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Teaching Factory through a Digital Ethnoscience-Based Pottery Firing Project: Effects on Electronics Engineering Students' Design Thinking

Habibi[1*], Moh Faisatullah[2], Noel Jimbai Balang[3]

[1] Department of Physics Education, State University of Surabaya, Surabaya, INDONESIA
[2] State Vocational High School 1 Pringgabaya, East Lombok, INDONESIA
[3] Universiti Kebangsaan Malaysia, Selangor, MALAYSIA

*Corresponding author e-mail: habibi_fis@unesa.ac.id

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Abstract

This study investigated the effects of Teaching Factory implemented through a digital ethnoscience-based pottery-firing project on Electronics Engineering students' design thinking and explored the processes underlying the observed changes. An explanatory sequential mixed-methods design, preceded by preliminary ethnoscience exploration, was employed with 39 Grade XI students assigned to experimental (n = 19) and control (n = 20) intact classes. Design thinking was assessed using a 30-item instrument covering six dimensions, while classroom observations, digital firing records, prototype-testing data, design-iteration logs, and interviews with students, a teacher, and pottery artisans provided explanatory evidence. The experimental group showed greater improvement than the control group in posttest, gain, and N-gain scores, with mean N-gain values of .666 and .399, respectively. After controlling for baseline differences, ANCOVA confirmed a significant group effect, $F(1, 36) = 186.696$, $p < .001$, partial $\eta^2 = .838$. Improvement occurred across all six design-thinking dimensions, with mindfulness of process and impacts on others showing the highest experimental N-gain (.721). Qualitative and process evidence indicated that authentic user needs, digital evidence, troubleshooting, collaborative specialization, iterative prototyping, and artisan feedback supported design-thinking development. The findings suggest that culturally grounded, digitally supported Teaching Factory experiences can strengthen design thinking while positioning digital measurements as complementary to, rather than replacements for, artisan experiential knowledge within authentic vocational engineering learning contexts and production practices.

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INTRODUCTION

Vocational education is increasingly expected to prepare students for workplaces shaped by digital transformation, automation, data-driven production, and rapidly changing technological practices. Consequently, vocational competence can no longer be defined only by the ability to perform standardized technical procedures. Students also need to interpret information, identify problems, collaborate across technical roles, make evidence-informed decisions, adapt to uncertainty, and develop workable solutions under authentic constraints. Digital technologies further intensify these demands because contemporary production systems increasingly combine physical components with sensors, microcontrollers, software, data acquisition, and digital interfaces (Haleem et al., 2022). For Electronics Engineering students, this shift means that learning should provide opportunities not merely to assemble circuits or reproduce predetermined procedures, but to understand user needs, diagnose technical problems, interpret system behavior, test alternative solutions, and improve products iteratively. Learning Factory and Teaching Factory (TEFA) approaches are particularly relevant to these expectations because they connect educational activities with production-oriented environments and authentic work processes, thereby reducing the separation between classroom knowledge and vocational practice (Reining & Kauffeld, 2022; Wahjusaputri & Bunyamin, 2022). More recent TEFA developments have also incorporated digital learning technologies, automation, and technologically mediated production, indicating that vocational learning environments are evolving alongside the transformation of contemporary industry (Maksum et al., 2025; Rifai et al., 2026; Wahjusaputri et al., 2024).

One competence that is particularly relevant to this form of vocational learning is design thinking. Design thinking enables learners to approach technical problems not as fixed tasks with single predetermined answers, but as situations requiring problem framing, consideration of users and contexts, generation of alternatives, experimentation, evaluation, and iterative improvement. In engineering and technology education, these processes are closely associated with creativity, problem solving, collaborative engagement, and the ability to move between conceptual understanding and material experimentation (Bathla et al., 2025; Deng et al., 2026; Lin et al., 2024). Design thinking is therefore highly compatible with Electronics Engineering, where students routinely encounter uncertain sensor behavior, programming errors, component limitations, safety requirements, calibration problems, and competing design alternatives. Within educational contexts, the design-thinking mindset has been represented through six dimensions: being comfortable with uncertainty and risks, human-centeredness, mindfulness of the process and impacts on others, collaboratively working with diversity, orientation toward learning by making and testing, and being confident and optimistic in using creativity (Ladachart et al., 2022). These dimensions extend beyond technical competence because they capture how students respond to uncertainty, interact with users, negotiate evidence, collaborate with peers, and learn from testing and failure. Meta-analytic and systematic-review evidence further indicates that design-thinking interventions can positively influence learning, creativity, problem solving, and engagement, although their effectiveness depends strongly on the instructional context and the quality of opportunities for authentic iteration (Bathla et al., 2025; Mayer & Schwemmle, 2025; Yu et al., 2024).

TEFA provides a potentially productive environment for cultivating such dispositions because its educational value lies in engaging students in authentic production activities rather than treating technical knowledge and its application as separate learning domains. Students working within TEFA are expected to respond to real or realistic needs, organize tasks and roles, develop products, evaluate performance, respond to constraints, and revise their work. Evidence from vocational and learning-factory research suggests that such environments can promote competence development when students are given meaningful responsibility for production processes and are required to connect technical decisions with product requirements and user expectations (Reining & Kauffeld, 2022; Wahjusaputri & Bunyamin, 2022). Project-based TEFA has also been associated with soft skills, entrepreneurial intention, troubleshooting ability, creative thinking, and other higher-order competencies (Hulyadi et al., 2025; Maksum et al., 2024). Direct evidence linking TEFA with design thinking was provided in a previous study involving Electronics Engineering students who developed an Automatic Plant Watering System. Students receiving TEFA demonstrated greater improvement in overall design thinking and across its six dimensions than students receiving expository instruction (Faisatullah et al., 2026). These findings indicate that user-oriented problem identification, prototyping, troubleshooting, testing, role-based collaboration, and product revision within TEFA can create conditions that support design-thinking development.

However, authentic vocational problems do not need to originate exclusively from formal industrial environments or contemporary technological products. Local production practices and traditional technologies also contain complex systems of experiential knowledge concerning materials, processes, environmental conditions, risk, quality, and decision making. This is particularly relevant in regions where community-based production remains economically and culturally significant. Recent TEFA research has begun to recognize regional potential as a legitimate source of authentic projects, especially where access to large industrial environments is limited (Syahril et al., 2024). Ethnoscience offers a complementary perspective by examining knowledge developed within communities through prolonged interaction with natural phenomena, materials, tools, and culturally embedded practices. When integrated carefully into education, such knowledge can provide more than a cultural illustration; it can become a contextual resource for investigating scientific concepts and technological problems. Studies integrating indigenous or local knowledge with STEM, inquiry, and project-based learning indicate that culturally grounded contexts can support scientific literacy, critical thinking, creativity, and meaningful engagement with scientific ideas (Babalola & Keku, 2024; Sumarni et al., 2022; Verawati & Wahyudi, 2024). The growing literature on Ethno-STEM and ethnoscience-based project learning similarly suggests that the educational value of local knowledge increases when students actively reconstruct relationships between community practices, scientific explanations, and technological applications rather than merely learning descriptions of cultural traditions (Nirmala et al., 2025; Rifa'i et al., 2025; Wahyu et al., 2025).

Traditional pottery firing provides a particularly suitable context for this integration. Pottery artisans develop practical knowledge through repeated experience with clay preparation, fuel, heat development, flame and smoke conditions, material transformation, firing duration, maturation, and cooling. Their decisions during firing are often based on observable and experiential indicators accumulated through apprenticeship and repeated practice. Scientifically, however, pottery firing is also a complex thermal process involving heat transfer, combustion, temperature-time relationships, firing atmosphere, mineralogical transformation, and thermal shock. Studies of traditional and archaeological ceramic production have demonstrated that firing conditions cannot be represented adequately by maximum temperature alone because heating rate, duration, atmosphere, spatial variation, and exposure time also influence ceramic transformation (Gliozzo, 2020; Livingstone Smith, 2001; Rasmussen et al., 2012). This relationship creates an educationally productive space in which artisan knowledge can be examined alongside scientifically measurable phenomena without reducing one knowledge system to the other. Traditional pottery has already been introduced as a culturally grounded context for science education and scientific literacy, indicating its potential to bridge cultural practices with formal scientific concepts (Putri et al., 2026). Nevertheless, the educational possibilities become substantially broader when students are required not only to understand the firing process but also to design technological systems that can document and represent aspects of that process.

Digital technology can provide this additional representational layer. The integration of ethnoscience and technology is increasingly recognized as an emerging educational direction because digital tools can enable culturally embedded phenomena to be documented, visualized, compared, and investigated in ways that support scientific and technological reasoning (Akmar et al., 2026; Yusof et al., 2024). Previous studies have integrated ethnoscientific contexts with e-learning platforms, virtual assistive technologies, mobile technologies, and project-based activities, producing positive outcomes in critical thinking, scientific reasoning, creative performance, and design thinking (Ardi et al., 2024; Prayogi et al., 2022; Wahyudi et al., 2023, 2025). Particularly relevant is evidence that digital technologies combined with local wisdom can create opportunities for students to engage in design-oriented problem solving and develop technological products grounded in contextual needs (Ardi et al., 2024; Kwangmuang et al., 2026). In pottery firing, a digital monitoring system based on thermocouples, microcontrollers, data logging, and digital visualization can transform otherwise transient thermal events into temperature-time profiles that can be synchronized with artisan observations and firing actions. Such digital evidence is not intended to establish that sensor measurements are superior to artisan knowledge. Instead, it creates another form of evidence that students can compare with experiential indicators, use to question assumptions, diagnose technical problems, and support design decisions. This relationship is especially relevant to vocational electronics education because students must simultaneously understand a community-based problem, reconstruct aspects of it scientifically, design sensing and monitoring technology, deal with technical failures, and evaluate whether the resulting system is meaningful and usable for its intended users.

Embedding these processes within TEFA can therefore extend authentic vocational learning in an important way. Students are no longer given only a predetermined electronic product to assemble; they must first understand a production practice and its users, identify information that can be meaningfully measured, translate scientific interpretation into technological requirements, construct a prototype, and test the system under actual firing conditions. Prototype testing can generate failures related to sensing accuracy, sensor placement, heat protection, communication stability, interface readability, or alarm configuration. These failures subsequently provide evidence for redesign rather than being treated merely as errors to be eliminated. Such processes are closely aligned with central characteristics of design thinking, particularly comfort with uncertainty, human-centeredness, learning through making and testing, collaboration, and creative confidence (Ladachart et al., 2022). Research connecting design thinking with project-based and engineering education similarly emphasizes iteration, reflective interaction, knowledge integration, prototyping, and evidence-informed refinement as mechanisms through which design competence develops (Hariharasakthisudhan et al., 2025; Mayer & Schwemmle, 2025; Zhao et al., 2025). A digital ethnoscience-based pottery firing project therefore provides more than an alternative project theme. It creates a learning environment in which cultural knowledge, scientific interpretation, digital evidence, engineering production, user feedback, and iterative design are interdependent components of the same vocational problem.

Study Novelty

Existing research provides substantial evidence for the individual components of this study, but these research strands remain largely separated. TEFA and Learning Factory studies have demonstrated the potential of production-oriented environments for developing vocational competencies and higher-order capabilities (Hulyadi et al., 2025; Reining & Kauffeld, 2022; Rifai et al., 2026). Design-thinking research has established the importance of human-centered problem framing, uncertainty, collaboration, prototyping, experimentation, and iterative improvement in engineering and technology education (Deng et al., 2026; Ladachart et al., 2022; Yu et al., 2024). Ethnoscience and Ethno-STEM studies have shown that community knowledge can provide culturally meaningful contexts for scientific inquiry and higher-order thinking (Babalola & Keku, 2024; Sumarni et al., 2022; Verawati & Wahyudi, 2024), while emerging research has begun to connect ethnoscience with digital and virtual technologies (Akmar et al., 2026; Prayogi et al., 2022; Wahyudi et al., 2025; Yusof et al., 2024). However, limited evidence is available on how these components operate together within vocational engineering education when traditional community knowledge becomes the starting point for a TEFA production problem and is subsequently connected with scientific reconstruction, digital measurement, prototype development, authentic testing, and iterative redesign.

The novelty of the present study therefore lies in establishing an ethnoscience-to-digital evidence pathway within Teaching Factory, rather than simply adding cultural content or digital devices to an existing project. Artisan knowledge provides the initial basis for identifying firing practices, empirical indicators, user needs, and production problems. These observations are subsequently reconstructed in relation to scientific concepts and measurable variables, which guide the development of a digital pottery-firing monitoring system. During authentic firing, students compare artisan observations with sensor-generated evidence, evaluate prototype performance, identify failures, revise technical components, retest the system, and obtain feedback from artisan users. In this arrangement, digital technology functions simultaneously as an engineering product and as an epistemic tool for examining relationships between experiential and scientific representations. The study also extends previous evidence that TEFA improved design thinking within an Automatic Plant Watering System project (Faisatullah et al., 2026). Rather than proposing a new TEFA model, it investigates whether and how the previously observed effects can be reproduced in a substantially different context where culturally embedded knowledge, digital evidence, authentic users, and iterative engineering design are integral to the production process. The use of quantitative design-thinking outcomes together with classroom observations, digital firing records, prototype-testing evidence, design-iteration logs, and perspectives from students, teachers, and artisans further allows the study to examine not only whether change occurs but also the processes through which it may be explained.

Research Objectives and Questions

Based on this gap, the study aimed to investigate the effects of Teaching Factory implemented through a digital ethnoscience-based pottery firing project on Electronics Engineering students' design thinking and to explain how ethnoscientific knowledge, digital evidence, prototyping, authentic testing, and design iteration contributed to the observed development. Design thinking was examined as an overall construct and through six dimensions: being comfortable with uncertainty and risks, human-centeredness, mindfulness of the process and impacts on others, collaboratively working with diversity, orientation toward learning by making and testing, and being confident and optimistic in using creativity (Ladachart et al., 2022). Consistent with the explanatory sequential mixed-methods orientation, quantitative evidence concerning changes in design thinking was subsequently connected with process, technological, prototype, and qualitative evidence to develop an integrated explanation of the findings.

Accordingly, the study addressed the following research questions:

1) What effects does Teaching Factory implemented through a digital ethnoscience-based pottery firing project have on Electronics Engineering students' overall design thinking and its six dimensions compared with expository instruction?
2) How do ethnoscientific knowledge, digital evidence, prototyping, authentic testing, and design iteration explain the development of students' design thinking during the Teaching Factory intervention?

METHODS

Research Design

This study employed an explanatory sequential mixed-methods design preceded by a preliminary ethnoscience exploration. The preliminary stage was conducted before the main experiment to document knowledge embedded in traditional pottery-firing practices and to reconstruct relevant artisan observations in relation to scientific concepts and digitally measurable variables. This preliminary work served as contextual preparation for the intervention and was therefore distinguished from the explanatory qualitative phase conducted after the quantitative analysis. The main study used a quasi-experimental pretest-posttest control-group design followed by qualitative inquiry to explain patterns identified in the quantitative findings (Creswell & Creswell, 2018; Fetters et al., 2013). The research procedure included preliminary ethnoscience exploration and reconstruction, pretesting, implementation of the experimental and control conditions, posttesting, quantitative analysis, purposive selection of qualitative participants, explanatory interviews, and mixed-methods integration.

Research Context and Participants

The study was conducted at a vocational secondary school in West Nusa Tenggara Province, Indonesia. The quantitative phase involved 39 Grade XI Electronics Engineering students from two intact classes, comprising 19 students in the experimental group and 20 students in the control group. Individual randomization was not conducted because the existing classroom organization was retained. Participants were 16–18 years old, with an overall mean age of 16.74 years (SD = 0.64). As summarized in Table 1, the groups also varied in gender composition and prior experience with electronics, microcontrollers, programming, and pottery-related practices. These characteristics were documented because differences in technical readiness and familiarity with pottery practices could influence students' participation in and engagement with the digital engineering project.

Table 1. Participant Characteristics by Study Group

Characteristic	Experimental (n = 19)	Control (n = 20)
Age, years, M ± SD	16.79 ± 0.63	16.70 ± 0.66
Gender, male/female, n	9/10	16/4
Electronics experience, basic/intermediate/advanced, n	2/13/4	7/12/1
Microcontroller experience, none/basic/intermediate, n	1/12/6	0/11/9
Programming experience, none/basic/intermediate, n	3/13/3	6/6/8
Pottery experience, none/limited exposure/observed firing, n	11/7/1	15/3/2

The preliminary ethnoscience exploration involved five pottery artisans with 12–31 years of experience (M = 20.40 years, SD = 7.57). Their production experience included cooking pots, water vessels, decorative pottery, household pottery, and traditional vessels. Following the quantitative phase, seven experimental-group students were purposively selected for explanatory interviews based on variation in their observed improvement. Two represented high N-gain profiles and five represented moderate profiles. One Electronics Engineering teacher and the five participating artisans were also interviewed to provide instructional and user perspectives.

Preliminary Ethnoscience Exploration and Reconstruction

Ethnoscience exploration was conducted through interviews with artisans and observation of traditional pottery-firing practices. Data collection focused on locally recognized firing stages, observable indicators, fuel management, actions taken during firing, reasons underlying firing decisions, cooling practices, and the transmission of knowledge through family and community apprenticeship. Local terminology and culturally specific interpretations were documented when relevant.

The documented knowledge was subsequently reconstructed by identifying relationships among artisan knowledge, observable firing indicators, relevant scientific concepts, digitally measurable variables, appropriate instruments, and potential classroom applications. Scientific measurement was treated as an additional form of evidence that could be compared with artisan experience rather than as a replacement for community knowledge.

Table 2. Framework for Ethnoscience Reconstruction and Digital Integration

Artisan or Observable Knowledge	Scientific Reconstruction	Digital Representation	Instrument	Classroom Operationalization
Changes in flame and heat conditions	Combustion and heat transfer	Temperature-time profile	K-type thermocouple	Compare artisan observations with thermal patterns
Firing duration and stage transition	Thermal exposure	Elapsed time and temperature	Data logger	Examine timing of firing stages
Changes in pottery-body appearance	Material transformation under heat	Temperature at observed transition	Thermocouple and documentation	Relate visible changes to thermal conditions
Fuel addition and heat response	Combustion dynamics	Rate of temperature change	Thermocouple and data logger	Examine thermal response following fuel adjustment
Combined firing indicators	Decision-making under uncertainty	Temperature, duration, and event records	Digital dashboard/event log	Compare multiple forms of evidence
Gradual cooling	Thermal shock	Cooling rate	Thermocouple and data logger	Examine cooling patterns and thermal risk

Digital Ethnoscience-Based Teaching Factory Intervention

The experimental group participated in six Teaching Factory meetings organized around the development of a digital pottery-firing monitoring system. The intervention combined identification of local knowledge and user needs, problem formulation, scientific reconstruction, digital investigation, engineering design, prototype production, testing, revision, artisan feedback, and reflection. This structure retained the authentic production and iterative characteristics of TEFA while extending the project through ethnoscientific knowledge and digitally generated evidence (Faisatullah et al., 2026; Hulyadi et al., 2025).

Table 3. Teaching Factory Intervention Procedure

Meeting	Main Stage	Core Activities	Main Output
1	Ethnoscience and User-Problem Orientation	Examine artisan practices, user needs, firing problems, and empirical indicators.	User-needs and problem map
2	Scientific Reconstruction and Digital Investigation	Relate empirical indicators to scientific concepts and measurable variables.	Ethnoscience-science-digital matrix
3	Engineering and Digital System Design	Determine sensing, data logging, display, sensor placement, protection, and group roles.	Initial system design
4	Prototype Production and Initial Testing	Assemble, program, integrate, calibrate, and test the system.	Prototype 1
5	Authentic Firing Test and Evidence-Based Revision	Compare artisan observations with digital records, identify technical failures, and determine revisions.	Revision decisions
6	Retesting, User Feedback, and Reflection	Retest prototypes, obtain artisan feedback, refine the system, and reflect on design decisions.	Improved prototype

Students worked in five groups (G01–G05). The monitoring system used a K-type thermocouple and interface connected to a microcontroller-based data-logging and digital-display system. Three firing trials were documented. Each trial included 25 synchronized observations collected at five-minute intervals over 120 minutes. The records included elapsed time, thermocouple temperature, ambient conditions, artisan-recognized firing stage, observable indicators, firing actions, sensor status, and event markers.

The control group received expository instruction consisting of teacher explanation, demonstration, and structured exercises. Learning objectives, instructional content, number of meetings, and duration were kept comparable with those of the experimental group. However, the control condition did not systematically include ethnoscience reconstruction, authentic digital investigation, artisan feedback, Teaching Factory production cycles, or iterative prototype redesign.

Research Instruments and Data Collection

Design thinking was the primary educational outcome and was assessed before and after instruction using a 30-item five-point Likert questionnaire based on the six-dimensional framework of Ladachart et al. (2022). The instrument retained the structure used in the preceding TEFA study to support contextual replication (Faisatullah et al., 2026). It measured being comfortable with uncertainty and risks (BC, 6 items), human-centeredness (HC, 4 items), mindfulness of process and impacts on others (MF, 3 items), collaboratively working with diversity (CW, 5 items), orientation toward learning by making and testing (OL, 4 items), and confidence and optimism in using creativity (CO, 8 items). Total scores ranged from 30 to 150, with higher scores representing stronger design-thinking dispositions.

Table 4. Research Instruments and Data Sources

Instrument or Data Source	Participant/Data Unit	Main Analytical Function
Design Thinking Questionnaire	39 students	Overall and dimension-level design-thinking outcomes
Artisan Interview and Observation Guide	5 artisans	Ethnoscience exploration and reconstruction
Treatment Fidelity Sheet	12 class meetings	Intervention implementation
Classroom Observation Sheet	Experimental and control groups	Learning-process evidence
Digital Sensor Log	3 firing trials	Thermal and event evidence
Prototype Testing Sheet	5 student groups	Technical and usability performance
Design Iteration Log	5 student groups	Evidence-based redesign processes
Semi-Structured Interviews	7 students, 1 teacher, 5 artisans	Explanatory qualitative evidence

Internal consistency was examined using Cronbach's alpha. The overall questionnaire demonstrated acceptable internal consistency at pretest (α = .768) and high internal consistency at posttest (α = .893). Corrected item-total correlations were additionally inspected as diagnostic evidence. Because the number of participants was limited relative to the multidimensional structure of the questionnaire, the total score was treated as the primary psychometric outcome, while dimension-level results were interpreted more cautiously.

Data Analysis

Quantitative analysis included descriptive statistics, raw gain, normalized gain (N-gain), assumption testing, within-group change, between-group comparison, effect-size estimation, and adjusted posttest analysis. N-gain was calculated by dividing the difference between posttest and pretest scores by the difference between the maximum possible score and the pretest score. Values were classified as high when N-gain was at least .70, moderate when it ranged from .30 to .69, and low when it was below .30 (Hake, 1998).

Normality and homogeneity of variance were examined using Shapiro-Wilk and Levene tests. Paired-samples *t* tests were used to evaluate pretest-posttest changes within each group, while independent-samples *t* tests examined between-group differences in pretest, posttest, gain, and N-gain scores. Cohen's *d* and *dz* were reported to indicate the magnitude of between-group and within-group differences, respectively (Lakens, 2013). Because pre-existing differences could occur in an intact-class quasi-experiment, ANCOVA was additionally performed using posttest design-thinking score as the dependent variable, instructional group as the fixed factor, and pretest score as the covariate. The homogeneity-of-regression-slopes assumption was examined before interpreting the adjusted analysis. Analyses were planned for both overall design thinking and the six constituent dimensions.

Qualitative interview data were analyzed thematically through transcript familiarization, initial coding, theme development, comparison across participants, refinement, and interpretation (Braun & Clarke, 2006). The six design-thinking dimensions informed interpretation but did not restrict the development of inductive themes related to technical constraints, usability, safety, cultural relevance, authenticity, and artisan acceptance. Mixed-methods integration involved connecting quantitative findings with participant selection and merging quantitative outcomes with classroom observations, digital firing records, prototype-testing results, design-iteration evidence, and student, teacher, and artisan perspectives during interpretation (Fetters et al., 2013).

Treatment Fidelity, Quality Assurance, and Research Ethics

Treatment fidelity was assessed by comparing planned intervention components with those implemented during each meeting. Classroom observation was analyzed separately because it focused on engagement, collaboration, evidence use, troubleshooting, user orientation, and teacher facilitation rather than procedural implementation alone. Technical quality assurance included sensor checking, prototype testing and retesting, and documentation of sensor status during the authentic firing trials.

The study followed ethical principles for educational research, including institutional permission, voluntary participation, confidentiality, participant coding, and consent for interviews and audiovisual documentation. Artisan consent additionally covered the documentation and academic representation of community-based pottery knowledge. Culturally specific interpretations were represented in relation to their artisan sources to minimize decontextualization or misrepresentation.

RESULTS AND DISCUSSION

Ethnoscientific Reconstruction and Intervention Implementation

The preliminary ethnoscience exploration involving five pottery artisans identified four recurring stages in traditional pottery firing: initial heating, heat build-up, maturation, and completion or cooling. Across these stages, artisan decisions were informed by combinations of flame and smoke conditions, perceived heat development, changes in the appearance of the pottery body, elapsed firing time, and responses following fuel adjustment. During initial heating, fuel was added gradually to control heat development. During heat build-up and maturation, changes in flame characteristics, pottery-body appearance, and perceived thermal conditions informed decisions regarding the continuation or reduction of fuel supply. Completion was identified through a combination of observable firing cues and elapsed time before fuel reduction and gradual cooling. The artisans described this knowledge as having been acquired predominantly through family and community apprenticeship.

The reconstruction process related these experiential indicators to scientific concepts concerning combustion, heat transfer, thermal exposure, material transformation, changes in heating rate, and thermal shock. The relevant phenomena were subsequently represented using measurable variables, including temperature-time profiles, elapsed time, rates of temperature change, event records, and cooling patterns. These reconstructed relationships provided the contextual basis for the digital investigation and prototype-development activities undertaken by the experimental group.

Treatment-fidelity records indicated that all planned components were implemented throughout the six experimental meetings, while the planned instructional components in the control group were also implemented consistently. To characterize differences in classroom processes between the two instructional conditions, observation scores were summarized across the six meetings. Table 5 presents the means and standard deviations for student engagement, collaboration, evidence use, troubleshooting, user orientation, teacher facilitation, and the number of technical issues documented per meeting.

Table 5. Classroom Process Indicators across the Six Meetings

Process Indicator	Experimental, M ± SD	Control, M ± SD
Student engagement	3.32 ± 0.32	2.55 ± 0.12
Collaboration	3.17 ± 0.38	1.97 ± 0.15
Evidence use	3.02 ± 0.46	1.52 ± 0.13
Troubleshooting	3.12 ± 0.40	1.62 ± 0.21
User orientation	3.02 ± 0.50	1.35 ± 0.12
Teacher facilitation	3.25 ± 0.05	2.98 ± 0.12
Technical issues per meeting	2.67 ± 1.51	0.83 ± 0.41

Note. Values represent means and standard deviations across six classroom meetings. Classroom-process indicators were scored on a 1–4 observation scale.

As shown in Table 5, the experimental group obtained higher mean scores for student engagement, collaboration, evidence use, troubleshooting, and user orientation. The largest descriptive differences occurred in evidence use, troubleshooting, and user orientation. Variation across meetings was also generally greater in the experimental condition, particularly for user orientation (SD = 0.50) and evidence use (SD = 0.46), reflecting changes in the prominence of these activities across successive phases of the intervention. Teacher facilitation remained relatively stable in both conditions, particularly in the experimental group (M = 3.25, SD = 0.05). Technical issues were more frequent and more variable across experimental meetings (M = 2.67, SD = 1.51) than across control meetings (M = 0.83, SD = 0.41), consistent with the greater technological complexity of prototyping, sensor integration, programming, and authentic firing activities. Within the experimental group, collaboration increased from 2.60 in the first meeting to 3.60 in the sixth meeting, evidence use from 2.50 to 3.60, troubleshooting from 2.60 to 3.70, and user orientation from 2.20 to 3.20.

Effects on Overall Design Thinking

The first research question examined whether students participating in the digital ethnoscience-based Teaching Factory demonstrated stronger improvement in design thinking than students receiving expository instruction. Descriptive and inferential statistics were therefore calculated for pretest, posttest, raw gain, and normalized gain scores. The results of the between-group comparisons are presented in Table 6.

Table 6. Overall Design-Thinking Outcomes by Study Group

Outcome	Experimental (n = 19), M ± SD	Control (n = 20), M ± SD	$t(37)$	p	Cohen's d
Pretest	96.32 ± 7.83	90.70 ± 5.80	2.553	.015	0.82
Posttest	131.63 ± 6.71	114.10 ± 6.49	8.295	< .001	2.66
Gain	35.32 ± 2.94	23.40 ± 2.52	13.596	< .001	4.36
N-gain	.666 ± .074	.399 ± .060	12.412	< .001	3.98

Table 6 shows that both groups improved, but the magnitude of change was substantially larger in the experimental group. Its mean score increased from 96.32 to 131.63, resulting in a mean raw gain of 35.32 and a mean N-gain of .666. The control group increased from 90.70 to 114.10, yielding a mean gain of 23.40 and an N-gain of .399. The differences in posttest, gain, and N-gain scores were statistically significant, with very large effect sizes.

The distribution of N-gain categories supported this pattern. Eight students in the experimental group (42.1%) reached the high category and 11 students (57.9%) reached the moderate category, while none were classified as low. In the control group, 19 students (95.0%) were classified as moderate and one student (5.0%) as low, whereas no student reached the high category. Within-group analyses also showed significant improvement in both conditions. The experimental group demonstrated a significant pretest-posttest increase, $t(18) = 52.272$, $p < .001$, $dz = 11.99$, while the control group also improved significantly, $t(19) = 41.502$, $p < .001$, $dz = 9.28$.

Assumption testing indicated that pretest, gain, and N-gain distributions did not significantly depart from normality in either group. The experimental-group posttest showed a slight departure from normality, $W = .898$, $p = .045$, whereas the control-group posttest remained normally distributed, $W = .951$, $p = .379$. Levene tests showed homogeneous variances for pretest, posttest, gain, and N-gain, with all p values greater than .35.

A significant baseline difference was detected because the experimental group obtained a higher initial score than the control group, $t(37) = 2.553$, $p = .015$. Consequently, ANCOVA was used to obtain an adjusted comparison of posttest scores. The pretest-by-group interaction was not significant, $F(1, 35) = 3.369$, $p = .075$, indicating that the homogeneity-of-regression-slopes assumption was satisfied. After controlling for pretest performance, instructional group remained significantly associated with posttest design thinking, $F(1, 36) = 186.696$, $p < .001$, partial $\eta^2 = .838$. The adjusted mean was 129.09 for the experimental group and 116.51 for the control group, corresponding to an adjusted difference of 12.58 points, 95% CI [10.71, 14.44]. The model residuals showed no significant departure from normality, $W = .977$, $p = .605$. Thus, the experimental group maintained a clear posttest advantage after the initial difference between groups was statistically controlled.

Digital Firing Evidence and Prototype Iteration

The digital component of the intervention generated process evidence documenting how artisan-recognized firing events corresponded with measurable thermal conditions.

Three authentic firing trials were conducted, each consisting of 25 measurements recorded at five-minute intervals over 120 minutes. In total, 75 synchronized observations were obtained. Four recurrent artisan-recognized firing events were documented in each trial. Table 7 presents the temperatures associated with these events across the three firing trials.

Table 7. Digital Temperature Records at Artisan-Recognized Firing Events

Firing Event	Time (min)	T01 (°C)	T02 (°C)	T03 (°C)	Mean ± SD (°C)
Smoke/flame transition	20	189.7	217.1	212.2	206.33 ± 14.61
Flame/heat indicator	45	379.0	379.6	405.8	388.13 ± 15.30
Body/flame maturation indicator	80	618.8	610.9	640.6	623.43 ± 15.38
Completion cue	110	794.2	811.7	822.8	809.57 ± 14.42
Peak recorded temperature	120	853.3	875.1	886.8	871.73 ± 17.00

As shown in Table 7, the artisan-recognized events occurred within relatively consistent thermal ranges across the three trials. The smoke or flame transition was associated with a mean temperature of 206.33°C, the flame or heat indicator with 388.13°C, the maturation indicator with 623.43°C, and the completion cue with 809.57°C. Peak temperatures ranged from 853.3°C to 886.8°C. The variation across trials indicates that the artisan-recognized events were not associated with a single fixed temperature but occurred within comparable thermal conditions across repeated firing processes.

To provide a continuous representation of the firing process rather than isolated temperature points, all measurements were plotted against elapsed firing time. Figure 1 displays the complete temperature-time profiles for the three firing trials together with the four artisan-recognized event markers.

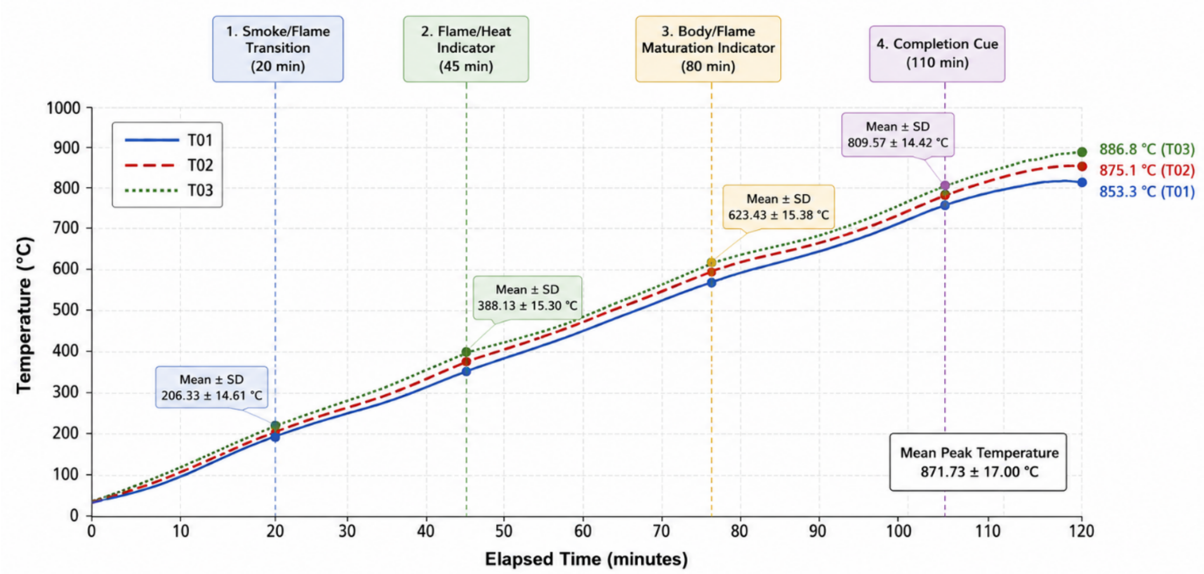

Figure 1. Temperature-time profiles across three pottery-firing trials with artisan-recognized firing event markers

Figure 1 shows that the three firing trials followed broadly comparable heating trajectories despite differences in absolute temperature. Temperatures increased progressively throughout the 120-minute period, and the artisan-recognized firing events occurred at similar temporal positions across the three trials. The graphical alignment of experiential event markers with digitally recorded temperatures provided a common reference for comparing artisan observations with sensor-generated evidence during prototype evaluation and design revision.

The performance of the monitoring system also changed substantially between the first and second prototype cycles. Across the five student groups, mean sensor mean absolute error decreased from 15.44°C (SD = 1.30) to 7.54°C (SD = 2.04), representing a reduction of approximately 51.2%. Mean data-transmission success increased from 87.76% to 96.70%, dashboard latency decreased from 4.29 seconds to 2.19 seconds, alarm-response time decreased from 3.45 seconds to 1.85 seconds, and mean usability ratings increased from 3.40 (SD = 0.37) to 4.08 (SD = 0.36).

All five first prototypes required revision. Following the second testing cycle, G03 and G05 met all predefined acceptance criteria, while G01, G02, and G04 still required refinement in at least one technical or usability criterion. The design-iteration records showed that these revisions were linked directly to testing evidence. G01 improved cable insulation and sensor positioning in response to heat exposure and temperature instability. G02 simplified the dashboard and enlarged the principal temperature display after readability limitations were identified. G03 introduced local data backup and repositioned the communication module to improve transmission stability. G04 revised alarm thresholds and delays following false-alarm events, whereas G05 modified enclosure placement and heat shielding in response to excessive enclosure temperature. The prototype data therefore demonstrated measurable technical improvement while also documenting unresolved limitations after the second iteration.

Changes across Design-Thinking Dimensions

To determine whether the overall improvement was distributed across different components of design thinking, N-gain was calculated separately for the six dimensions. Table 8 summarizes the mean N-gain scores, between-group tests, and effect sizes for being comfortable with uncertainty and risks (BC), human-centeredness (HC), mindfulness of process and impacts on others (MF), collaboratively working with diversity (CW), orientation toward learning by making and testing (OL), and confidence and optimism in using creativity (CO).

Table 8. N-Gain Differences across Design-Thinking Dimensions

Dimension	Experimental, M ± SD	Control, M ± SD	$t(37)$	p	Cohen's d
BC	.676 ± .156	.350 ± .138	6.919	< .001	2.22
HC	.685 ± .143	.440 ± .134	5.504	< .001	1.76
MF	.721 ± .138	.457 ± .189	4.971	< .001	1.59
CW	.677 ± .173	.404 ± .097	6.108	< .001	1.96
OL	.672 ± .152	.388 ± .131	6.240	< .001	2.00
CO	.645 ± .094	.409 ± .118	6.878	< .001	2.20

Table 8 shows that the experimental group achieved higher improvement across all six design-thinking dimensions, with every between-group difference reaching statistical significance. MF produced the highest mean N-gain in the experimental group (.721), followed by HC (.685), CW (.677), BC (.676), OL (.672), and CO (.645). Although CO showed the lowest mean improvement within the experimental condition, its value remained substantially higher than the corresponding control-group score. To make both the magnitude of the differences and their categorical positions more visible, the mean N-gain scores were plotted together with the thresholds defining low, moderate, and high improvement. Figure 2 presents the experimental and control means for the six dimensions.

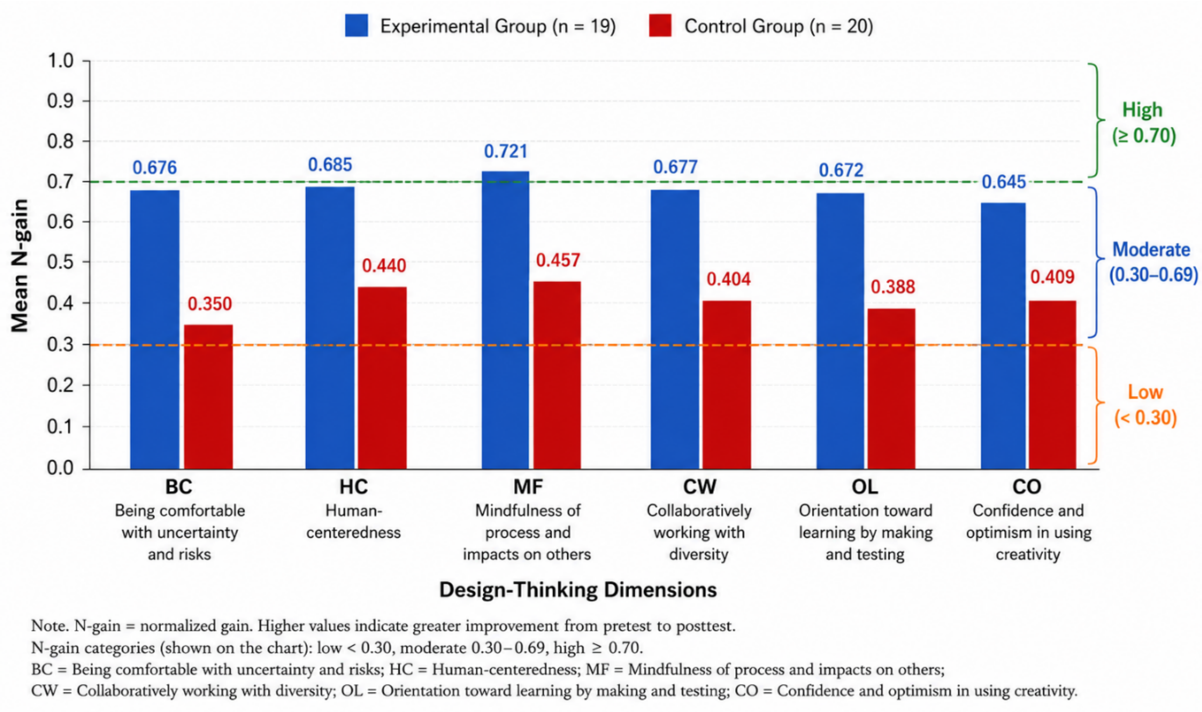

Figure 2. Mean N-gain across the six dimensions of design thinking in the experimental and control groups

As illustrated in Figure 2, the experimental group consistently exceeded the control group across every dimension. MF was the only experimental-group dimension to exceed the .70 threshold and therefore reached the high N-gain category. The remaining experimental dimensions were located near the upper range of the moderate category. All control-group means remained within the moderate category and were concentrated between .350 and .457. The graphical pattern therefore indicates that the intervention was associated with broadly distributed improvement rather than an increase restricted to one component of design thinking.

Qualitative Findings on the Development of Design Thinking

The explanatory qualitative phase investigated how students experienced the processes accompanying the quantitative improvement. Seven students from the experimental group, one Electronics Engineering teacher, and five pottery artisans participated in the interviews. Analysis identified interconnected themes concerning user-oriented problem framing, evidence-based troubleshooting, iterative making and testing, collaborative specialization, attention to safety and process consequences, creative confidence, and the role of digital information in relation to artisan experience. These themes and their relationships with the six design-thinking dimensions are summarized in Table 9.

Table 9. Qualitative Themes Explaining Students' Design-Thinking Development

Theme	Main Qualitative Evidence	Data Sources	Related Dimension(s)
Human-centered problem framing	The engineering task was increasingly considered in relation to artisan needs, readability, practicality, and safe operation.	Students, teacher, artisans	HC, MF
Evidence-based troubleshooting	Temperature records and prototype-testing evidence informed decisions concerning sensing, communication, and system configuration.	Students, teacher	BC, OL
Learning through making and testing	Prototype failure, calibration, retesting, and redesign were repeatedly identified as important learning experiences.	Students, teacher	OL, BC
Collaborative technical specialization	Work was distributed across hardware, programming, testing, documentation, and communication roles.	Students, teacher	CW
Attention to safety and process consequences	Sensor positioning, heat exposure, enclosure protection, and firing conditions influenced technical decisions.	Students, teacher, artisans	MF, HC
Developing creative confidence	Students generated and implemented design modifications, although familiar or technically safer alternatives remained common under constraints.	Students, teacher	CO
Digital evidence as complementary knowledge	Digital records were regarded as useful for documenting and discussing firing conditions without replacing artisan experience.	Artisans	HC, MF

As summarized in Table 9, the qualitative findings were not limited to perceptions of technical performance. Instead, they linked technical activities with user needs, uncertainty, collaboration, iteration, safety, and creative decision making. The convergence of student, teacher, and artisan perspectives also allowed the learning process to be examined from participant, instructional, and user viewpoints.

Students consistently described the pottery-firing project as making the engineering task more closely connected to identifiable users and practical needs. Rather than focusing only on whether the monitoring system functioned technically, they increasingly considered how the system would be used during actual firing. Their accounts emphasized display readability, safe installation, sensor placement, and practical usefulness. The teacher reported a similar pattern, noting that students progressively incorporated user requirements into technical decisions. Artisan interviews reinforced this perspective through repeated emphasis on clear temperature information, safe installation, and minimal interference with established firing practices.

This user-oriented perspective was closely associated with the way students responded to technical problems. Students reported using sensor outputs and testing evidence when evaluating temperature instability, communication interruptions, interface limitations, and alarm behavior. These problems became sources of information for subsequent design decisions rather than merely implementation failures. The teacher similarly observed that students increasingly referred to recorded data when justifying revisions instead of relying exclusively on unsystematic trial and error. This qualitative pattern was consistent with the prototype-testing and design-iteration records.

Prototyping, testing, failure, and revision also emerged as central components of the students' learning experiences. All seven interviewed students described direct involvement in making and testing the monitoring system as important for understanding the relationship between design decisions and actual system performance. The first testing cycle exposed limitations that were not always apparent during initial design, while the second cycle required students to reconsider previous decisions and refine their solutions. The teacher likewise identified repeated testing and revision as an important element of the intervention. These accounts corresponded with the documented improvements in sensing accuracy, transmission success, dashboard latency, alarm-response time, usability, and hardware configuration.

As the project progressed, collaboration became more technically differentiated. Students increasingly divided responsibilities involving hardware assembly, programming, sensor testing, documentation, and communication with users. Attention to process consequences also became more evident in decisions concerning cable exposure, enclosure temperature, sensor location, and potential interference with firing activities. Creative confidence developed alongside these experiences, although it appeared more constrained than several other aspects of design thinking. Students proposed and implemented alternative technical solutions, but the teacher noted that limited project time and differences in technical readiness sometimes encouraged the selection of familiar or comparatively safe solutions.

The artisan interviews provided an additional perspective on the digital system. Across the five artisans, four recurring needs were identified: clear temperature and trend information, evidence that could be discussed with learners, safe and durable installation, and support for the transmission of firing knowledge. Their mean perceived usefulness rating was 4.0 on a five-point scale. The artisans consistently characterized sensor-generated information as an additional source of evidence rather than a replacement for experiential judgment. Their feedback also contributed to revisions involving display design, cable protection, system placement, local data storage, and documentation of firing events. Taken together, the qualitative findings indicate that the intervention involved not only technological production but also negotiation among user needs, experiential knowledge, digital evidence, technical constraints, and iterative engineering decisions.

Mixed-Methods Integration

The final stage of analysis integrated quantitative outcomes with classroom observations, prototype-testing records, digital firing evidence, design-iteration logs, and interview findings. The purpose was to determine whether the mechanisms emerging from the process and qualitative data corresponded with the observed pattern of improvement across the six design-thinking dimensions. Table 10 presents the resulting joint display.

Table 10. Joint Display of Quantitative, Process, and Qualitative Findings

Quantitative Pattern	Process and Technical Evidence	Qualitative Explanation	Integrated Finding
MF showed the highest experimental N-gain (.721)	Safety, heat exposure, enclosure protection, and firing-process consequences were repeatedly documented	Students, teacher, and artisans emphasized consequences of technical decisions for users and process.	Authentic firing required attention to technical performance and consequences of design decisions.
HC N-gain was .685	User orientation increased from 2.20 to 3.20	Artisan needs, readability, safety, and practicality were repeatedly identified.	Interaction with authentic users accompanied stronger attention to human-centered requirements.
CW N-gain was .677	Collaboration increased from 2.60 to 3.60	Technical work became differentiated across hardware, programming, testing, documentation, and communication.	Project complexity was accompanied by increasingly interdependent collaboration.
BC N-gain was .676	Troubleshooting increased from 2.60 to 3.70 and repeated technical problems occurred	Students described using evidence to reconsider initial technical decisions.	Technical uncertainty became a recurring context for evidence-informed problem solving.
OL N-gain was .672	Evidence use increased from 2.50 to 3.60 and all groups completed testing and redesign	Students emphasized prototype failure, retesting, and revision as learning experiences.	Repeated making, testing, and redesign corresponded with stronger learning-by-testing orientation.
CO showed the lowest experimental N-gain (.645)	Multiple design alternatives were implemented, although not all final prototypes met every criterion	Teacher data indicated time and technical-readiness constraints.	Creative confidence improved but remained comparatively more constrained.

Table 10 shows a coherent correspondence across the quantitative, observational, technical, and qualitative evidence. The strongest improvement, observed for MF, coincided with repeated attention to safety, thermal exposure, enclosure protection, and the consequences of engineering decisions during authentic firing. The improvement in HC occurred alongside increasing user orientation and repeated consideration of artisan needs. BC and OL corresponded with troubleshooting, digital evidence use, prototype failure, retesting, and redesign, while CW was reflected in increasingly specialized and interdependent group roles. CO improved substantially relative to the control condition but remained the lowest experimental N-gain, consistent with teacher observations that time limitations and differences in technical readiness sometimes constrained students' willingness to pursue less familiar solutions.

Overall, the integrated evidence indicated that the experimental group's stronger design-thinking outcomes occurred alongside observable changes in classroom participation, increasing use of digital evidence, repeated encounters with authentic technical problems, prototype revision, and interaction with artisan users. The qualitative findings clarified how students experienced these processes, while teacher and artisan perspectives provided complementary evidence concerning implementation, usability, safety, technological constraints, and the relationship between digitally recorded firing information and experiential knowledge.

Discussion

The findings indicate that Teaching Factory implemented through a digital ethnoscience-based pottery-firing project was associated with substantially stronger development of students' design thinking than expository instruction. Although both groups improved from pretest to posttest, the experimental group obtained markedly higher posttest, raw-gain, and N-gain scores. The experimental mean N-gain of .666 was considerably higher than the control mean of .399, and the between-group differences were accompanied by very large effect sizes. Importantly, the experimental group also entered the study with a significantly higher pretest score, which meant that the posttest difference could not be interpreted adequately from an unadjusted comparison alone. After baseline design-thinking performance was controlled through ANCOVA, the instructional-group effect remained statistically significant, with adjusted posttest means of 129.09 for the experimental group and 116.51 for the control group. This adjusted result strengthens the interpretation that the experimental advantage was not attributable solely to the higher initial score. However, because the study involved intact classes rather than individual random assignment, the findings should be interpreted as strong quasi-experimental evidence rather than as evidence of causality equivalent to that obtained from a randomized experiment.

The overall pattern extends earlier evidence that Teaching Factory can promote design-thinking development among Electronics Engineering students. In the preceding study, TEFA implemented through an Automatic Plant Watering System project produced greater improvement in overall design thinking and across its six dimensions than expository instruction (Faisatullah et al., 2026). The present study reproduces that general direction of effect in a substantially different project context. Instead of beginning with a conventional technological product whose engineering purpose was already apparent, students were required to understand a community-based production practice, identify artisan needs, reconstruct aspects of experiential firing knowledge in relation to scientific concepts, determine which phenomena could be represented digitally, and develop and refine a monitoring system under authentic firing conditions. The recurrence of a strong TEFA advantage across these different project contexts suggests that the educational value of TEFA may depend less on a particular product and more on the quality of the authentic production cycle in which students participate. This interpretation is consistent with studies emphasizing that Teaching Factory and Learning Factory environments become educationally meaningful when students engage directly in realistic production, problem solving, testing, decision making, and reflection rather than merely observing industrial procedures (Hulyadi et al., 2025; Reining & Kauffeld, 2022; Wahjusaputri & Bunyamin, 2022).

The classroom-process evidence helps explain this quantitative advantage. Compared with the control group, students in the experimental condition showed higher engagement, collaboration, evidence use, troubleshooting, and user orientation. Several of these indicators also became more prominent across the six meetings, particularly evidence use, troubleshooting, collaboration, and attention to users. These patterns are compatible with the characteristics commonly associated with design-thinking learning environments, in which learners are expected to frame problems from user perspectives, deal with ambiguity, combine multiple forms of evidence, and repeatedly test and revise proposed solutions (Deng et al., 2026; Mayer & Schwemmle, 2025; Yu et al., 2024). The higher frequency of technical problems in the experimental group should therefore not be interpreted simply as lower instructional efficiency. Many of the documented problems emerged precisely because students were building, programming, calibrating, installing, and testing a functioning system under authentic firing conditions. Under such circumstances, technical difficulty became part of the learning process because students had to identify the problem, examine available evidence, justify a modification, and determine whether the revised solution performed more effectively.

The dimension-level results provide a more differentiated account of how this learning occurred. Mindfulness of process and impacts on others produced the highest experimental N-gain at .721, followed by human-centeredness at .685. This pattern is especially meaningful given the nature of the project. Students were required not only to make the digital system function but also to consider whether sensor placement was safe, whether cables and enclosures could tolerate the thermal environment, whether the interface was readable during firing, and whether the monitoring system interfered with established artisan practices. The qualitative findings showed the same orientation through repeated attention to practicality, process consequences, safety, and artisan requirements. Such experiences provide plausible conditions for strengthening design thinking as a form of responsible technical judgment rather than merely as the generation of products. This interpretation is consistent with the human-centered orientation of design thinking, in which technical solutions are evaluated not only in terms of functionality but also in relation to users, context, usability, consequences, and the wider process in which the product will operate (Ladachart et al., 2022; Mayer & Schwemmle, 2025).

The improvement in human-centeredness was closely related to the ethnoscience component of the intervention. The artisans were not positioned merely as sources of cultural information introduced to make the project more locally attractive. Instead, they functioned simultaneously as knowledge holders, users, and evaluators whose production practices shaped the engineering problem itself. Students therefore had to recognize that the digital monitoring system was being introduced into an existing practice with established ways of interpreting heat, flame, smoke, timing, fuel behavior, and material transformation. This differs from instructional approaches in which local knowledge is used only as an introductory example before formal scientific knowledge becomes the dominant explanatory framework. Ethnoscience research increasingly emphasizes that community knowledge can become a meaningful basis for scientific inquiry when learners actively examine relationships among experiential observations, scientific concepts, and technological applications (Babalola & Keku, 2024; Sumarni et al., 2022; Verawati & Wahyudi, 2024; Yusof et al., 2024). In the present study, this relationship became operational because students had to translate observable firing phenomena into measurable variables while continuing to account for artisan interpretation and practical requirements.

The findings for being comfortable with uncertainty and risks and orientation toward learning by making and testing further clarify the mechanism of improvement. Experimental N-gain reached .676 for BC and .672 for OL, both substantially higher than the corresponding control-group values. These results were supported by the prototype records, which showed that all five student groups had to revise their first prototypes. Problems involving thermocouple heat exposure, unstable readings, communication interruptions, interface readability, false alarms, and enclosure overheating provided concrete reasons for redesign. More importantly, these problems generated evidence that students could use to evaluate whether their modifications were effective. Mean sensor error decreased from 15.44°C to 7.54°C, data-transmission success increased from 87.76% to 96.70%, dashboard latency and alarm-response time declined, and usability increased from 3.40 to 4.08. The learning process therefore involved more than constructing the same product twice. Students experienced technical failure, interpreted likely causes, altered elements of the design, and evaluated the consequences of their decisions during subsequent testing. Such iterative cycles are central to design thinking and engineering learning because understanding develops through making, testing, reflecting, and refining rather than through planning alone (Hariharasakthisudhan et al., 2025; Zhao et al., 2025).

The development of collaboratively working with diversity, with an experimental N-gain of .677, was similarly supported by the classroom and interview evidence. As the project became more technically demanding, student roles became increasingly differentiated across hardware assembly, programming, sensor testing, documentation, and communication with users. This differentiation created interdependence among group members because no individual technical component could guarantee that the prototype would function adequately during authentic firing. Accurate sensing without a readable interface, reliable communication without safe installation, or a technically functional system that disrupted artisan practice would still constitute an incomplete solution. The project therefore required students to coordinate different forms of technical expertise and user-related information within a single product-development process. This finding is consistent with research emphasizing that design thinking in engineering contexts is inherently collaborative because complex problems require learners to integrate different perspectives, knowledge bases, and technical responsibilities (Deng et al., 2026; Liu & Leong, 2022).

Confidence and optimism in using creativity also improved substantially relative to the control condition, although it remained the lowest experimental N-gain at .645. The qualitative findings provide a useful explanation for this relative position. Students generated and implemented alternative solutions involving sensor arrangements, interface configuration, communication systems, alarm logic, insulation, and thermal protection. At the same time, the teacher reported that limited project time and differences in technical readiness sometimes encouraged students to select comparatively familiar or safer technical alternatives. This finding is important because it prevents an overly uniform interpretation of design-thinking improvement. Open-ended and authentic engineering projects may create opportunities for creative decision making, but creative confidence also depends on whether students possess sufficient technical knowledge, time, resources, and opportunities to explore multiple alternatives. Previous studies similarly indicate that creative confidence does not emerge automatically from exposure to open-ended tasks; learners require repeated opportunities to generate, test, reject, and reformulate ideas in environments where unsuccessful attempts are treated as legitimate components of learning (Mayer & Schwemmle, 2025; Yu et al., 2024). The comparatively lower CO score therefore suggests that this dimension may require longer exposure or additional design cycles before students become more willing to pursue unfamiliar solutions.

The digital firing data add another explanatory layer to these findings. Across the three authentic trials, artisan-recognized firing events occurred under broadly comparable thermal conditions, although not at identical temperatures. The smoke or flame transition was associated with a mean temperature of approximately 206°C, the subsequent flame or heat indicator with approximately 388°C, the maturation-related indicator with approximately 623°C, and the completion cue with approximately 810°C. Peak recorded temperatures ranged from 853.3°C to 886.8°C. The significance of these findings lies not in establishing exact scientific temperatures for traditional artisan judgments, but in showing how experiential observations could be documented alongside measurable thermal conditions. Pottery firing is influenced by multiple interacting factors, including temperature, duration, heating rate, atmosphere, spatial variation, and thermal history, making a simple one-to-one correspondence between visual indicators and fixed temperatures inappropriate (Gliozzo, 2020; Livingstone Smith, 2001; Rasmussen et al., 2012). The recorded profiles therefore served as additional representations that allowed students to compare repeated firing events and examine how experiential indicators occurred within measurable thermal patterns.

This complementary relationship between digital evidence and experiential knowledge represents one of the most important contributions of the study. The artisan interviews consistently indicated that sensor-generated information was useful for documenting and discussing firing conditions but should not replace experiential judgment. This position avoids framing ethnoscientific knowledge as an incomplete form of knowledge waiting to be corrected through modern instrumentation. Instead, digital technology operated as an additional evidentiary layer through which learners could examine relationships between observable events and measurable variables. This interpretation is consistent with research highlighting the potential of digital tools to support the documentation, visualization, and investigation of culturally embedded knowledge while maintaining attention to its original social and practical context (Akmar et al., 2026; Prayogi et al., 2022; Wahyudi et al., 2025; Yusof et al., 2024). In this study, the digital system therefore fulfilled two educational functions. It was an engineering product that students were required to design, test, and improve, while also serving as an epistemic tool through which they could investigate a culturally situated production process.

The mixed-methods findings strengthen this interpretation because the quantitative, observational, technical, and qualitative evidence converged rather than functioning as isolated data streams. The highest improvement in mindfulness corresponded with repeated attention to safety, thermal exposure, installation, and consequences for the firing process. Human-centeredness was accompanied by greater user orientation and repeated consideration of artisan requirements. Comfort with uncertainty and learning through making and testing were reflected in technical failure, evidence use, troubleshooting, prototype revision, and retesting. Collaborative working was reflected in increasingly differentiated and interdependent technical roles, while the comparatively lower improvement in creative confidence corresponded with reported limitations related to time and technical readiness. Such convergence provides a more informative explanation than posttest differences alone because changes in students' self-reported design-thinking dispositions were accompanied by observable activities and documented engineering decisions. This also illustrates the value of explanatory mixed-methods designs when the research question concerns not only whether an intervention is associated with improvement, but also what processes may help explain the observed outcome (Fetters et al., 2013).

The findings also clarify the novelty of the present study within the broader literature on Teaching Factory, ethnoscience, and design thinking. The contribution does not lie in claiming the development of a separate Digital Ethnoscience Teaching Factory model. Teaching Factory remained the principal pedagogical framework. What changed was the structure and epistemic character of the authentic project through which TEFA was implemented. Community knowledge informed problem identification and user requirements, scientific reconstruction supported interpretation of relevant phenomena, digital technology provided measurable evidence, and authentic testing generated problems that required iterative engineering decisions. This integration distinguishes the study from TEFA projects focused primarily on formal industrial production and from ethnoscience studies in which cultural knowledge functions predominantly as instructional content. It also extends emerging research that combines local wisdom, digital technology, and design thinking by embedding these elements within a vocational production cycle involving real users, actual production constraints, and a functioning technical prototype (Ardi et al., 2024; Kwangmuang et al., 2026).

From a vocational-education perspective, the findings suggest that authentic Teaching Factory projects may be developed from community-based technologies as well as from formal industrial settings. This possibility is particularly relevant for vocational institutions located in regions where local production practices are economically or culturally significant but direct access to advanced industrial partners may be limited. Regional-potential Teaching Factory approaches have already been proposed as a means of making production-oriented vocational learning more contextually accessible (Syahril et al., 2024). The present study extends this proposition by showing that local production practices can support technologically demanding learning when students are required to engage with sensing, programming, data logging, visualization, prototype testing, and evidence-based redesign. Authenticity in Teaching Factory learning therefore need not depend exclusively on reproducing a conventional factory environment. It can also be created through engagement with real users, authentic production constraints, meaningful community knowledge, and technical problems whose consequences can be directly observed and evaluated.

Taken together, the findings support a view of design-thinking development as emerging from the interaction of authentic users, uncertainty, culturally grounded knowledge, digital evidence, collaborative production, and iterative testing. The experimental advantage was not confined to the overall design-thinking score but appeared across all six dimensions, while process and qualitative evidence clarified how different elements of the intervention were associated with these changes. The study therefore extends previous evidence for Teaching Factory in Electronics Engineering by showing that its potential for supporting design thinking can also be realized when students must negotiate experiential community knowledge and digitally generated evidence within the same engineering problem. At the same time, the significant baseline difference, the small intact-class sample, the uneven reliability of several dimension-level subscales, and the incomplete technical success of some second prototypes require caution when interpreting the magnitude and transferability of the effects. Accordingly, the findings are best understood as strong context-specific evidence for the educational potential of digitally supported, culturally grounded

Teaching Factory experiences rather than as a basis for universal claims regarding their effectiveness.

CONCLUSION

This study demonstrates that Teaching Factory implemented through a digital ethnoscience-based pottery-firing project was associated with stronger development of Electronics Engineering students' design thinking than expository instruction. The experimental group achieved higher posttest, gain, and N-gain scores, and the advantage remained statistically significant after controlling for the initial difference in pretest performance. Improvement was evident across all six design-thinking dimensions, with mindfulness of process and impacts on others showing the highest N-gain, followed by human-centeredness, collaborative working, comfort with uncertainty and risks, orientation toward learning by making and testing, and confidence and optimism in using creativity. These results indicate that the intervention supported design thinking as a multidimensional capability rather than improving only a single aspect of students' design behavior.

The process, technical, and qualitative findings clarify how this improvement developed during the intervention. Students increasingly engaged in evidence use, troubleshooting, collaboration, and user-oriented decision making while working with authentic firing problems. Prototype testing required them to respond to sensor instability, communication problems, interface limitations, alarm behavior, thermal exposure, and usability concerns through repeated revision and retesting. At the same time, artisan knowledge provided the experiential context through which technical requirements were identified and evaluated. Digital temperature records allowed students to examine recurring firing events alongside measurable thermal conditions, while artisan perspectives ensured that these records were interpreted as complementary evidence rather than as a replacement for experiential judgment. The combination of authentic users, culturally grounded knowledge, digital measurement, prototyping, and iterative testing therefore provided a meaningful environment for developing design-thinking practices.

The study consequently extends previous evidence on Teaching Factory in vocational Electronics Engineering by showing that authentic production learning can be constructed around community-based technologies as well as conventional industrial products. Its principal contribution lies in demonstrating how TEFA can be enacted through a culturally grounded engineering problem in which ethnoscientific knowledge shapes problem understanding, digital technology supports evidence generation, and prototype development requires negotiation among technical performance, user needs, safety, and existing production practices. The findings therefore support the potential of digitally supported, culturally grounded Teaching Factory experiences as a contextual approach for strengthening design thinking in vocational education, while maintaining the distinction between technological evidence and the experiential knowledge embedded in local practice.

LIMITATION

Several limitations should be considered when interpreting the findings. The study involved only 39 students from two intact classes in a single Electronics Engineering program, limiting the extent to which the results can be generalized to other vocational fields, institutions, or student populations. Because group assignment was not randomized and the experimental group had a significantly higher pretest score, residual selection effects cannot be completely excluded despite the use of ANCOVA to adjust for baseline differences. The overall design-thinking instrument showed acceptable reliability, but several dimension-level subscales had relatively weak internal consistency, particularly at pretest, so the dimension-specific findings should be interpreted more cautiously than the overall score. The intervention was also relatively short, and only two prototype cycles were completed, with three of the five final prototypes still requiring further refinement. In addition, design thinking was assessed primarily through self-report, although classroom observations, technical records, prototype data, and interview findings were used to provide complementary evidence.

RECOMMENDATION

Future studies should examine this approach with larger and more diverse samples, multiple vocational schools and expertise areas, longer intervention periods, and, where feasible, randomized or stronger quasi-experimental designs. Further research should also refine and validate the dimension-level design-thinking measures, include performance-based assessments of design processes and products, and investigate whether the observed gains are retained over time and transferred to new engineering problems. From an instructional perspective, future implementations should provide additional time for iterative prototyping, greater preparatory support in programming and sensor integration, and more opportunities for students to explore alternative solutions before finalizing their designs. Replication in other community-based production contexts is also recommended to determine whether the integration of Teaching Factory, digital evidence, and ethnoscientific knowledge can support similarly strong design-thinking development across different cultural and technological settings.

Author Contributions
The authors have sufficiently contributed to the study, and have read and agreed to the published version of the manuscript.

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Conflict of Interests
The authors declare no conflict of interest.

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