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Design and Development of a Low-Cost Automated Coloured-Paint Mixing System for Small and Medium-sized Enterprises

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Abstract

Manual and semi-automated paint mixing in small and medium enterprises (SMEs) across sub-Saharan Africa, particularly Nigeria, generates significant colour inconsistency, material waste of 10–15%, prolonged cycle times, and low productivity. This paper presents the design, development, and evaluation of a low-cost automated colour mixing system tailored for resource-constrained environments. The prototype integrates a gravity-assisted mild steel frame fabricated from recycled industrial drums, three upper pigment storage tanks (Tanks A, B, and C), a central mixing tank (Tank D), 12V DC motors with peristaltic-style pumps, an Arduino Uno-based control system, and a custom real-time human-machine interface (HMI) named Messager Genius Auto Paint Software. A hybrid RGB/RYB colour model with empirical calibration matrices was employed, supporting both preset and custom colour selection. Testing across ten colour formulations achieved an average colour difference of $\Delta E = 1.65$ (90% success rate at $\Delta E < 2.0$), reduced material waste to 3.7%, and completed a 5-liter batch in approximately 9.4 minutes (58% improvement over manual methods). This work demonstrates the technical and economic feasibility of frugal mechatronics for pigment-based paint production in developing economies.

Keywords: Automated Coloured-paint mixing; frugal mechatronics; RGB/RYB colour model; Sub-Saharan Africa; colour accuracy; low-cost automation

Introduction

Paint mixing is a critical operation across building, automotive, and decorative manufacturing. While industrialised nations have largely adopted automated systems since the 1980s, small and medium enterprises (SMEs) in sub-Saharan Africa particularly Nigeria continue to rely on manual or semi-automated methods. These approaches generate batch rejection rates of 10-20%, pigment waste of 10-15%, and productivity levels approximately 30% of automated equivalents (Akintola, 2024; Ogunmodede & Lule, 2024). Modern automated mixing systems deploy high-precision volumetric dosing, achieving accuracy of ±0.01%, integrated digital colorimetry with AI-based formula retrieval, and real-time spectrophotometric feedback maintaining $\Delta E < 1.0$ (Zhao, 2024; Smith & Jones, 2024). However, such systems cost between Ten Million Naira (₦10,000,000) and Fifty Million Naira (₦50,000,000), which requires a stable voltage of 220V AC supply, and demand specialist maintenance personnel. These factors make them inaccessible to the Nigerian small and medium-sized enterprises (SMEs). Recent literatures confirm the viability of microcontroller-based prototypes for small-scale colour production. Arduino and ESP32 platforms with peristaltic pumps and basic RGB sensors achieve ΔE values of 1.5-2.0, dispensing repeatability of ±2-5%, and processing times of 3-8 minutes per batch at component costs below USD 300 (Wafi et al., 2024). The existing manual and semi-automated paint-mixing systems have indeterminate colour proportions and inconsistent mix quality challenges that usually affect the end-product quality. These systems also have repeatability and reliability challenges resulting from human deficiencies, as humans play major role in paint colour-mixing.

The design and development of a robust and economical automated paint mixing system, specifically adapted to SMEs, vocational training centers, and craft workshops, is what the developing countries especially those of sub-Saharan Africa need to address the numerous colour-mixing challenges and many others. The aim was to design and develop an automated colour mixing system for paint production in SMEs. The five objectives that were pursued are: (i) design a compact mechanical prototype with dosing and mixing units; (ii) select and calibrate sensors and actuators for volumetric dosing and mixture homogeneity; (iii) develop an intuitive HMI; (iv) construct and integrate the system using a hybrid RGB/RYB colour model; and (v) evaluate the prototype's performance against manual benchmarks.

This automated coloured-paint mixing system will support SMEs in improving quality, reducing waste, and increasing productivity in industrial environments throughout sub-Saharan Africa.

Evolution of Paint Mixing Systems

The importance of colour cannot be overemphasized as it serves as one of the major factors of identification, description and beautification of objects, images, houses amongst others. Colours are being used daily to assist in the organization or classification of different activities relating to either pleasure or orderliness. Paint mixing systems

have evolved along three technological generations. Manual mixing characterised by hand stirrers, subjective colour judgement, and colour homogeneity indices of only 70–85% remains prevalent in Nigerian SMEs (Graco, 2024). Researches have shown that traditional or manual coloured-paint matching is no longer meeting up with the current products quality needs (Zhang, 2024). Semi-automated systems introduce motorised agitators and calibrated dispensers, improving repeatability but retaining human-controlled proportioning with associated inter-operator variability (Wafi et al., 2024). A technology known as paint matching system is being utilized globally in several enterprises especially in painting, printing and production activities for improved products quality (Zhang, 2024).

Colour Models for Automated Mixing

The RGB (Red, Green, Blue) additive model provides superior digital interface compatibility, native sensor output, and an extremely wide colour gamut, but requires empirical calibration matrices to bridge the gap between digital input and physical subtractive mixing behaviour (Ali et al., 2024). The RYB colour model has been used in many automated prototypes because of its ability to relate to pigments locally available to users and also because most users have some level of familiarity with the colour model, even if not a great deal (Al Mawali & Hussain, 2023). An automated colour mixing system is being utilized in determining the different colour proportions required for the production of any desired colour of paint. This automated system ensures faster production of any colour of paint with greater reliability and efficiency (Ammar et al., 2017).

Control Algorithms and Calibration

Proportional-Integral-Derivative (PID) closed-loop control remains the dominant algorithm in low-cost prototypes, iteratively adjusting dispensing durations based on RGB sensor feedback until $\Delta E < 2.0$ (CIEDE2000) is achieved (Wafi et al., 2024). Empirical 3×3 transformation matrices-derived through least-squares regression on reference mixtures-compensate for non-linear subtractive interactions and are stored in microcontroller EEPROM for real-time retrieval (Ali et al., 2024).

Design Approach

A hybrid waterfall-agile systems engineering methodology was adopted, ensuring traceability between requirements and verification while enabling iterative refinement under prototype constraints. The system was designed to achieve $\Delta E < 2.0$ (CIEDE2000), process 1-5 liters batches, operate on 12V DC from battery backup, and be maintained by semi-skilled operators using locally available parts in Abuja and Kaduna markets.

Mechanical Design and Fabrication

The support frame was fabricated from mild steel square tubing and angle iron, forming a rectangular base of 180 cm × 100 cm with 90 cm vertical supports to enable gravity-assisted

dispensing. Diagonal cross-braces and gusset plates at load-bearing joints provided torsional rigidity capable of supporting 40-60 kg per filled drum. Three recycled industrial metal drums (diameter ≈ 26.5 cm, height ≈ 27 cm) were cleaned, inspected, and mounted as upper pigment storage tanks (Tanks A, B, C). A fourth drum (diameter ≈ 28 cm, height ≈ 24 cm) was positioned centrally at base level as the mixing tank (Tank D), with approximately 65 cm clearance for unobstructed gravity flow as show in Figure 1. Each storage tank was fitted with a dedicated electric stirring motor to prevent pigment sedimentation. A drip tray was incorporated beneath the frame for spill containment.

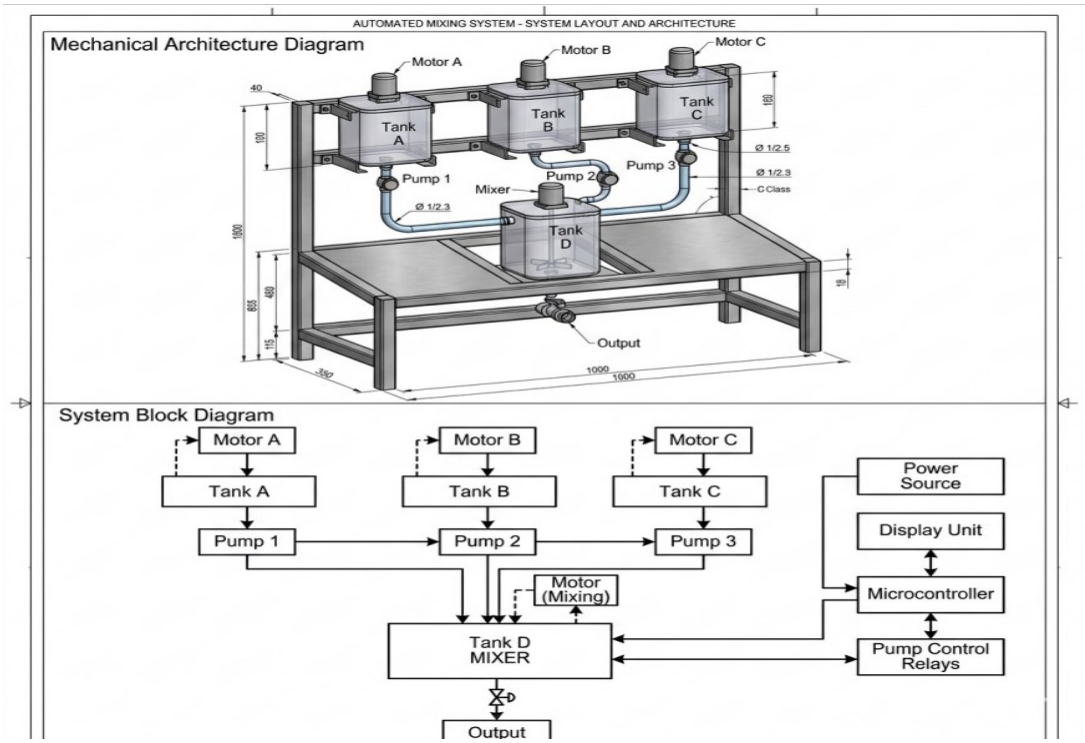


Figure 1: The mechanical architecture of the automated coloured-paint mixing system.

Electronic System

The control system centers on an Arduino Uno (ATmega328P), executing a finite state machine (FSM) with states for Idle, Colour Selection, Formula Calculation, Dispensing, Mixing, Colour Verification, and Corrective Adjustment. Seven single-channel relay modules (5V, optically isolated) switch 12V DC to peristaltic pumps and motors, driven through TIP31C NPN power transistors with 1N4007 flyback diodes for inductive spike protection. The circuit diagram of the automated coloured-paint mixing system is as presented in Figure 2. The 12V DC backbone ensures compatibility with lead-acid battery backup critical for continuous operation during Nigerian grid outages. All wiring was colour-coded, routed through conduits, and terminated in vibration-resistant connectors.

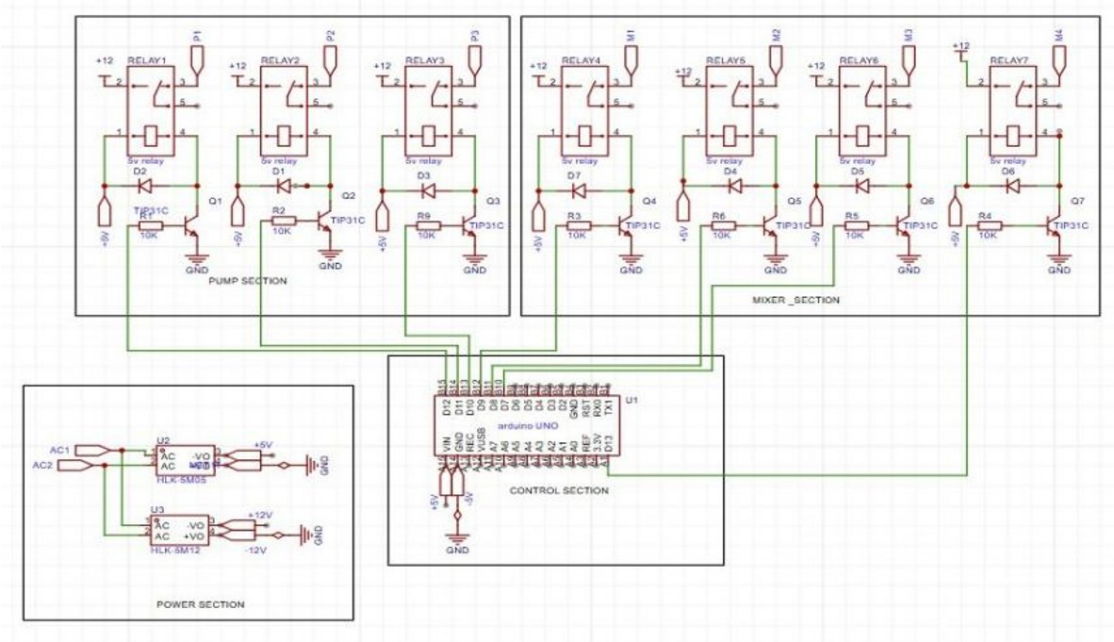


Figure 2: The circuit diagram of the automated coloured-paint mixing system

Colour Model and Calibration Algorithm

The system employs an RGB approach as show in Figure 3. Operators select target colours via the HMI using preset buttons, an interactive RGB colour wheel, or 0-255 scale sliders. Selected RGB values serve as the digital reference. A pre-calibrated 3×3 empirical transformation matrix converts these values into physical pigment dispensing volumes in milliliters, correcting for non-linear subtractive interactions, pigment strength variations, and base opacity. The matrix was derived offline through least-squares regression on a dataset of reference mixtures measured with a TCS34725 colour sensor under controlled LED illumination. Pump flow rates were calibrated at ±1% volumetric accuracy across 50 test cycles.

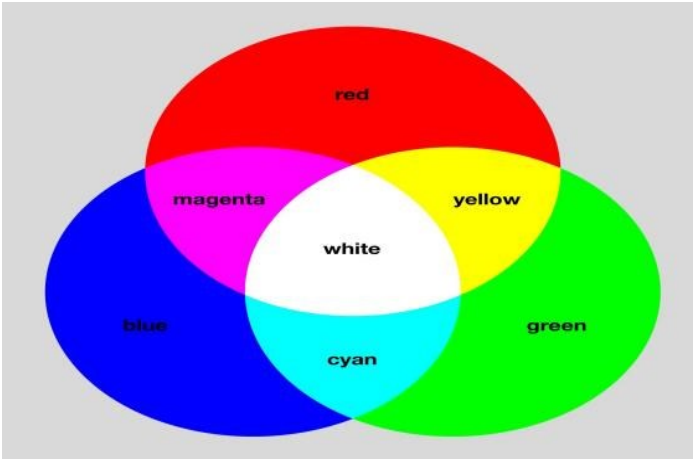


Figure 3: Additive RGB colour model (Muratbekova et al., 2026)

HMI Software

A custom application Messager Genius Auto Paint Software was developed as the primary HMI, running on a connected laptop. The interface features three dynamic tank level

indicators, a colour composition bar, live timestamped event logs, preset colour selection for 11 standard shades, batch volume input (1-5 litres), a prominent emergency stop button, automated wash cycle controls, and manual RGB channel override buttons for calibration. The FSM firmware (C++ on Arduino IDE) manages sequential dispensing with timed PWM control, PWM-based agitator speed regulation, emergency stop interrupt handling, and serial communication with the HMI for real-time status exchange.

The operational sequence of the automated colour mixing system is illustrated in Figure 4. The flowchart defines a clear, logical, and fail-safe process that ensures system safety, material availability, and process repeatability.

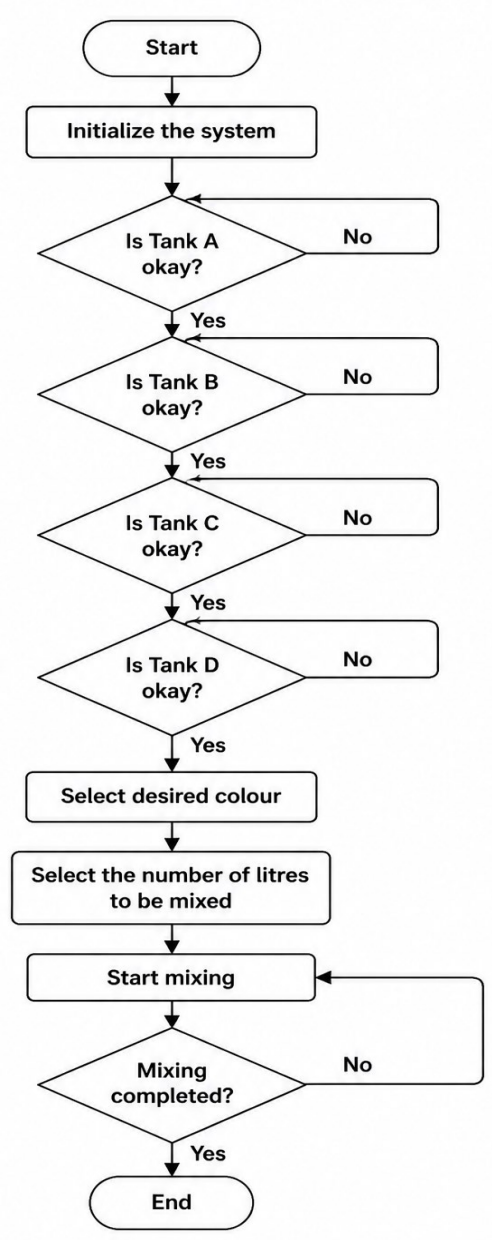


Figure 4: The flowchart of the automated coloured-paint mixing system

Testing Protocol

Testing proceeded through three hierarchical stages. Unit testing subjected individual components to isolated performance Evaluation: the relay module completed 200 switching cycles with no failure (average response time 28 ms), and the agitator motor maintained 60-120 RPM under simulated 5-litre viscous load for 30 continuous minutes without stalling or overheating. Integration testing combined mechanical and electrical subsystems over 15 full cycles with water as the test medium, verifying dispensing, agitation synchronisation, emergency stop response (< 10 ms), and absence of leakage. Full system testing used actual pigments across ten colour formulations in 3-5 litre batches under real workshop conditions. Colour accuracy was measured using a handheld colorimeter (CIEDE2000), with comparison against manual mixing benchmarks. Four different pump models were evaluated during development; compatibility failures with ortho-base and oil-based paints required iterative testing until a suitable model was identified.

Results

This final configuration successfully combines the mechanical structure, fluid handling system,

and electronic control into a compact, robust, and functional unit. The modular design ensures excellent accessibility for maintenance, cleaning, and future upgrades such as automated solenoid valves or colour sensor integration. The completed prototype presented in Figure 5 is well-suited for practical deployment in small and medium-scale paint production environments in Nigeria.

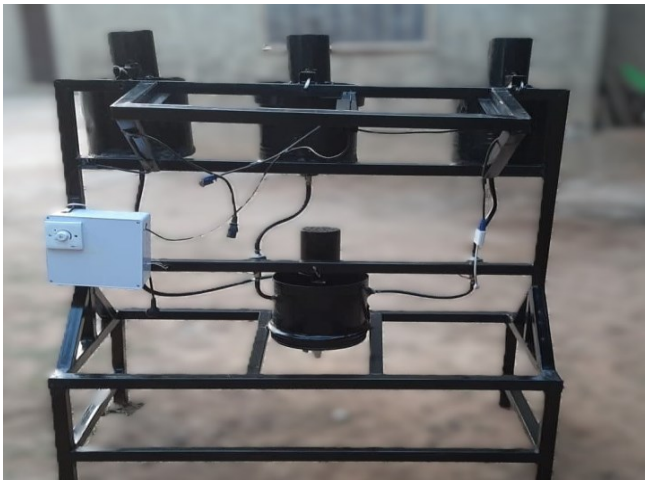


Figure 5: The prototype of the automated coloured-paint mixing system

The software interface was tested with semi-skilled operators as shown in Figure 6, and it required fewer than 15 minutes of training to achieve confident independent operation.

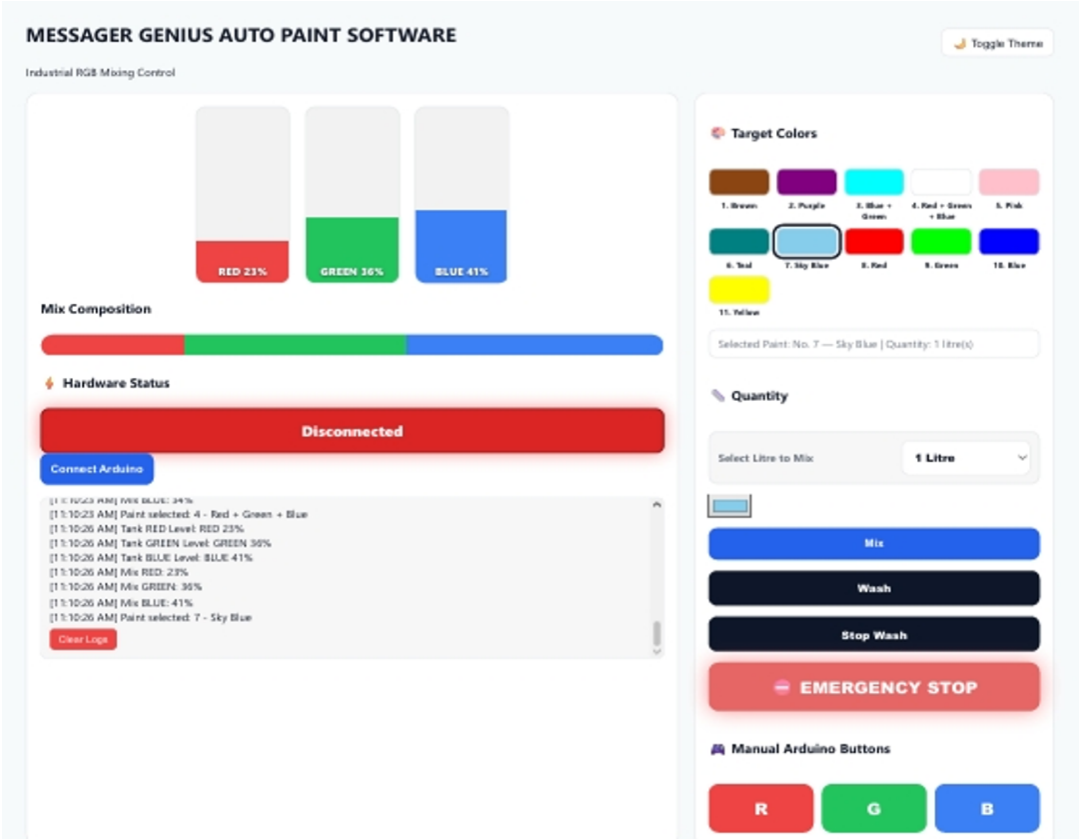


Figure 6: Real-Time HMI of the Messager Genius Auto Paint Software.

Table 1 presents selected colour accuracy results from full system testing. The system achieved an average ΔE of 1.65 across all ten formulations, with a 90% success rate at ΔE < 2.0. The lowest ΔE recorded was 0.9 for pure red (single-tank dispensing), and the highest was 2.3 for complex secondary shades, consistent with published Arduino-based prototype benchmarks of ΔE 1.5–3.0 by [5].

Table 1. Selected colour accuracy results (ΔE, CIEDE2000 metric).

Test No.	Target Colour	Tank A (%)	Tank B (%)	Tank C (%)	ΔE
1	Purple	50	0	50	1.4
2	Yellow	50	50	0	1.7
3	Red	100	0	0	0.9
4	Balanced Mix	33	33	34	1.6
5–10	Various	—	—	—	1.2–2.3

Average ΔE = 1.65; Success rate (ΔE < 2.0) = 90%.

Average cycle time (colour selection + dispensing + agitation + discharge) was 9.4 minutes for a 5 liters batch, representing a 58% improvement over the manual baseline of 22-25 minutes. Mixing homogeneity was confirmed visually and physically: paint swatches applied to white paper showed uniform colour distribution with no visible pigment separation or streaking across five identical batches of each colour formulation.

Material waste (spillage + residue) averaged 3.7% per batch, a 69% reduction compared to the 10-15% observed in manual operations. Repeatability across five identical batches of the same formulation yielded a coefficient of variation (CV) of 3.2% in ΔE values, compared to approximately 18% CV in manual mixing. Table 2 presents the performance comparison study between this automated coloured-paint mixing system and the traditional/manual method.

Table 2. Comparative performance: automated prototype vs. manual mixing (5-litre batch).

Parameter	Manual Mixing	Automated Prototype	Improvement
Cycle Time (5 L)	22–25 min	9.4 min	58% faster
Colour Accuracy (ΔE)	4.5–8.2	1.65 (avg)	63% better
Material Waste	10–15%	3.7%	69% less
Repeatability (CV)	18%	3.2%	82% better
Batch Rejection Rate	10–20%	<4%	>75% reduction

The HMI dashboard updated live tank proportions instantaneously as configurations changed. Three semi-skilled technicians rated the interface as highly intuitive after 15 minutes of training. The 12V battery backup provided 45 minutes of autonomous operation during simulated grid outages-sufficient for complete batch processing. Pigment settling was resolved by incorporating brief pre-agitation pulses in the firmware. Minor sensor drift under

dusty conditions was corrected through periodic recalibration and enclosure sealing, both achievable by local technicians.

Discussion

The prototype successfully met the predefined goals, demonstrating that industrial-grade colour accuracy is achievable using this automated coloured-paint mixing system. The achieved ΔE of 1.65 meets the CIEDE2000 target of $\Delta E < 2.0$ and is directly comparable to documented low-cost prototype performance (Wafi et al., 2024; Al Mawali & Hussain, 2023), while the 58% cycle time reduction and 69% waste reduction translate to substantive economic benefits for Nigerian SME operators. The 3×3 empirical transformation matrix approach proved effective at compensating for non-linear subtractive pigment interactions without requiring Kubelka-Munk spectral databases or AI-based formulation tools, confirming the suitability of this method for resource-constrained settings. The 12V DC architecture's compatibility with battery backup addresses the most fundamental operational constraint in Nigerian workshops grid instability while the open-source Arduino platform and locally maintainable peristaltic tubing sets ensure long-term serviceability without recourse to proprietary technical support. The present system, while more comprehensive, delivers performance improvements consistent with this pattern and provides a replicable model for inclusive automation in sub-Saharan African manufacturing.

Conclusion

This paper presents a complete, locally fabricated prototype developed and tested under real workshop conditions in Kaduna, Nigeria, demonstrating that industrial-grade colour accuracy is attainable at a fraction of commercial system costs. Integrating a locally welded mild steel frame, recycled industrial drums, Arduino-based control with peristaltic dispensing, and a custom real-time HMI, the prototype achieved $\Delta E = 1.65$ (90% pass rate), 3.7% material waste, 9.4-minute cycle times, and 3.2% repeatability CV demonstrating comprehensive superiority over manual mixing across every measured performance dimension. The work fills a documented gap in the literature by providing a fully tested prototype adapted to variable paint viscosities, unstable power supply, and semi-skilled operator environments characteristic of West and Central African manufacturing contexts. It contributes to the body of knowledge in frugal mechatronics by demonstrating that the gap between craft-trade and industrial-grade colour reproduction can be bridged with this system, thereby supporting sustainable SMEs development aligned with the United Nations Sustainable Development Goals.

Key limitations include the small batch scale (1-5 liters), the absence of long-term durability data under continuous industrial use, and the current reliance on a laptop-based HMI that may be impractical in some workshops. Future work should integrate dedicated solenoid valves, an onboard touchscreen display, IoT connectivity (ESP32 + Blynk) for remote monitoring,

solar/battery hybrid power, and extended field trials across multiple paint formulation types and SME sites.

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