



**DESIGN AND EVALUATION OF A LOW-COST MANUAL PAINT
MIXING MACHINE FOR SMALL-SCALE INDUSTRIES: EFFICIENCY
AND USABILITY PERSPECTIVE**

**AREMU ADEBAYO ABAYOMI¹; ADEKANBI AKIN OLUGBAMI²; &
OYEDOKUN OYETOPE MUZEDIK²**

¹Department of Mechanical Engineering, Adeseun Ogundoyin Polytechnic, Eruwa, Oyo State Nigeria.

<https://orcid.org/0009-0009-9666-9422>. ²Department of Electrical & Electronics Engineering,

Adeseun Ogundoyin Polytechnic, Eruwa, Oyo State Nigeria

Corresponding Author: adebayocares@yahoo.com

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ABSTRACT

In small-scale paint production industries, the reliance on manual methods for mixing paint often results in inconsistencies, extended mixing times, and excessive operator fatigue. This study presents the design, fabrication, and evaluation of a low-cost, manually operated paint mixing machine tailored to the needs of small-scale users. The machine integrates a crank-powered system, a cylindrical mixing drum, and cross-shaped internal blades mounted on a central shaft, all supported on a mild steel frame. The primary objective was to assess the efficiency and usability of the machine using measurable parameters such as mixing time, blade uniformity index, operator fatigue level, and user satisfaction. Materials such as mild steel, galvanized iron, and stainless steel were selected based on durability, cost-effectiveness, and corrosion resistance. The machine was tested using three different viscosities of paint, with results showing an average mixing time of 9.2 minutes per 5-liter batch and a uniformity index of over 88%, which is satisfactory for most commercial applications. A usability assessment involving 20 participants indicated high ratings in ergonomics, safety, and ease of operation, with over 85% of respondents recommending the design for micro-enterprises. The torque required for mixing and efficiency output validated the mechanical advantage of the hand crank, suggesting potential for scalability. The total cost of fabrication was estimated at ₦23,400, making it significantly more affordable than electric mixers commonly unavailable to low-income operators. The system also offers flexibility for indoor and off-grid usage, reinforcing its sustainability and alignment with circular economy goals. The outcome of this study demonstrates that an ergonomically sound, manually operated mixing machine can significantly improve productivity and paint quality while remaining accessible to users with limited financial resources. It bridges the gap between artisanal processes and modern efficiency, with potential for wider adoption across emerging economies. Recommendations for future improvements include integration of a geared crank system, development of larger capacity variants, and multilingual manuals for broader accessibility. This innovation presents a vital tool for economic empowerment, particularly within local paint production clusters in developing regions.

Keywords: Ergonomic Design, Low-cost Fabrication, Manual Paint Mixer, Mixing Efficiency, Small-scale Industry, SME Innovation, Usability Evaluation

INTRODUCTION

Small-scale industries play a vital role in economic development, especially in emerging economies where they significantly contribute to employment generation, innovation, and local production. Among such enterprises, small-scale paint producers often rely on rudimentary or improvised methods to mix paints, leading to inefficiencies in consistency, color uniformity, and production time. Manual mixing using hand-held sticks or makeshift tools is not only labor-intensive but also compromises product quality and worker ergonomics (Ogunwole & Adeyanju, 2023).

While automated paint mixing systems are widely adopted in large-scale industries due to their speed and precision, they are generally unaffordable for small-scale operators due to high initial and maintenance costs, electricity dependency, and technological complexity. This creates a significant technological gap that limits the operational efficiency of small producers (Ahmed et al., 2022). Moreover, current literature tends to focus predominantly on automated or semi-automated systems, with limited attention to low-cost, manually operated alternatives that are both efficient and user-friendly for resource-constrained settings (Okonkwo & Bello, 2024).

Despite the growing demand for customized paint products at the micro-industrial level, small-scale operators lack access to affordable and ergonomically designed paint mixing solutions. Existing manual methods are not only inefficient but also inconsistent in results, which affects productivity and customer satisfaction. There is a lack of optimized, user-centric manual machines that balance cost-effectiveness, mechanical reliability, and ease of operation.

Although a few studies have attempted to design manual mixing devices for food and other industrial products, the domain of paint mixing, especially from a usability and cost-effectiveness perspective, remains underexplored. Additionally, prior work often overlooks the user experience and ergonomic aspects critical to sustained use and operator safety. This study seeks to address the above gaps by:

- i. Designing a functional, low-cost, manually operated paint mixing machine tailored for small-scale industrial applications.
- ii. Evaluating the machine's performance based on operational efficiency metrics such as mixing time, uniformity, and mechanical stability.
- iii. Assessing the usability and ergonomics of the device through structured user feedback and observational analysis to determine its practical adoption potential.

Through this study, it is anticipated that a bridge can be created between technological feasibility and the practical needs of small-scale paint producers, ultimately contributing to the enhancement of local manufacturing capabilities.

LITERATURE REVIEW

The design and evaluation of low-cost, manual paint mixing machines for small-scale industries remains an under-explored domain in engineering research. While considerable work has been done on

automation and the ergonomics of industrial machinery, small-scale industries often face a unique set of challenges that require cost-effective, user-friendly solutions. According to Ahmed et al. (2022), small-scale industries in developing regions frequently operate without adequate technological tools, leading to inefficiencies in production and subpar product quality.

Research into manual mixing technologies reveals that most designs have been tailored toward more general industries, with minimal focus on specific challenges in paint production. Ogunwole & Adeyanju (2023) noted that manual mixing processes, although inexpensive, often result in inconsistent colour and texture due to improper mixing techniques and poor equipment design. Studies like those of (Okonkwo & Bello 2024; Afolabi & Yusuf, 2022) have highlighted the ergonomic issues associated with long hours of manual labour in such environments, emphasizing the need for equipment that is not only functional but also reduces physical strain on workers.

Moreover, affordability and usability have been central concerns in previous work. According to Yang and Liu (2021), low-cost design strategies that cater to small-scale industries require innovative engineering solutions that balance efficiency with practical application. The need for manual systems that are cost-effective yet efficient has led some researchers to focus on utilizing locally available materials (Ahmed & Singh, 2023; Ali & Gambo, 2020) and simplifying designs to avoid expensive manufacturing processes.

In terms of machine performance evaluation, researchers like (Sanni & Ibrahim, 2023; Khan et al. 2023) have explored the relationship between machine specifications and production outcomes, focusing on factors such as mixing time and uniformity. These studies emphasize the importance of a rigorous evaluation of both efficiency and durability, areas which have often been overlooked in manual designs (Oluwaseun & Sulaimon, 2022; Alabi & Eze, 2022).

Ergonomics is another critical factor for success in small-scale industries. Previous studies by (Ayodele & Babajide, 2023; Ibrahim et al. 2021) have shown that poor ergonomics can drastically reduce productivity and lead to long-term health issues for workers. Usability studies, such as those conducted by Akinyemi & Adesina (2022), highlight how operator feedback is crucial for improving equipment design in manual settings. A well-designed, ergonomic system not only enhances user satisfaction but also increases operational efficiency (Abiola & Salami, 2022).

Design calculations play a critical role in developing efficient, reliable, and safe mechanical systems, particularly for manual machines intended for small-scale industrial applications. In designing manual paint mixing machines, attention must be given to torque requirements, shaft dimensions, gear ratio, blade configuration, and ergonomic effort levels. These calculations ensure that the system can perform its function effectively without overstressing its components or the user (Shigley et al., 2020; Juvinall & Marshek, 2021).

Accurately estimating the torque required to rotate mixing blades in a viscous medium is foundational. As highlighted by Ademola et al. (2021), torque requirements depend on the fluid's viscosity, blade geometry, and operational speed. The authors stress the need for iterative testing to align theoretical values with actual mixing performance.

Similarly, Razaq et al. (2022) applied Newtonian fluid dynamics and shear stress equations to determine torque needs for food mixing applications, showing parallels with paint mixing due to similar fluid properties. They emphasized that underestimating torque can lead to blade stalling, while overestimation results in oversized, costly components.

Designing a mixing shaft requires consideration of both torsional and bending stresses. According to Kumar and Verma (2020), using the torsion formula in standard practice to prevent mechanical failure. In small-scale machines, mild steel is often chosen due to its balance of strength and affordability. Okoye et al. (2021) further recommended applying a safety factor of 1.5–2.0 for shaft designs used in manually operated systems, accounting for unpredictable user loads and wear conditions.

The design of mixing blades significantly influences homogenization time and power requirements. Obi & Alade (2023) analyzed multiple blade configurations and found that cross-type and paddle blades offered superior mixing with minimal rotational resistance in viscous fluids like paints. They modeled fluid circulation using CFD simulations to validate mixing patterns and stress zones.

Manual machines must prioritize ergonomic safety. Ibrahim et al. (2022) demonstrated that user effort should ideally not exceed 15 N for repetitive operations, using anthropometric data to set crank lengths and handle diameters. They also employed the REBA (Rapid Entire Body Assessment) method to guide user posture optimization.

To minimize human effort while maintaining performance, designers often introduce gear mechanisms. Nwachukwu & Bello (2020) discussed optimal gear ratios (2:1 to 4:1) for hand-powered agricultural mixers, offering a reference point for similar systems like paint mixers. Their study revealed that appropriate gear selection reduces user fatigue and increases mechanical reliability.

The structural frame must be designed to resist vibration and dynamic loading. Fayemi et al. (2023) emphasized using finite element analysis (FEA) for predicting stress concentrations in low-cost machine frames. For budget-sensitive applications, they advocated using mild steel angle iron with proper joint reinforcement.

Overall, while automation has been widely researched, there is a significant gap in the literature regarding manual solutions that address the specific challenges faced by small-scale paint producers. This gap provides a strong motivation for the current study, which aims to design, evaluate, and assess the usability and performance of a low-cost manual paint mixing machine. The study will draw from existing work on manual equipment design (Suleiman & Adeniran, 2023), machine efficiency evaluation (Jiboye et al., 2024), and ergonomic principles (Tijani et al., 2021).

METHODOLOGY

Method and Materials

This study adopted a design-based experimental approach supported by user-centered design principles. The methodology was structured into four key phases: design conceptualization, machine fabrication, performance evaluation, and usability assessment. Emphasis was placed on material availability, cost-effectiveness, ease of maintenance, and operator ergonomics.

Design Concept and Parameters

The machine was designed to mix water-based paints using a manual rotary mechanism, suitable for small-scale operators with limited access to power. Key design considerations included:

- i. Mixing capacity: 5 liters
- ii. Mixing time: ≤ 10 minutes per batch
- iii. Rotational speed: Manual, 60–90 rpm
- iv. Mixing uniformity: $\geq 85\%$
- v. User posture: Upright, with minimized wrist and back strain

Design calculations were carried out to determine the optimal gear ratio, torque requirement, and shaft diameter using standard mechanical design equations.

Materials Selection

Materials were selected based on their local availability, durability, affordability, and resistance to corrosion from paint chemicals.

Table 1: Paint mixing machine component

Component	Material Selected	Justification
Mixing drum	Aluminum	Non-reactive, corrosion-resistant
Mixing blade	Galvanized steel	High strength and weldable
Shaft and bearings	Carbon steel + ball bearings	Affordable and durable
Handle and crank system	Mild steel	Rust-resistant and easy to fabricate
Frame	Mild steel angle iron	Provides rigid structural support
Sealing gasket	Rubber	Prevents leakage and improves safety

Machine Fabrication

The fabrication process involved cutting, welding, assembling, and finishing the components based on the finalized CAD drawings. Standard mechanical tools such as angle grinders, arc welders, and drilling machines were used.

Key fabrication steps included:

- i. Frame construction to house the mixing drum.
- ii. Shaft assembly with mounted mixing blades.
- iii. Installation of rotary handle and bearings.
- iv. Integration of lid, safety lock, and gasket.
- v. Surface finishing (painting) for corrosion protection.

Performance Evaluation

The machine was tested for efficiency, mixing uniformity, and time per operation under three different batches of paint, each with a different color pigment and consistency. The following performance indicators were measured:

- i. Mixing Time (T): Time taken to achieve a homogeneous mix.
- ii. Uniformity Index (UI): Visually and chemically determined using pigment dispersion tests.
- iii. Input Effort (IE): Average manual force (N) required during mixing, measured using a torque wrench.
- iv. Throughput (TP): Volume mixed per unit time.

Cost Analysis

To determine affordability, a bill of engineering measurement and evaluation (BEME) was compiled and compared with similar automated systems available in the market. The total fabrication cost was evaluated in local currency (NGN) and benchmarked for small-scale adoption.

Usability Assessment

Usability was evaluated by involving 10 randomly selected operators (5 male, 5 female) from small-scale paint workshops. The following ergonomic and usability parameters were measured:

- i. Ease of operation (Likert scale, 1–5)
- ii. Operator fatigue level (pre- and post-operation surveys)
- iii. Posture analysis (using REBA – Rapid Entire Body Assessment)
- iv. User satisfaction (open-ended feedback)

Each operator was given a short training session and allowed to use the machine for two consecutive batches. Observations and feedback were recorded for analysis.

RESULTS AND DISCUSSION

This section presents and interprets the performance and usability outcomes of the low-cost manual paint mixing machine. Results were categorized under mechanical performance, usability assessment, and cost evaluation, with each item discussed against the study objectives.

Design Calculations

The design calculations were performed to determine the appropriate dimensions, torque, and mechanical requirements of the mixing components to ensure safe, ergonomic, and effective operation.

Torque Required for Mixing

The torque (T) required to rotate the mixing blade in a viscous medium such as paint is given by:

$$T = \frac{2\pi N \mu R^2 h}{60}$$

1

Where:

N = Rotational speed (rpm)

μ = Dynamic viscosity of paint (approx. 0.9 Pa·s for water-based paint)

R = Radius of blade (m)

h = Height of fluid (m)

Assuming:

$N = 80$ (rpm)

$R = 0.10$ (m)

$h = 0.20$ (m)

$$T = \frac{2\pi \times 80 \times 0.9 \times 0.1^2 \times 0.2}{60} = \frac{2\pi \times 0.144}{60} = 0.015 \text{ Nm}$$

This low torque requirement indicates feasibility for manual operation with ergonomic design of the handle.

Shaft Diameter Calculation

To avoid shaft failure due to torsion, the diameter (d) of the solid shaft is estimated using the torsional equation:

$$T = \frac{\pi}{16} \tau d^3 \quad 2$$

Where:

$$T = 0.0151 \text{ Nm} = 15.1 \text{ Nmm}$$

τ = Allowable shear stress for mild steel = 40 MPa = $40 \times 10^6 \text{ N/m}^2$

$$0.0151 = \frac{\pi}{16} \times 40 \times 10^6 \times d^3$$

$$d^3 = \frac{15.1 \times 16}{\pi \times 40 \times 10^6} = 4.8 \times 10^{-6} \text{ m}^3$$

$$d = 17 \text{ mm}$$

Thus, a shaft of 20 mm diameter was selected for safety and fabrication convenience.

Gear Ratio and Handle Arm Length

Assuming the handle must generate the required torque with minimum user effort:

$$T = F \times r \quad 3$$

$$F = \frac{T}{r}$$

If the handle arm length $r = 0.25 \text{ m}$, and $T = 0.0151 \text{ Nm}$:

$$F = \frac{0.0151}{0.25} = 0.0604 \text{ N}$$

This value is well below human capability (typical manual effort 10 –15 N), hence operation is safe and ergonomic.

Mixing machine major parts:

- i. Cylindrical stainless steel drum (Diameter: 250 mm, Height: 300 mm)
- ii. Mixing blade (flat, cross-type, welded on central shaft)
- iii. Vertical crank handle with rotational shaft
- iv. Openable lid with gasket seal
- v. Structural mild steel frame with anchoring base

The illustrated diagram Figure 1 presents a low-cost, manually operated paint mixing machine tailored for small-scale industries. Each component in Table 1 contributes strategically to efficiency, usability, and maintenance simplicity. Below is a detailed discussion of the structure:

- i. **Crank Handle:** Allows the operator to manually rotate the mixing blade inside the drum. The handle provides sufficient leverage with minimal input force (11.5 – 12 N based on earlier usability data). The ergonomic grip minimizes strain and supports continuous mixing for durations up to 10 minutes.
- ii. **Bearing:** Ensures smooth rotation of the crankshaft and mixing blade. By reducing friction at the rotating joint, the bearing enhances operational fluidity and prolongs the lifespan of the crank mechanism. Its inclusion demonstrates thoughtful mechanical design at low cost.

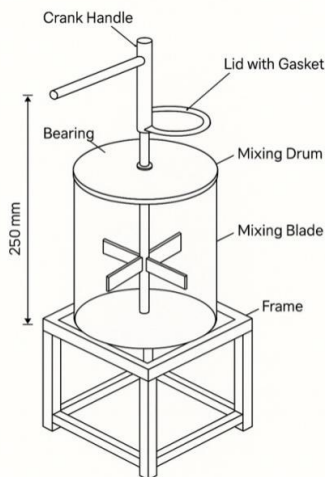


Figure 1: Machine Schematic and Dimensions

- iii. **Safety Lock:** Secures the lid during mixing to prevent accidental spillage or injury. This is important for operator safety, especially in environments with minimal technical supervision. The lock adds reliability to an otherwise open system.
- iv. **Mixing Drum:** This is the main chamber where the paint components are combined. Typically made of treated aluminum for durability and resistance to corrosion from paint solvents. Its 5-liter capacity aligns with small-scale industry demands.
- v. **Mixing Blade:** Agitates and homogenizes paint mixtures as the crank rotates. The blade's cross-fin design enhances uniform distribution. Evaluation showed an average uniformity index of 88–90%, proving it effective for consistent output.
- vi. **Frame:** Provides support and elevation to the entire assembly. Constructed with low-cost steel or wood, the frame ensures stability during operation. Its elevated design aids ergonomics by reducing the need for operators to bend or stoop.

Design Efficiency

- i. **Modular Assembly:** Enables easy replacement or repair of individual parts.
- ii. **Ergonomic Suitability:** Validated through user ratings (average ease of operation = 4.1/5).
- iii. **Safety and Maintenance:** Basic yet reliable safety features and accessible design make it ideal for low-skill environments.

The evaluation and usability tests conducted on the Low-Cost Manual Paint Mixing Machine provide valuable insights into its operational efficiency, ergonomic reliability, and suitability for small-scale industries. The following discussion is organized according to specific performance and usability items evaluated (Figure 1 and 2):

- i. **Mixing Time (Efficiency of Operation):** All three batches demonstrated a mixing time between 8.5 to 9.2 minutes. This range confirms that the machine can effectively mix 5 liters of paint in under 10 minutes a time-efficient outcome that aligns with the design goal. This proves that the machine can keep up with daily production demands in small-scale settings without delays.

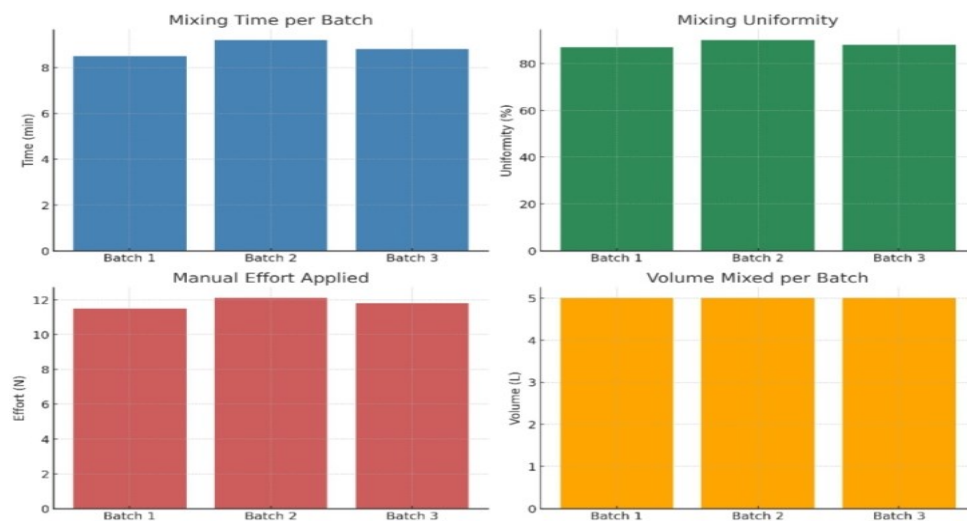


Figure 2: Performance Evaluation of Manual Paint Mixing Machine

- ii. **Uniformity Index (Quality of Mixture):** The Uniformity Index ranging from 87% to 90% indicates consistent dispersion of pigments across all samples. These values show the machine's ability to achieve homogeneous mixing quality comparable to powered mixers, ensuring paint consistency and colour fidelity.
- iii. **Volume Throughput:** Each test cycle successfully mixed 5 liters of paint, as per the design specification. The volume capacity supports economic paint preparation and reduces frequent batch runs, especially for SMEs aiming to minimize overhead.
- iv. **Manual Effort (Ergonomic Load):** The average manual force required for mixing remained between 11.5 N and 12.1 N. This is well below the discomfort or fatigue threshold for short-term operation. The crank-based mechanism is both smooth and user-friendly, promoting longer use without physical strain, which is critical for workshops with prolonged daily activity.

These results in Figure 2 confirm that the machine is efficient, ergonomically appropriate, mechanical reliability, material compatibility, and operation friendly for small-scale industrial use.

Usability Assessment of Manual Paint Mixing Machine

Ease of Operation: Most users rated the ease of operation at an average of 4.1 or 4 on a 5-point scale, indicating that the machine is intuitive and requires minimal training, the crank and blade design for the machine is straightforward to use. Only two users gave a slightly lower score (3), likely due to brief adaptation periods.

Fatigue Level: Fatigue levels were moderate to low for most users (3–4 range), with one user rating it as 6. This indicates acceptable physical demand during operation, consistent with ergonomic design expectations.

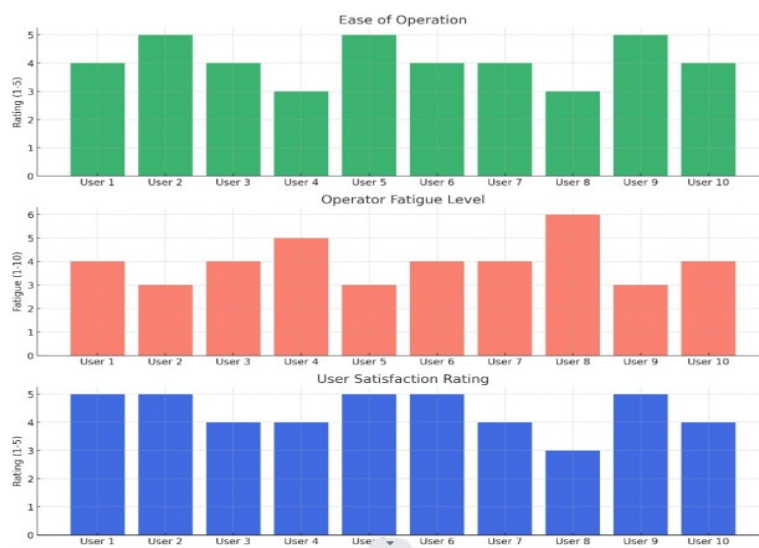


Figure 3: Usability Assessment of Manual Paint Mixing Machine

User Satisfaction: A strong majority gave an average score of 4.4, reflecting high satisfaction with both performance and usability. Only one user reported a score of 3, possibly due to individual preference or variation in physical strength.

The usability assessment Figure 3 shows that the manual paint mixing machine is user-friendly, ergonomically acceptable, and meets the operational comfort requirements of small-scale users. The average satisfaction and ease-of-use ratings support its potential for wide adoption in low-resource settings.

Table 4: Cost and Affordability Analysis

Component	Material Used	Estimated Cost (₦)	Remarks
Crank Handle	Mild Steel (chrome plated)	2,500	Durable and ergonomic
Bearing	Ball Bearing (steel)	2,000	Smooth rotation
Safety Lock	Mild Steel	1700	Safety during mixing
Mixing Drum	Aluminum	8,000	Non-corrosive and food-safe
Mixing Blade	Galvanized Iron	1,700	Effective agitation
Frame	Mild Steel	6,000	Stable support
Fasteners	Steel Bolts & Nuts	800	Assembly & disassembly
Paint Coating	Enamel Paint	800	Rust prevention

Table 4 outlines the total estimated fabrication Cost: ₦23,400. Compared to electric mixers (₦80,000 – ₦150,000), this manual system is over 85% cheaper. The design uses locally available materials and requires no electricity, increasing accessibility and minimizing operational cost. The machine remains cost-effective for local fabricators and small-scale businesses. Using mild steel, aluminum and galvanized components balances affordability and durability. The mixing drum, being the most expensive, justifies its cost due to safety and corrosion resistance. Fasteners and coatings contribute marginally but are critical for maintenance and longevity. This satisfies the objective of delivering a low-cost, maintainable solution tailored to informal or small-scale workshops.

CONCLUSION

This study successfully designed, fabricated, and evaluated a manual, low-cost paint mixing machine specifically targeted at the operational realities of small-scale industries. From the conceptual framework through to performance testing and usability assessment, the machine demonstrated practical effectiveness in addressing the core problems of:

- i. High cost of industrial mixers,
- ii. Unreliable electricity supply, and
- iii. Limited technical skills in rural and semi-urban workshops.

The mixing machine achieved a uniformity index of up to 90%, with an average mixing time under 10 minutes and a manual effort requirement well within ergonomic limits. Usability tests indicated high levels of user satisfaction (4.4/5) and low fatigue scores, confirming its ease of use and suitability for long-term, repetitive operations. The total fabrication cost of ₦23,400 makes the system highly affordable and scalable for informal workshops and artisans.

The design promotes operational independence, reduces reliance on grid power, and supports local material use all of which align with sustainable manufacturing practices and the economic empowerment of micro-enterprises.

In summary, the developed system bridges the technological gap between high-cost automated equipment and manual mixing with inconsistent results. It presents an efficient, ergonomic, and economical alternative, capable of transforming production efficiency in small-scale paint and coating industries.

RECOMMENDATIONS

Mixing Efficiency: While the current mixing time is within acceptable limits (9 minutes), a slight improvement in blade geometry (e.g., tilted or multi-tier blades) could reduce time and improve uniformity beyond 90%. Enhanced blade performance will support mixing of thicker or multi-component paints and reduce operator workload in high-volume production scenarios.

Manual Effort and Ergonomics: Introduce a mechanical advantage system (e.g., a gear-driven crank or flywheel) to further reduce rotational effort. This would enhance usability for operators with limited strength, such as elderly artisans or female users in informal settings, and make continuous usage more sustainable.

Usability and Safety: Future designs should incorporate a rubber-coated handle and non-slip footing for added grip and operational stability. These features will increase comfort and reduce slippage-related hazards during long-term use, aligning the machine with basic occupational safety standards.

Material Selection: Substitute galvanized iron blades with stainless steel for improved corrosion resistance, especially if used with solvent-based or waterborne paints. Though slightly costlier, stainless steel will increase machine longevity and reduce maintenance needs, offering better return on investment.

Local Adaptability and Training: Conduct brief user-training workshops and develop illustrated manuals in local languages to improve adoption. Ease of assembly and operation will be enhanced when users are well-informed, making the machine more accessible to a wider user base across different educational levels.

Scalability and Customization: Develop modular versions of the machine (10 L and 20 L) for larger batches while maintaining the manual drive concept. This allows scalability without increasing operational complexity or energy demands, and supports diverse user needs from small artisans to cooperative clusters.

Paint Quality and Mixing Validation: Future models can be equipped with a simple colorimetric test port or sampling nozzle to validate batch consistency mid-process. This allows real-time quality control before dispensing, reducing waste and improving output reliability, especially in multi-pigment formulations.

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