations for red, green, and blue glazes, refining firing process parameters (Shi, 2020). Techniques such as SEM/EDS, XRD, and XPS are utilized to elucidate the microscopic mechanisms of glaze coloration, clarifying the synergistic coloration effects of phase separation structures, light scattering, and copper colloidal particles. The physicochemical properties and environmental friendliness of the novel glazes are systematically validated by the Chinese National Standard (GB/T 3532-2022), resulting in national quality inspection certification. This enables the transformation into standardized production protocols, ensuring glaze color controllability, enhanced product performance, and the scientific advancement of intangible cultural heritage techniques. The study provides a comprehensive paradigm for the modernization and internationalization of traditional ceramic craftsmanship.

1.8 Limitation of Study

In the research process of various sciences, there are always some limitations, which also apply to the research on the development and coloration mechanism of the blue, green, and red glazes of the Cu-series in Jun porcelain. In this study, the possible limitations are as follows:

Limited Research Scope. This study focuses solely on the development and mechanistic analysis of Cu-series red, green, and blue-colored glazes, excluding other metal oxide glazes (e.g., iron, manganese, cobalt) or multi-color composite glaze systems. Consequently, the applicability of the research findings is constrained to a specific scope.

Variability in Raw Materials and Formulation Control. Natural raw materials, such as quartz, feldspar, and kaolin, exhibit batch-to-batch compositional fluctuations, and controlling copper content precisely is challenging. These variations may introduce subtle but non-negligible effects on glaze coloration.

Instability in Firing Conditions. The control precision of variables such as temperature and atmosphere in gas kilns is limited. Minor fluctuations in redox atmospheres may lead to subtle differences in glaze color, affecting experimental reproducibility.

Human-Induced Errors in Operational Processes. Manual operations, such as glaze application thickness, sample placement, and mixing uniformity, are challenging to standardize. Although efforts were made to minimize errors through controlled variables, subjective operational factors may still influence the final coloration outcomes.

Limitations in Theoretical Model Interpretation. The coloration analysis relies on theories such as Rayleigh scattering, colloidal color, and phase separation, which are based on idealized conditions. These models struggle to capture the complex coloration phenomena in multiphase glaze systems fully.

Exclusion of Aesthetic Preferences and Market Response. This study focuses on physicochemical properties and does not address social dimensions such as consumer aesthetic preferences, artistic acceptance, or market evaluations, making it challenging to predict the cultural acceptance of the glazes in practical applications.

Need for Further Interdisciplinary Research Depth. Although this study attempts to integrate materials science with ceramic art, a unified interdisciplinary evaluation model has yet to be established. Future research could incorporate methodologies from design studies and cultural anthropology to deepen the exploration.

1.9 Outline of the Thesis

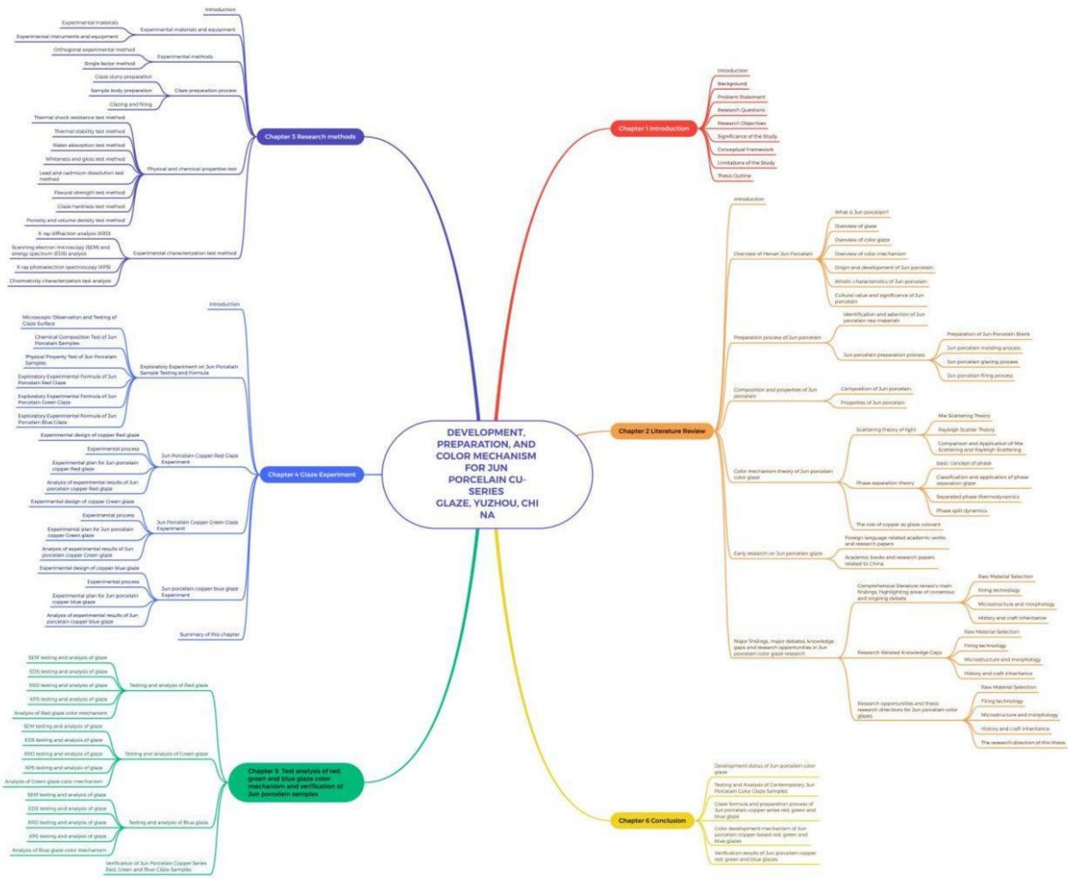

Plate 1.2 Thesis framework diagram.

Chapter 1. Introduces this study's content and summarizes the thesis's research background. Discuss the issues around knowledge and outline the research objectives (Plate 1.2). Author January 2022 - July 2022 to complete.

Chapter 2. This chapter mainly summarises the literature review of this study, introduces the research background of Jun porcelain, and analyses the development status, preparation process, and physicochemical properties of Jun porcelain Cu-series color glaze in past dynasties and the contemporary period. An overview of Jun porcelain color glaze, its origin and development, color theory, and previous research is summarized to provide background and support for this research topic. The research on the production process system of Jun porcelain in previous dynasties and the contemporary period includes the identification and selection of raw materials, the preparation of blank materials, the molding process, the glazing process, the firing process, and the exploration of critical technologies. This chapter summarizes the main findings, significant controversies, knowledge gaps, and research opportunities in studying Jun porcelain color glaze. Finally, the main research direction of this paper is proposed. Author August 2022 - December 2022 to complete.

Chapter 3. This chapter describes in detail the methods used for experiments, testing, and verification of Jun porcelain color glaze, including experiments for glaze development, tests for the analysis of the coloration mechanism, and experiments for verifying ceramic standards. The experimental methods include orthogonal experiments and single-factor experiments. The testing and characterization methods include chroma measurement, gloss measurement, glaze hardness testing, morphological observation (SEM), X-ray diffraction analysis (XRD), energy dispersive X-ray spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS), etc. The evaluation testing methods include the determination of thermal shock resistance of daily-use ceramic ware, the determination of water absorption rate, the determination of lead and cadmium leaching, the determination of porosity and bulk density, etc. Author January 2023 - April 2023 to complete.

Chapter 4. This chapter mainly introduces the experimental results of the formula composition and preparation process of the three colors of red, green, and blue glaze of Jun porcelain. In the exploratory experiments of Jun porcelain sample testing and formula exploration, the samples' chemical composition, hardness, chroma, and other properties were tested and analyzed to obtain the basic formula of the red, green, and blue glaze of Jun porcelain. In the experiments on the Cu-series red, green, and blue glazes of Jun porcelain, the effects of the formula composition, firing system, process conditions, etc., on the glaze effect were studied using single-factor and orthogonal experiments, and the optimal glaze formula and preparation process were finally determined. The experimental results were analyzed. Author April 2023 - December 2023 to complete.

Chapter 5. This chapter focuses on the test analysis and results of the coloration mechanism of the Cu-series red, green, and blue glazes of Jun porcelain, as well as the verification tests for the research results of the new formula for the color glaze. Through experimental testing and analysis, the coloring principles and influencing factors of different colored Cu-series Jun porcelain color glazes were explored. The coloring principles of different colored Cu-series Jun porcelain color glazes, as well as the state and content of copper under different firing conditions, were studied using experimental testing methods such as XRD, EDS, SEM, and XPS. The effects of process parameters such as firing temperature and firing atmosphere on the coloring effect of Cu-series Jun porcelain color glazes were studied, and the relationship between the coloration mechanism and process parameters was explored. The coloring effects and influencing factors of the red, green, and blue glazes of the Cu-series of Jun porcelain are compared, and the coloring rules are summarised. The performance of the red, green, and blue glazes of Jun porcelain is verified mainly through physical and chemical property testing. Finally, the research results are verified by institutions in the ceramic industry. The author obtained a report from the China National Ceramic Products Quality Inspection and Testing Center through testing. The new glaze was tested to see if it met national ceramic standards by testing Chinese daily-use ceramic standards. The test included testing properties such as chroma, porosity, density, flexural strength, glaze hardness, gloss, water absorption, etc., to ensure that the performance meets the national ceramic standards and performs excellently. Author January 2024 - June 2024 to complete.

Chapter 6. This chapter summarises the formula composition, preparation process, and coloration mechanism of the red, green, and blue glazes of the Cu-series of Jun porcelain. Then, the results of each chapter are summarised. Finally, this chapter further discusses the potential of Jun porcelain color glazes and proposes suggestions for further research related to this study. Author July 2024 - October 2024 to complete.

1.10 Summary

This chapter systematically elaborates on the research framework, questions, objectives, and background of Jun porcelain Cu-series color glaze, highlights its significant historical, cultural, and economic benefits, and also indicates the need for innovation so that we can meet the requirements of modern aesthetic and environmental protection, as well as the inheritance of traditional craftsmanship. The study focuses on Jun porcelain from the Cu-series color glaze (red, green, and blue). The aims include a new glaze formulation for an optimal combination of the problems of low yield, complex formulation, difficulty in firing, and lack of systematic research, as well as verifying the research results through industry standards. This chapter also presents the research approaches, including glaze testing (SEM, XRD, EDS, XPS) and performance evaluation. It details the possible limitations of the research, including the quality of raw material and firing conditions. The study not only plays a theoretical supplement role for Jun porcelain Cu-series color glaze coloring theory but also practically guides sustainable development and process innovation, thus promoting interdisciplinary integration between ceramics, material science, and design. This chapter provides a holistic and intellectual basis for future research and guidance for increasing the artistic and commercial value of Jun porcelain.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

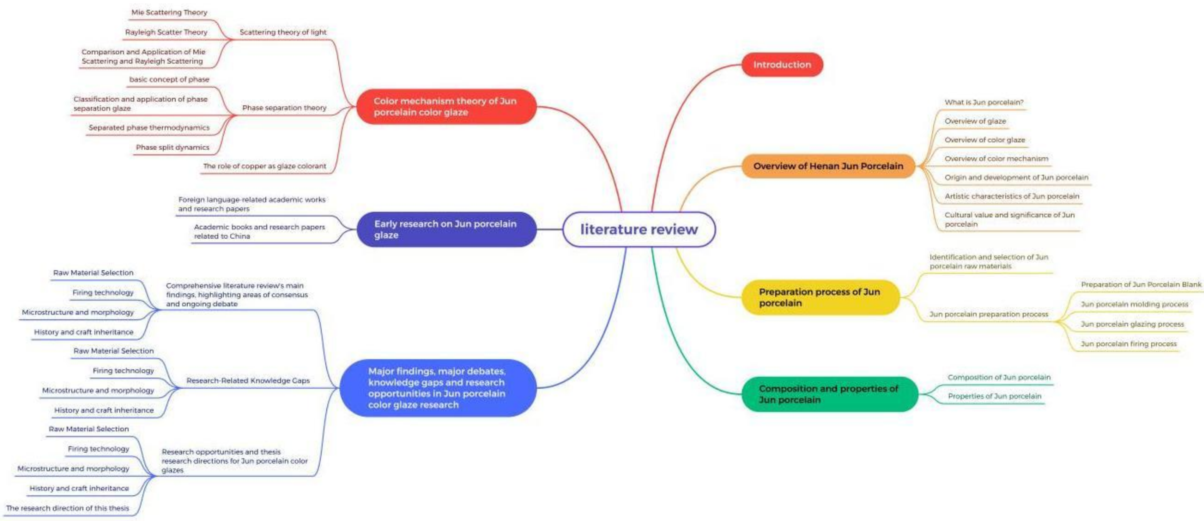

Plate 2.1 Framework diagram of the literature review.

This literature review (Plate 2.1) will systematically analyze the history, artistic characteristics, cultural significance, preparation process, and an overview of keywords related to Jun porcelain. The production process of Jun porcelain involves selecting various raw materials and a series of strict preparation processes. These processes include the preparation of the blanks, forming, glazing, and firing, which are vital steps. In order to fully understand the modern preparation process of Jun porcelain, the methods and technical requirements of each process will be systematically reviewed to reveal the uniqueness of Jun porcelain production. At the same time, the theory of color development of color glaze will be scientifically sorted out, and the research progress and future trends of Jun porcelain's Cu-series color glaze in the context of modern science and technology will be discussed. In exploring the theory of color development of Jun porcelain color glaze, the primary research will