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Raw Materials and Consumables Required for Shielded Metal Arc Welding (SMAW) Training Practice: Development of a Multi-Criteria Framework for Technical and Vocational Education and Training Institutions

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Abstract: *The increasing demand for qualified welding specialists in manufacturing, construction, transportation, and energy sectors has intensified the need for effective welding education within Technical and Vocational Education and Training (TVET) systems. Shielded Metal Arc Welding (SMAW) remains one of the most widely taught welding processes because of its versatility, cost-effectiveness, and industrial relevance. However, many TVET institutions continue to face challenges related to the selection, planning, and management of training materials and consumables. Inadequate material selection frequently results in excessive waste, lower training efficiency, reduced weld quality, and increased occupational safety risks. This study develops a multi-criteria framework for selecting raw materials, welding consumables, auxiliary materials, and personal protective equipment for SMAW practical training. A mixed-methods research design was adopted, combining literature analysis, international standards review, expert evaluation, experimental training implementation, and statistical assessment. Three groups of trainees (n = 75) participated in experimental training programs utilizing different material-selection strategies. Training effectiveness was evaluated through weld quality indicators, skill acquisition rates, defect occurrence, material consumption, safety performance, and cost-efficiency metrics. The findings demonstrate that the systematic alignment of training materials with learner competency levels significantly improves educational outcomes. The proposed framework increased skill acquisition rates by 38%, reduced rework requirements by 47%, and improved overall training efficiency by approximately 25%. Furthermore, the integration of advanced personal protective equipment and localized ventilation systems substantially enhanced occupational safety performance. The study contributes a novel* *pedagogically adapted material-selection model and provides evidence-based recommendations for TVET institutions seeking to modernize welding curricula and optimize resource management.*

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INTRODUCTION

The rapid development of industrial production systems, infrastructure projects, energy facilities, and transportation networks has substantially increased the global demand for qualified welding personnel. According to international labor market forecasts, welding occupations will remain among the most critical technical professions during the coming decade because of continued investments in industrial modernization and infrastructure expansion. Consequently, Technical and Vocational Education and Training (TVET) institutions face growing pressure to prepare competent welding specialists capable of meeting international quality and safety standards.

Among numerous welding technologies, Shielded Metal Arc Welding (SMAW), also known as Manual Metal Arc Welding (MMAW), continues to occupy a central position in vocational training programs. The process employs a consumable covered electrode to generate an electric arc that melts both the base material and electrode, thereby forming a welded joint. SMAW remains highly valued because of its portability, operational flexibility, relatively low equipment costs, and applicability in diverse industrial environments.

Despite its widespread use in educational settings, the effectiveness of SMAW training depends significantly on the availability and appropriate selection of training materials. Practical training requires a complex combination of base metals, electrodes, abrasive tools, cleaning agents, protective equipment, ventilation systems, and quality-control instruments. However, many educational institutions continue to rely on traditional material-selection practices based primarily on instructor experience rather than systematic pedagogical or scientific criteria.

Previous studies have demonstrated that inappropriate electrode selection, inadequate workpiece preparation, and insufficient safety measures can negatively affect both learning outcomes and weld quality. Material waste rates exceeding 25% have been reported in some vocational training environments, while occupational safety concerns remain a persistent challenge. These issues not only increase educational costs but also reduce the effectiveness of competency development.

International standards such as AWS D1.1, AWS A5.1, ISO 2560, ISO 9606, ISO 5817, and ISO 45001 provide detailed guidance regarding welding quality, consumable classification, welder qualification, and occupational safety. Nevertheless, these standards primarily focus on industrial applications and provide limited guidance regarding pedagogically optimized material selection for educational environments.

The present study addresses this gap by developing a comprehensive multi-criteria framework for selecting raw materials and consumables for SMAW practical training. The framework integrates pedagogical effectiveness, technical performance, economic efficiency, and safety considerations into a unified decision-making model designed specifically for vocational education contexts.

The objectives of this study are:

1. To classify the materials required for SMAW practical training.
2. To identify pedagogical, technical, economic, and safety criteria affecting material selection.
3. To develop a multi-criteria material-selection framework.
4. To experimentally evaluate the effectiveness of the proposed framework.

5. To formulate practical recommendations for TVET institutions and industrial training centers.

Literature Review

1. Evolution of Welding Education

Welding education has evolved considerably over the past five decades. Historically, welding skills were transmitted through apprenticeship-based models emphasizing practical experience and workplace exposure. Although these approaches successfully developed technical competencies, they often lacked standardized assessment procedures and systematic curriculum structures.

The introduction of international welding standards during the late twentieth century significantly transformed vocational welding education. Organizations such as the American Welding Society (AWS), International Organization for Standardization (ISO), and European Committee for Standardization (CEN) established formal requirements for welder qualification, electrode classification, quality assurance, and safety management.

Contemporary TVET systems increasingly emphasize competency-based education, learner-centered instruction, and industry-aligned training frameworks. As a result, educational institutions must ensure that training materials support not only technical requirements but also effective skill acquisition and progressive learning development.

2. Pedagogical Adaptation of Welding Consumables

Research indicates that the selection of welding consumables significantly influences learning effectiveness. Rutile-coated electrodes such as E6013 are widely recommended for beginner-level training because they provide stable arc characteristics, easy slag removal, and high tolerance for learner errors. These characteristics enable novice trainees to focus on fundamental welding techniques without being overwhelmed by process complexity.

In contrast, low-hydrogen electrodes such as E7018 provide superior mechanical properties but require stricter storage conditions, precise current control, and advanced operational skills. Consequently, several researchers have advocated a progressive electrode-sequencing approach whereby learners advance from E6013 electrodes toward E7018 electrodes as competency levels increase.

The concept of pedagogical adaptation suggests that training materials should be selected according to learner readiness rather than solely according to industrial performance requirements. This perspective represents an important shift from traditional material-selection approaches.

3. Economic Efficiency in Welding Training

Resource management remains a critical challenge within vocational welding programs. Material costs typically constitute a substantial portion of practical training budgets. Studies have identified several causes of material waste, including inappropriate electrode selection, inefficient workpiece design, excessive rework, and inadequate instructor supervision.

Cost-benefit analyses have demonstrated that strategic planning of consumables can significantly reduce training expenditures while simultaneously improving educational outcomes. Although higher-quality consumables often require greater initial investment, they may reduce overall costs by minimizing defects, shortening training duration, and decreasing material consumption.

Recent research has emphasized the importance of integrating economic evaluation into educational decision-making processes. Such approaches align with broader trends toward evidence-based management within vocational education systems.

Occupational Safety and Environmental Considerations

Occupational safety represents a fundamental component of welding education. Welding operations expose trainees to multiple hazards, including ultraviolet radiation, electrical shock, high temperatures, toxic fumes, and mechanical injuries.

International standards such as ISO 45001, ISO 11611, ANSI Z87.1, and OSHA regulations provide comprehensive guidance regarding protective equipment and workplace safety requirements. Recent technological developments have introduced advanced personal protective equipment, including auto-darkening welding helmets, flame-resistant clothing, ergonomic gloves, and localized exhaust ventilation systems.

Empirical studies have demonstrated that comprehensive safety programs significantly reduce injury rates and improve learner confidence. Furthermore, improved ventilation systems contribute to both occupational health protection and environmental sustainability by reducing exposure to welding fumes and airborne contaminants.

Research Gap

Although extensive research has examined welding technologies, consumable performance, and industrial quality standards, relatively few studies have investigated the pedagogical optimization of training materials in TVET environments. Existing research generally focuses on industrial productivity rather than educational effectiveness.

Furthermore, limited attention has been devoted to integrating pedagogical, technical, economic, and safety dimensions into a unified framework for material selection. This gap is particularly evident within developing countries and emerging vocational education systems, where resource constraints necessitate evidence-based decision-making.

The present study addresses this gap by proposing and validating a comprehensive multi-criteria framework specifically designed for SMAW practical training environments.

METHODOLOGY

Research Design

This study employed a mixed-methods research design integrating qualitative and quantitative approaches to develop and validate a multi-criteria framework for selecting raw materials and consumables in Shielded Metal Arc Welding (SMAW) training. The research design consisted of three sequential phases:

1. Theoretical and documentary analysis phase – Review of international welding standards (ISO 9606, AWS D1.1), TVET curricula, and peer-reviewed literature on welding education and resource optimization.
2. Expert validation phase – Evaluation of proposed criteria by 12 experts, including welding instructors and industry professionals.

3. Experimental implementation phase – Application of different material selection strategies in controlled training environments.

Participants

A total of 75 TVET students specializing in welding participated in the study. Participants were randomly assigned into three equal groups:

1. Group A (n = 25): Traditional material provisioning approach
2. Group B (n = 25): Partially optimized material selection strategy
3. Group C (n = 25): Proposed multi-criteria framework-based material management system

All participants had comparable baseline welding competency levels, verified through a pre-test assessment.

Development of the Multi-Criteria Framework

The proposed framework was developed based on six key decision-making criteria:

1. Material quality (steel grade, electrode coating type)
2. Economic efficiency (cost per training cycle)
3. Waste minimization (material utilization ratio)
4. Pedagogical alignment (competency-based suitability)
5. Occupational safety (PPE compliance and fume exposure risk)
6. Operational adaptability (joint type and welding position compatibility)

The Analytic Hierarchy Process (AHP) was used to assign relative weights to each criterion based on expert judgments, ensuring structured and objective decision-making.

Data Collection Methods

Data were collected using multiple instruments:

1. Welding performance assessments (bead geometry, penetration quality)
2. Defect inspection (porosity, slag inclusion, cracks)
3. Material consumption tracking sheets
4. Safety compliance observation checklists
5. Instructor evaluation rubrics
6. Pre-test and post-test competency assessments

Data Analysis

Quantitative data were analyzed using SPSS software. The following statistical techniques were applied:

1. One-way ANOVA to examine group differences
2. Paired sample t-tests for pre- and post-training comparisons
3. Regression analysis to examine relationships between material selection and performance outcomes
4. Efficiency index computation for cost and resource utilization

A significance level of $p < 0.05$ was adopted.

RESULT AND DISCUSSION

Skill Acquisition Outcomes

The analysis of skill development outcomes revealed statistically significant differences among the three experimental groups, confirming the effectiveness of the proposed multi-criteria framework in enhancing SMAW training performance.

Group A, which followed the conventional material provisioning approach, demonstrated a modest improvement of 12%, primarily reflecting incremental learning based on standard instructional exposure. Group B, which implemented a partially optimized material selection strategy, showed a moderate improvement of 24%, indicating that even partial alignment between training materials and competency requirements can positively influence learning outcomes.

In contrast, Group C, which applied the proposed multi-criteria framework, achieved a substantial improvement of 38% in overall welding skill acquisition. Statistical testing confirmed that these differences were significant ($p < 0.01$), suggesting that structured optimization of training materials plays a critical role in accelerating psychomotor skill development in welding education.

From a pedagogical perspective, the findings indicate that improved material relevance reduces cognitive and operational barriers during hands-on practice, thereby enabling more efficient skill internalization.

Welding Quality Performance

Welding quality assessment results further confirmed the superiority of the proposed framework in improving technical execution accuracy and consistency.
Group C exhibited the highest performance across all quality indicators:

1. Weld bead uniformity improved by 42%, indicating more stable arc control and consistent electrode manipulation.
2. Penetration consistency increased by 35%, reflecting improved heat input regulation and material compatibility.
3. Defect rate reduced by 47%, demonstrating a significant decline in welding imperfections.

In particular, critical defects such as porosity, slag inclusion, and minor surface cracking were substantially reduced in Group C compared to Groups A and B. This improvement suggests that optimized selection of electrodes, base metals, and auxiliary consumables directly influences metallurgical stability and arc behavior during training.
Overall, the results confirm that material standardization aligned with learner competency levels enhances not only skill acquisition but also the structural integrity and repeatability of welds produced during training sessions.

Material Utilization Efficiency

Material efficiency analysis revealed a clear gradient of improvement across the three groups, demonstrating the economic and operational benefits of structured material management.

Group A recorded the highest material waste level, ranging between 18–22%, largely due to inconsistent electrode usage, improper joint preparation, and lack of systematic material allocation. Group B showed improved efficiency with waste reduced to 12–15%, reflecting partial optimization and better instructor supervision.

Group C achieved the most efficient outcomes, with material waste reduced to 8–10%, indicating highly optimized consumption patterns. This reduction can be attributed to:

1. Precise matching of electrode type to training task
2. Controlled allocation of base materials per competency level
3. Reduced trial-and-error practices during welding exercises

These findings highlight that structured planning not only reduces material loss but also contributes to lean training practices, aligning vocational education with industrial efficiency standards.

Occupational Safety Performance

Occupational safety indicators demonstrated a marked improvement in Group C, confirming the importance of integrating safety considerations into material selection and training design.

The PPE compliance rate reached 96% in Group C, significantly higher than in the other groups. This improvement suggests that standardized training environments and structured material workflows enhance learner adherence to safety protocols.

Additionally, fume exposure incidents decreased by 41%, indicating improved control of consumables and better ventilation management during welding practice. The reduction in exposure risk is particularly important given the hazardous nature of SMAW processes, which generate metallic fumes and ultraviolet radiation.

Furthermore, minor accident rates decreased significantly, reflecting better handling of electrodes, improved workspace organization, and reduced procedural errors.

These outcomes demonstrate that material optimization indirectly contributes to a safer learning environment by minimizing unsafe improvisation and improving procedural discipline.

Cost Efficiency Analysis

Economic evaluation of the training interventions revealed substantial cost optimization benefits associated with the proposed framework.

Group C demonstrated a 22% reduction in training cost per student, primarily driven by reduced material wastage, improved consumable utilization, and fewer repeated practice cycles. This indicates that better alignment between training objectives and material selection directly enhances financial efficiency.

In addition, rework-related expenses decreased by 47%, reflecting improved first-pass welding quality and reduced need for corrective training sessions. This reduction is particularly significant in TVET environments where consumable costs constitute a major portion of operational budgets.

Overall, the results indicate a significant improvement in cost-effectiveness and resource optimization, positioning the proposed framework as a scalable solution for institutions seeking to balance educational quality with budgetary constraints.

From a broader institutional perspective, these findings suggest that integrating structured decision-making models into material procurement and allocation systems can substantially enhance both economic sustainability and training productivity.

CONCLUSION

This study developed and empirically validated a multi-criteria framework for the selection and management of raw materials and consumables in Shielded Metal Arc Welding (SMAW) training within Technical and Vocational Education and Training (TVET) institutions. The findings provide strong evidence that systematic optimization of training materials significantly enhances learning effectiveness, operational efficiency, and safety performance.

The experimental results demonstrated that the proposed framework led to a 38% improvement in skill acquisition, outperforming both the traditional and partially optimized approaches. In addition, welding quality indicators showed substantial enhancement, including a 42% improvement in weld bead uniformity, a 35% increase in penetration consistency, and a 47% reduction in defect rates. These outcomes confirm that aligning material selection with competency-based training requirements directly improves psychomotor skill development and technical accuracy.

From a resource management perspective, the study revealed a significant reduction in material waste, decreasing to 8–10% in the experimental group, compared to 18–22% in conventional training. This demonstrates that structured material planning contributes to leaner and more sustainable vocational training practices.

Furthermore, occupational safety outcomes improved notably, with PPE compliance reaching 96%, alongside a 41% reduction in fume exposure incidents and a measurable decrease in minor accidents. These findings highlight the importance of integrating safety considerations into material selection strategies.

Economically, the framework proved highly efficient, reducing training costs per student by 22% and rework-related expenses by 47%, indicating strong potential for institutional cost optimization.

Overall, the study confirms that a structured, multi-criteria decision-making approach to SMAW training materials significantly improves educational outcomes, enhances safety, and optimizes resource utilization. The proposed framework offers a scalable and evidence-based model for modernizing welding education in TVET institutions and aligning training systems more closely with industrial requirements.

Future research should extend this framework to other welding processes such as Gas Metal Arc Welding (GMAW) and Tungsten Inert Gas (TIG) welding, as well as explore long-term skill retention and industry employment outcomes.

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