Production and Optimization of Standard Emulsion Paint Using Titanium Dioxide and Kaolin as Prime Pigment via Response Surface Methodology

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Abstract. The rising exchange rate between the naira and the US dollar has recently increased importation costs, making raw materials for emulsion paint production, like most commodities, more expensive. From those above, it becomes imperative to look inward for substitutes or supplements for some of these costly raw materials to bring down the cost of production without compromising the quality of products. In emulsion paints, the prime pigment is the second most expensive component. For instance, prime pigment (titanium dioxide) costs about 110 times higher than its local equivalent (kaolin). To reduce the production cost of emulsion paints, a study of the production and optimization of emulsion paints using mixtures of titanium dioxide (TiO_2) and kaolin as the primary pigment and polyvinyl acetate (PVA) as a binder was carried out using the Central Composite Design (CCD) software using the Surface Response Methodology (RSM) method. The paints were produced in a benchtop multifunctional batch mixer and analyzed using standard procedures. Results revealed that the best process variables using the CCD were TiO_2 (0.5 kg), kaolin (0.1 kg), and PVA (1.4 l), in addition to other paint ingredients, which are kept constant. The best paint sample (Run 5) produced had the following characteristics: viscosity (943 cP), pigment-to-binder ratio, PBR (3.65), and cost of production (₦ 10,108.00 per 20 l). On optimization, the optimum process variables were TiO_2 (0.5 kg), kaolin (0.1 kg), and PVA (1.28 l), in addition to other paint ingredients, which are kept constant. The Optimised/Validated paint produced had the following characteristics: viscosity (978 cP), pigment-to-binder ratio, PBR (3.98), and cost of production (₦ 9,616.00 per 20 l). Therefore, there was a 19.53 % reduction in the cost of production without compromising the quality of the paint produced. Instead, the hybridized pigment sample attained a slight increase in viscosity of 3.58 %, which still met the standard specification set by the Nigerian Industrial Standard (NIS).

Keywords: Cost of Production; Exchange Rate; Local Materials; Low Cost; Pigment Binder Ratio; Quality of Paints.

INTRODUCTION

An emulsion is called because the pigments are dispersed in water emulsified with an emulsifying agent. Emulsion paints are famous for their durability, easy-to-use features, and low cost. They can be used on exterior and interior walls, furniture, canvas, or other surfaces [1, 2].

Emulsion paints are also known as emulsified paints. Many types of emulsion paint are available, the most common being gloss, semi-gloss, matte, eggshell, or velvet. Emulsion paint comprises four main ingredients: pigment, emulsifier, coagulant, and water authors [3]. The functions of these four ingredients are as follows:

1. The pigment gives the paint its colour, which can be organic or inorganic.

2. The emulsifier binds the pigment to the water and helps keep it dispersed evenly throughout the mixture.

3. The coagulant is a substance that causes small particles to clump together, eventually forming paint droplets.

4. Finally, water is the solvent for all these ingredients.

The quality of emulsion paints can vary depending on the type of pigments used and the amount of solid content (pigment + emulsifier) in the mix. More advanced emulsion paints usually have better-quality pigments and emulsifiers, producing a more viscous emulsion [4].

The emulsion paint process is relatively simple, with a few steps involved. It is also important to note that emulsion paint requires no priming, sanding, or surface prepping before application [5]. The steps involved in the application of emulsion paints are:

1. First, the emulsion paint is thoroughly mixed to ensure there are no lumps in the mixture and it is evenly mixed.

2. After that, prepare the surface by removing dirt and debris.

3. The next step is applying the emulsion paint itself. Do this in three ways: Spraying, Brushing, and Rolling with a brush-like motion. Suppose a roller is used for the application. In that case, one must ensure that it is similar to what would be used on an exterior wall as they have thicker nap covers, allowing more emulsion paint to adhere, resulting in fewer strokes required.

After completing these steps, the painted surface must be allowed for several hours to dry before using the surface. Applying emulsion paint in thick coats or humid conditions may take longer to dry.

Features of emulsion paint. Emulsion paints must have low volatile organic compound (VOC) levels (low odour) to prevent harming those exposed to these fumes. They also allow exterior applications without harming others. Emulsified paints must achieve higher levels of shine, allowing an attractive final product, mainly when used on furniture or other decorative pieces. Emulsion paints must provide a long-lasting, durable surface to make them ideal for a house or apartment's interior and exterior walls. They should also resist mildew growth, making them perfect for bathrooms where moisture accumulates [2].

Types of emulsion paint. Two different types of emulsion paint are available, each with unique properties. That is the interior and the exterior emulsion paints: the interior is designed for use on interior surfaces such as walls, ceilings, and furniture. The interior paint comes in various finishes, including gloss, semi-gloss, matte, eggshell, and velvet. On the other hand, the exterior emulsion paint is formulated to withstand outdoor elements such as wind and rain. The exterior paint typically has a higher sheen level than its indoor counterpart and is available in both gloss and semi-gloss varieties authors [2, 5].

Usually, the pigment in an emulsion paint is of two types: the hiding/prime pigment (titanium dioxide) and the extender pigment (calcium carbonate). The hiding pigment is usually imported into Nigeria, while the extender pigment is abundant in the country. In an attempt to cut down the cost of production of emulsion paints, small-scale emulsion paints manufacturers have resorted to supplementing titanium dioxide with kaolin, which is readily available in abundance in the country and about 112.50 times cheaper than titanium dioxide. Until this study, there is no comprehensive engineering data on using kaolin to supplement titanium dioxide for emulsion paint production in the open literature. In addition, only a few pieces of literature are available on optimizing process variables of paint using software. The only literature closely related to this is the work of authors [6], who studied the production and optimization of pigments and binders in low-cost emulsion house paint using Response Surface Methodology (RSM). Still, their work does not consider blending prime pigments for economic gain. Therefore, this study aims to produce and optimize standard emulsion paints using kaolin to supplement titanium dioxide as hiding or prime pigment via the Central Composite Design of the Response Surface Methodology.

METHOD

The following sections present the procedures for producing paints and their quality parameters.

Paint Production. The required volume of water (5.2 l) was measured as indicated in the formulation table (Table 1b), transferred into a mixer, and started. Six kilograms (6 kg) of calcium carbonate was gradually dispersed into the mixing tank and allowed to grind for 5 minutes. Then titanium dioxide, kaolin (as indicated in Table 2a), and sodium tripolyphosphate (STPP) were dispersed in the required amounts and ground for another 10 minutes. At this stage, the researchers added 50% of the necessary quantity of brightener. As indicated in Table 1b, they added the other ingredients in the following order: defoamer (antifoam), texanol, genepur, and the preservative. The mixture was allowed to grind correctly, and then binder (PVA), as given in Table 2a, with the remaining 50 % brightener, was added and mixed correctly. Finally, the researchers gradually added the thickener and allowed it to mix appropriately before packaging. They then conducted quality parameter tests and examined the rheological properties of the produced paints.

Quality Parameter Tests. The rheological and pH tests were conducted on the twenty runs obtained by the Central Composite Design (Table 2a) and the Control Sample (Table 2b). In addition, the following quality parameter tests were carried out on the Control and Optimized paint samples using the following methods: viscosity (viscometer), pH (digital pH meter), colour (visual), drying time (stopwatch), brightness (visual observation), paint opacity and coverage authors [1] and bacterial/fungi analyses [7, 8].

Table 1a - Limits of Process Variables (Factors) and their Costs

Variable	Lower Limit	Upper Limit	Cost (₦ / kg)
Titanium Dioxide (TiO_2) (kg)	0.50	0.75	4,500
Kaolin (kg)	0.10	0.25	40
Polyvinyl acetate (PVA) (l)	1.20	1.40	2,000

Note: Prices of Raw Materials at the Open Market as of November 2023.

Table 1b - Other Common Ingredients in Paint and their Costs [9]

Component	Quantity	Cost (₦)
Water, l	5.2	20/l
Calcium Carbonate ($CaCO_3$), kg	6	120/kg
STPP, g	0.4	2600/kg
Brightener, ml	0.1	1500/l
Antifoam, g	40	400/kg
Genepur, g	40	400/kg
Taxanol, g	16	3000/kg
Preservative, g	40	1500/kg
Ammonia, ml	60	1500/l
Thickener, mg	50	12000/kg

Notes: Prices of Raw Materials at the Open Market as of November 2023.

Table 2a - Design of Experiment Using Central Composite Design

Run	TiO_2 (kg)	Kaolin (kg)	PVA (l)	Viscosity (cP)	Cost (₦)/20 l	PBR
1	0.625	0.3011345	1.3	1198	13,189.27	4.10
2	0.75	0.1	1.2	884	11,558.00	4.39
3	0.5	0.1	1.2	1030	9,308.00	4.23
4	0.835224	0.175	1.3	1008	12,731.02	4.15
5	0.5	0.1	1.4	943	10,108.00	3.63
6	0.625	0.0488655	1.3	630	10,828.91	3.95
7	0.625	0.175	1.3	605	10,839.00	4.02
8	0.625	0.175	1.3	387	10,839.00	4.02
9	0.5	0.25	1.4	342	10,120.00	3.71
10	0.625	0.175	1.131821	360	10,166.28	4.62
11	0.75	0.1	1.4	600	12,358.00	3.76
12	0.625	0.175	1.3	558	10,839.00	4.02
13	0.625	0.175	1.468179	805	11,511.72	3.56
14	0.5	0.25	1.2	840	9,320.00	4.33
15	0.625	0.175	1.3	556	10,839.00	4.02

Run	TiO_2 (kg)	Kaolin (kg)	PVA (l)	Viscosity (cP)	Cost (₦)/20 l	PBR
16	0.75	0.25	1.2	679	11,570.00	4.49
17	0.625	0.175	1.3	960	10,839.00	4.02
18	0.625	0.175	1.3	665	10,839.00	4.02
19	0.414776	0.175	1.3	408	8,946.98	3.90
20	0.75	0.25	1.4	555	12,370.00	3.85

Table 2b - Production of Emulsion Paint Using Only TiO2 as Prime Pigment

Run	TiO_2 (kg)	Kaolin (kg)	PVA (l)	Viscosity (cP)	Cost (₦)/20 l	PBR
Control	0.75	0	1.3	805	11,950.00	3.99

RESULTS AND DISCUSSION

The researchers used the central composite design of the Response Surface Methodology (RSM) for the experimental design in this study. The three-level – three-factor model was adopted with limits as provided in Table 1a, and the software generated twenty runs as presented in Table 2a. In addition, other joint paint ingredients and their prices are presented in Table 1b. The paint formulation in Table 1a and Table 1b is for the production of ten litres. However, to analyze the results, we scaled up the cost of production to 20 l.

Six of the twenty runs generated (Table 2a) were outliers (i.e., runs 1, 4, 6, 10, 13, and 19). Therefore, they were not considered for selecting the best production conditions because they could overestimate or underestimate the process conditions, which could lead to a fatal error. In addition, since the intention was to minimize the cost of production without compromising its quality, runs 3, 5, 6, 7, 8, 9, 12, 14, 15, 18, and 19 cost less than that of the control as presented in Table 2b. However, as a rule of thumb, in the paint industry, the minimum value of the viscosity of paint for application should not be less than 100 cP [10]. Also, according to NIS 269:2008, an excellent standard emulsion paint should possess a viscosity greater or equal to 600 cP. Therefore, runs 8, 9, 12, and 15 do not meet the second requirement. In addition, the PBR of runs 3, 7, 12, 14, 17, and 18 do not fall within an acceptable range of 1:1 and 1:4 by [10]. Therefore, run 5 with TiO_2 (0.5 kg), kaolin (0.1 kg), and PVA (1.4 l), in addition to other components presented in Table 1b, possessed all the qualities required for the production of emulsion paint at a low cost. Run 5 was selected as the best run for producing low-cost emulsion paint using the blend of TiO_2 and kaolin as a prime pigment.

Response 1 (Viscosity of Paint). As shown from ANOVA for Response 1 (viscosity), the viscosity is represented by a mean model with zero-sum of squares and degree of freedom as presented in Table 3.

Table 3 – ANOVA for Response 1 (Viscosity)

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model	0.0000	0			
Residual	20441.30	19	1075.86		
Lack of Fit*	17778.80	14	1269.91	2.38	0.1724
Pure Error	2662.50	5	532.50		
Cor Total	20441.30	19			

Note: * – not significant.

In addition, fit statistics revealed a standard deviation of 32.80, mean of 112.60, CV of 29.13 %, R^2 of 0.0000, adjusted R^2 of 0.0000 and predicted R^2 of - 0.1080. A negative predicted R^2 implies that the overall mean may better predict the response than the current model; in some cases, a higher-order model may also predict better. The comparison of the experimental and expected values is presented in Figure 1.

The lack of fit F-value of 2.38 implies that the lack of fit is insignificant relative to the pure error. Therefore, there is a 17.24 % chance that a lack of fit F-value this large could occur due to noise. A non-significant lack is good because we want the model to fit.

The regression model equation for response one is given by Equation 1.

$$Viscosity = + 700.650 \tag{1}$$

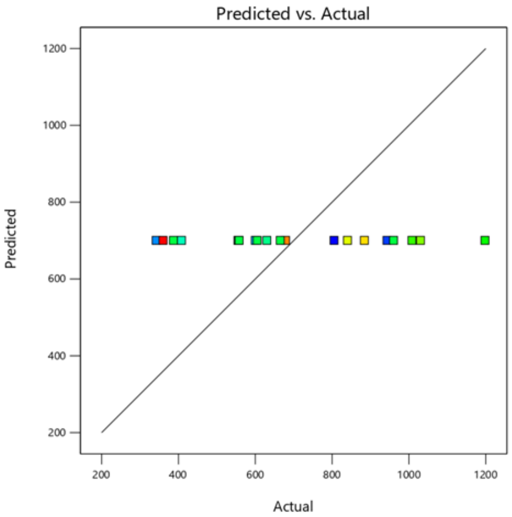

Figure 1 – Comparison of Experimental and Predicted Values for the Viscosity

Equation 1, in terms of coded factors, can be used to predict the response for a given level of each factor. By default, the high level of factors is coded as +1 and the low level as – 1. Equation 1 is helpful in identifying the relative impact of the factors by comparing the factor coefficients. This model does not depend on any factor but derives from their mean value.

Response 2 (Pigment to Binder Ratio). From the ANOVA for Response 2, The high F-value (40213.86) and lower P-value (below 0.05 at 95 % confidence) from the ANOVA findings (Table 4) illustrate the reliability of the model.

Table 4 - ANOVA for Response 2 (PBR)

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model*	1.45	9	0.1608	40213.86	< 0.0001
A-Titanium Dioxide	0.0752	1	0.0752	18814.38	< 0.0001
B-Kaolin	0.0271	1	0.0271	6773.18	< 0.0001
C-PVA	1.34	1	1.34	3.341E+05	< 0.0001
AB	0.0000	1	0.0000	0.0000	1.0000
AC	0.0003	1	0.0003	65.54	< 0.0001
BC	0.0001	1	0.0001	23.59	0.0007
A^2	4.457E-08	1	4.457E-08	0.0111	0.9180
B^2	4.457E-08	1	4.457E-08	0.0111	0.9180
C^2	0.0084	1	0.0084	2103.32	< 0.0001
Residual	0.0000	10	3.999E-06		
Lack of Fit	0.0000	5	7.998E-06		
Pure Error	0.0000	5	0.0000		
Cor Total	1.45	19			

Notes: * - Significant

The model R^2 value of 1.00 indicates an appropriate correlation between the observed and predicted values (Figure 2). The model F-value of 40213.86 implies the model is significant. There is only a 0.01 % chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are essential. A, B, C, AC, BC, and C^2 were significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The regression equation for response 2 revealed a quadratic model by Equation 2.

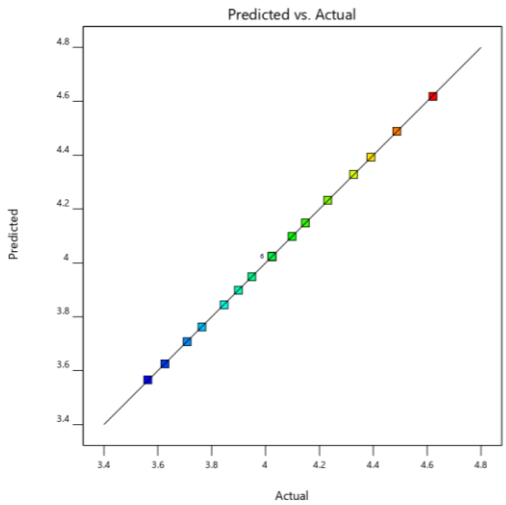

Figure 2 – Comparison of Experimental and Predicted Values for the Pigment to Binder Ratio

$$PBR = + 4.02 + 0.0742\,A + 0.044\,B - 0.3128\,C - 0.0000\,AB - 0.0057\,AC - 0.0034\,BC - 0.0001\,A2 - 0.0001\,B2 + 0.0242\,C2 \quad (2)$$

Equation 2 indicates the model equation for the three factors (TiO_2 (A), kaolin (B), and PVC (C)) against the response (PBR) in coded form. To predict the response for given levels of each factor, you can use the equation of the factors. By default, the high levels of the factors are coded as +1, and the low levels are coded as -1. The coded equation helps identify the relative impact of the factors by comparing the factor coefficients.

Response 3 (Cost of Production). From the ANOVA table (Table 5), the high F-value (27.07) and lower P-value (< 0.0500) imply the model is significant.

Table 5 - ANOVA for Response 3 (Cost of Production of Paint)

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model*	2.065E+07	3	6.884E+06	27.07	< 0.0001
A-Titanium Dioxide	1.728E+07	1	1.728E+07	67.98	< 0.0001
B-Kaolin	1.182E+06	1	1.182E+06	4.65	0.0467
C-PVA	2.185E+06	1	2.185E+06	8.59	0.0098
Residual	4.068E+06	16	2.543E+05		
Lack of Fit	4.068E+06	11	3.699E+05		
Pure Error	0.0000	5	0.0000		
Cor Total	2.472E+07	19			

Notes: * - Significant

There is only a 0.01 % chance that an F-value this large could occur due to noise. The Predicted R^2 of 0.9998 is in reasonable agreement with the Adjusted R^2 of 0.9999; i.e., the difference is less than 0.2. Adeq Precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable. In this case, the ratio of 744.018 obtained indicates an adequate signal. This model can be used to navigate the design space. The R^2 value of 1.0000 indicates an appropriate correlation between the observed and predicted values (Figure 3).

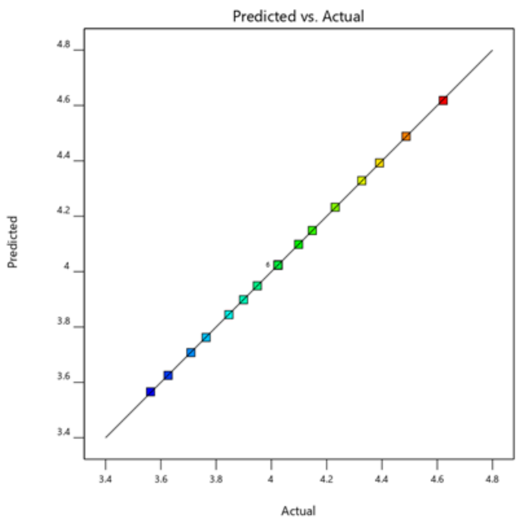

Figure 3 – Comparison of Experimental and Predicted Values for the Cost of Production of Paint

A linear model best fits the model equation, as presented in Equation 3.

$$Cost\ of\ Production = + 10956.01 + +1125.00\,A + + 294.18\,B + 400.00\,C \quad (3)$$

Equation 3, in terms of coded factors, can be used to predict the response for given levels of each factor. By default, the high levels of the factors are coded as +1, and the low levels are coded as -1. The coded equation helps identify the relative impact of the factors by comparing the factor coefficients.

Interaction Effects of Production Conditions. To clarify the relationship between factors, we developed 3-D diagrams using the corresponding regression model for each response: TiO_2, kaolin, and PVA on viscosity, pigment-to-binder ratio, and the cost of paint production (Figure 4).

Figure 4a shows the interactive effects of viscosity against TiO_2 and kaolin at constant PVA volume (1.3 l). It shows that as TiO_2 and kaolin increased from 0.5–0.75 kg and 0.1–0.25 kg, respectively, the paint's viscosity did not improve. This indicates that hiding pigments (TiO_2 and kaolin) at constant binder volume does not increase the paint's viscosity; this is justified by the model equation given by the mean value.

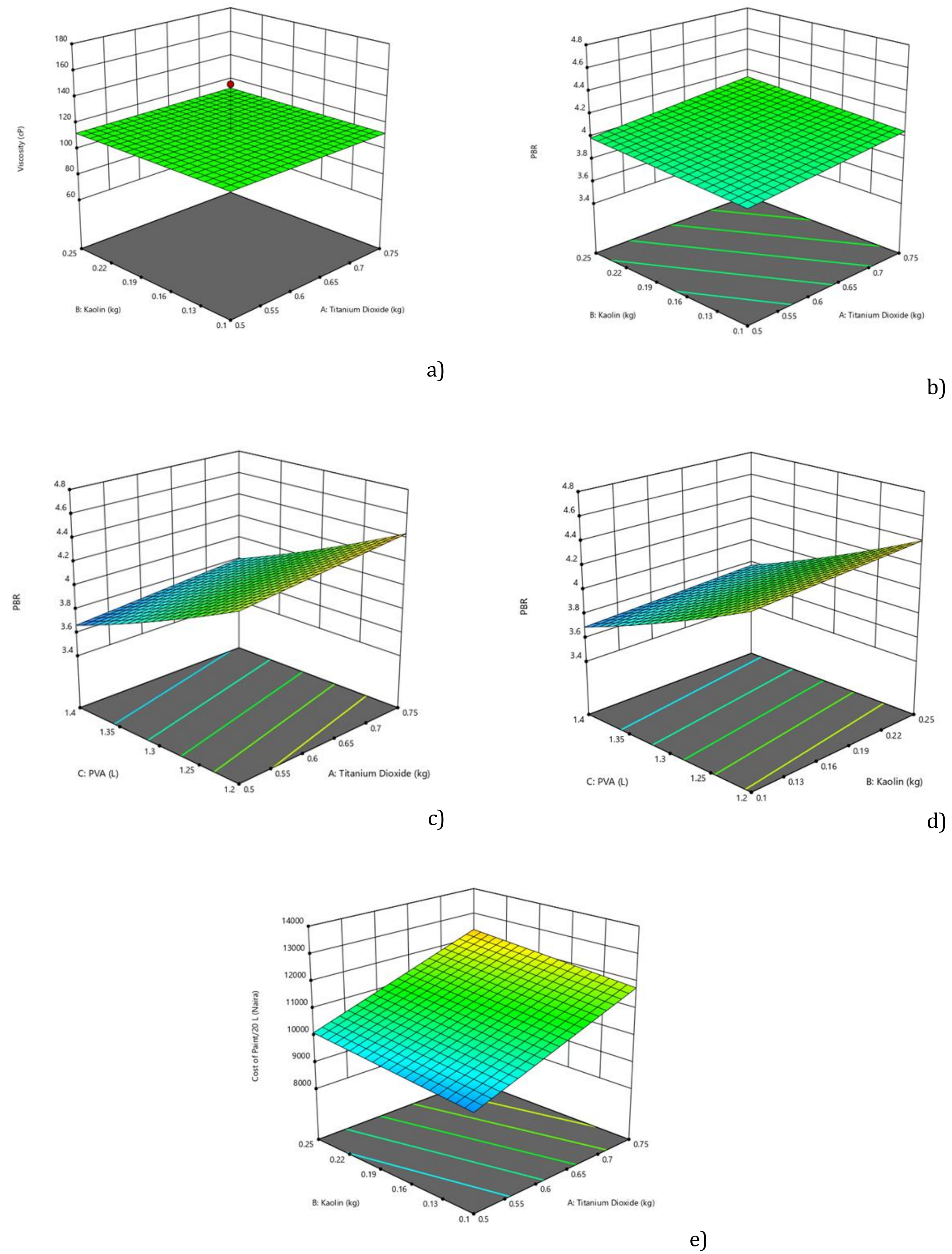

Figure 4 – 3-D Plot for the Interaction Effects between TiO_2, Kaolin, and their Responses (Viscosity, PBR, and Cost of Production)

In addition, Figures 4b, 4c, and 4d show the interactive effects of Pigment on PBR against TiO_2, kaolin, and PVA. From Figure 4 b (interaction effect of TiO_2 and kaolin on PBR), as the amounts of TiO_2 and kaolin increase from 0.5–0.75 kg and 0.1–0.25 kg, respectively, there is a corresponding increase in the PBR for both TiO_2 and kaolin, thus from 3.90 to 4.03 for kaolin and from 3.90 to 4.10 for TiO_2. The combination with the highest amount of kaolin (0.25 kg) and TiO_2 (0.75 kilograms) has the highest PBR (4.12), and that with the lowest combination of TiO_2 (0.5 kg) and kaolin (0.1 kg) has the lowest PBR (3.90). As expected, increased hiding pigments in the paint at constant binder volume impacts the PBR.

Figure 4c shows the interactive effects of TiO_2 and PVA at constant kaolin (0.175 kg). As depicted, as the amount of TiO_2 increases from 0.5–0.75 kg, there is a corresponding increase in PBR from 4.2–4.42. On the other hand, as the PVA volume rises from 1.2 to 1.4 L, the PBR decreases from 4.2 to 3.65; this is so because a low amount of TiO_2 in a low volume of PVA results in high PBR; a similar observation would result if the amount of TiO_2 is high and at a high PVA volume. However, at a low amount of TiO_2 and a high volume of PVA, the PBR decreases and vice versa.

Figure 4d shows the interactive effects of kaolin PVA at a constant amount of TiO_2 (0.625 kg). As depicted, as the amount of kaolin increases from 0.1–0.25 kg, there is a corresponding increase in PBR from 4.0–4.40. On the other hand, as the PVA volume rises from 1.2 to 1.4 l, the PBR decreases from 4.0 to 3.65; this is so because a low amount of kaolin and low volume of PVA results in high PBR; a similar observation would result if the amount of kaolin is high and at high PVA volume. However, the PBR decreases at low kaolin and high PVA volume and vice versa.

Furthermore, Figure 4e shows the interactive effects of the cost of production against TiO_2 and kaolin at a constant PVA of 1.3 L. From Figure 4e, at the highest combination of kaolin (0.25 kg) and TiO_2 (0.75 kg), the cost of production is highest (₦ 12,350.00). Similarly, at the lowest combination of kaolin (0.10 kg) and TiO_2 (0.50 kg), the cost of production is the lowest (₦ 9,550.00). It could also be seen that as the amounts of TiO_2 and kaolin increase from 0.5–0.75 kg and 0.1–0.25 kg, respectively, there are corresponding increases in the cost of production from ₦ 9,550.00 – ₦ 11,783.00 for TiO_2 and from ₦ 9,550 to ₦ 10,126.50 for kaolin as would be expected. This is because TiO_2 is expensive; the more TiO_2 is in a paint, the higher the cost of production of the paint. On the other hand, kaolin, which is also a hiding pigment, is cheap (i.e., ₦ 40/kg) but low in brightness. Thus, kaolin should not be used large enough for white paint. Therefore, a proper blend of the amount of TiO_2 and kaolin would result in a low cost of paint production without compromising the paint's quality.

Optimization of Cost of Paint Production. The main goal or objective function is to minimize production cost and the optimization constraints presented in Table 6. The RSM numerical optimization method is used.

Table 6 - Optimization Constraints

Name	Goal	Lower Limit	Upper Limit
A: Titanium Dioxide (kg)	is in range	0.5	0.75
B: Kaolin (kg)	is in range	0.1	0.25
C: PVA (L)	is in range	1.2	1.4
Viscosity (cP)	is in range	342	1198
PBR	is in range	3.5	4.5
Cost of Paint of Production /20 L (₦)	minimize	8946.98	13189.30

Based on the objective function and constraints in Tables 5 and 6, solutions with a desirability of 0.779–0.955 were found (Table 7). The higher the desirability, the lower the cost of production, and vice versa. For these optimized solutions, the cost of production ranged between ₦ 9,136.82 and ₦ 9,886.29 per 20 l of emulsion house paint. The optimized cost of production was between 17.36–23.54 % less compared to the control (₦ 11,950.00), as presented in Table 2b. Although, the software suggested Solution 1 with the least cost and the highest desirability. However, solution 48 was selected because it combined the required viscosity and PBR (3.99) as in that of the control. Therefore, optimized process conditions are TiO_2 (0.500), kaolin (0.100), PVA (1.273), and its corresponding responses are Viscosity (700.65 cP), PBR (3.98) and Cost of Production (₦ 9,443.57) with the desirability of 0.883. Based on this optimum condition, expect a 21 % reduction in the cost of production compared to the control; this represents a meaningful contribution to knowledge as the results of this study could reduce the commodity's price, making it more affordable for citizens.

Table 7 - Optimized Solutions

Number	Titanium Dioxide	Kaolin	PVA	Viscosity	PBR	Cost of Paint/20 l	Desirability
1	0.500	0.100	1.200	700.650	4.233	9136.824	0.955
2	0.500	0.101	1.200	700.650	4.233	9139.448	0.955
3	0.500	0.100	1.201	700.650	4.230	9140.323	0.954
4	0.500	0.102	1.200	700.650	4.234	9144.076	0.954
5	0.501	0.100	1.200	700.650	4.232	9146.903	0.953
6	0.500	0.100	1.203	700.650	4.224	9147.051	0.953
7	0.500	0.103	1.200	700.650	4.235	9148.878	0.952
8	0.501	0.101	1.200	700.650	4.234	9149.101	0.952
9	0.500	0.105	1.200	700.650	4.235	9154.628	0.951
10	0.500	0.100	1.205	700.650	4.215	9156.317	0.951
11	0.502	0.101	1.200	700.650	4.234	9157.372	0.950
12	0.503	0.100	1.200	700.650	4.234	9163.707	0.949
13	0.500	0.100	1.209	700.650	4.202	9171.590	0.947
14	0.504	0.100	1.200	700.650	4.235	9172.296	0.947
15	0.500	0.111	1.200	700.650	4.240	9179.752	0.945
16	0.500	0.100	1.211	700.650	4.195	9180.334	0.945
17	0.500	0.112	1.200	700.650	4.240	9182.194	0.945
18	0.500	0.113	1.200	700.650	4.241	9186.408	0.944
19	0.500	0.114	1.200	700.650	4.241	9190.752	0.943
20	0.500	0.115	1.200	700.650	4.242	9194.399	0.942
21	0.506	0.102	1.200	700.650	4.238	9197.599	0.941
22	0.500	0.100	1.216	700.650	4.178	9199.084	0.941
23	0.500	0.116	1.200	700.650	4.243	9199.262	0.941
24	0.500	0.118	1.200	700.650	4.244	9207.404	0.939
25	0.500	0.119	1.200	700.650	4.245	9212.734	0.937
26	0.500	0.100	1.219	700.650	4.165	9214.602	0.937
27	0.500	0.100	1.221	700.650	4.158	9222.363	0.935
28	0.511	0.100	1.200	700.650	4.240	9235.958	0.932
29	0.500	0.129	1.200	700.650	4.251	9250.068	0.929
30	0.500	0.132	1.200	700.650	4.253	9262.121	0.926
31	0.500	0.100	1.232	700.650	4.124	9263.421	0.925
32	0.500	0.138	1.200	700.650	4.257	9285.901	0.920
33	0.500	0.144	1.200	700.650	4.261	9308.478	0.915
34	0.500	0.100	1.243	700.650	4.085	9310.179	0.914
35	0.500	0.100	1.247	700.650	4.074	9323.163	0.911
36	0.500	0.100	1.248	700.650	4.070	9327.317	0.910
37	0.500	0.100	1.253	700.650	4.053	9349.066	0.905
38	0.500	0.154	1.200	700.650	4.267	9349.523	0.905
39	0.500	0.100	1.259	700.650	4.033	9372.734	0.900
40	0.500	0.100	1.260	700.650	4.031	9375.659	0.899
41	0.500	0.161	1.200	700.650	4.272	9376.868	0.899
42	0.501	0.163	1.200	700.650	4.273	9391.693	0.895
43	0.500	0.100	1.264	700.650	4.016	9394.465	0.895
44	0.530	0.100	1.200	700.650	4.252	9408.309	0.891
45	0.500	0.100	1.268	700.650	4.005	9408.425	0.891
46	0.500	0.100	1.269	700.650	4.001	9412.567	0.890

Number	Titanium Dioxide	Kaolin	PVA	Viscosity	PBR	Cost of Paint/20 l	Desirability
47	0.533	0.100	1.200	700.650	4.254	9437.577	0.884
48	**0.500**	**0.100**	**1.277**	**700.650**	**3.977**	**9443.565**	**0.883**
49	0.500	0.183	1.200	700.650	4.286	9461.390	0.879
50	0.500	0.185	1.200	700.650	4.287	9469.538	0.877
51	0.500	0.100	1.284	700.650	3.955	9471.437	0.876
52	0.540	0.100	1.200	700.650	4.258	9497.849	0.870
53	0.500	0.204	1.200	700.650	4.299	9544.613	0.859
54	0.500	0.206	1.200	700.650	4.300	9550.691	0.858
55	0.548	0.100	1.200	700.650	4.264	9572.974	0.852
56	0.500	0.222	1.200	700.650	4.311	9615.316	0.842
57	0.500	0.233	1.200	700.650	4.318	9658.645	0.832
58	0.500	0.236	1.200	700.650	4.320	9670.691	0.829
59	0.500	0.250	1.240	700.650	4.188	9886.288	0.779

The chosen optimized solution, i.e., solution 48 (Table 7) with the following factors: TiO_2 (0.500 kg), kaolin (0.100 kg), and PVA (1.277 L) were validated by re-running the experiment in the laboratory, and the average of triplicate determination of the responses (viscosity, PBR and cost of production) recorded as observed results as presented in Table 8. The percentage error between the predicted and observed values calculated using Equation 4 authors [11]:

$$\% \text{ Error} = \left|\frac{\text{Observed} - \text{Predicted}}{\text{Observed}}\right| \times 100 \quad (4)$$

The percentage errors for responses, PBR, and cost of production were 0.43 and 1.79, respectively, within the acceptable limit of 0–10 % authors [10]. Therefore, Equation 2–3 above can be utilized to predict the production of low-cost emulsion paint using TiO_2 supplemented with kaolin. However, the percentage error for the viscosity was 28.36 %, which is far above the acceptable limit of 10 %. Therefore, Equation 4 is not a good predictor of the viscosity of a paint because the viscosity is a function of the viscosities used in the paint. In this study, the amount of viscosifier used was kept constant. Hence, the model equation was given by a mean value and a poor regression coefficient. Furthermore, we should consider comprehensively optimizing the three factors considered in this study (i.e., TiO_2, kaolin, and PVA) and viscosities for a realistic prediction of emulsion paint. Table 8 compares the predicted and optimized results and their percentage errors.

Table 8 – Comparison Between Predicted and Optimized Results

Response	Predicted Mean	Predicted Median	Observed	Percentage Error (%)
Viscosity (cP)	700.65	700.65	978.00	28.36
PBR	3.997	3.997	3.98	0.43
Cost of Paint/20 L (₦)	9443.57	9447.57	9616.00	1.79

Quality Parameters of the Control and Optimized Paint Samples. The quality parameters of the Control and Optimized samples were analyzed; the parameters considered were viscosity, pH, specific gravity, drying time, bacterial/fungi growth colour, coverage, and opacity, as presented in Table 9.

The paint produced using the blend of TiO_2 and kaolin, termed optimized, achieved a viscosity of 700.65 cP during optimization (predicted), and during validation, we observed a viscosity of 978.00 cP. The paint produced (observed) exhibited higher viscosity than the control (without kaolin); this could attributed to the ability of kaolin to improve the viscosity of paint in addition to its other functions [12]. These values exceeded the minimum of 600 cP required by the [7] for standard emulsion paints. Therefore, the viscosity of emulsion paints produced in this study fell within the standard.

Table 9 – Quality Parameters of Control and Optimized/Observed Paint Samples

Parameter	Control	Optimized/Observed	Standard
Viscosity (cP)	805.00	700.65/978.00	> 600 [7]
pH	8.5	8.4	7.0-9.0 [7]
Specific Gravity	1.36	1.24	[8]
Drying time (minutes)	15	14	20 Max. [7]; 15-30 [8]
Bacteria Growth (cfu/ml)	NG	NG	Nil [7, 8]
Fungi Growth (cfu/ml)	NG	NG	Nil [7, 8]
Colour	Brilliant White	White	Brilliant White
Opacity/Coverage (m^2/l)	Good/8.2	Good/8.2	Good/8.0 [7]

The pH of the Control and Optimized samples were 8.50 and 8.40, respectively. These values were within the range of 7.0 and 9.0 required by the [7] for standard emulsion paints. Therefore, the pH for the samples complied with the standard.

The specific gravity of the Control and Optimized paint samples were 1.36 and 1.24, respectively; this is unexpected because pure TiO_2 with a particular gravity of 4.26 produced the control. In contrast, we used a blend of TiO_2 with a specific gravity of 4.26 and kaolin with a specific gravity of 2.65 for the optimization. The range of particular gravity obtained in this study was 1.2–1.6, specified by [8].

When applied on a clean wall, the drying times for the control and the Optimized paint samples were 15 and 14 minutes, respectively. The drying time for both paint samples fell below the maximum of 20 minutes specified by the [7, 8].

Bacterial and fungi analysis of the Control and Optimized paint samples revealed no bacterial or fungi growth within six months of storage. Additionally, no fungus was observed at the point of application six months later. Therefore, the produced paints comply with the standards [7, 8].

From the results obtained for the opacity/coverage, visual observation revealed excellent opacity after the second coating. 1 L of paint covered a surface area of 8.2 m^2 of ceiling board, above the minimum of 8.0 m^2/l specified by [7].

CONCLUSIONS

The study drew the following conclusions:

1. The best paint produced using hybridized prime pigment had the following process variables: TiO_2 (0.5 kg), kaolin (0.1 kg), and PVA (1.4 l) with the following responses: viscosity (943 cP), PBR (3.96), and cost of production (₦10,108.00 per 20 l); this indicates a reduction of 15.41 % when compared with the control.

2. The optimization of paint produced using hybridized prime pigment revealed the following process variables: TiO_2 (0.5 kg), kaolin (0.1 kg), and PVA (1.28 l), with the following responses: viscosity (978 cP), PBR (3.98), and cost of production (₦ 9,616.00 per 20 l). This indicates a reduction of 19.53 % when compared with the control and 4.87 % compared with the best-hybridized sample (Run 5).

3. Model equations obtained for producing standard emulsion paints using a hybrid of TiO_2 and kaolin as prime pigment are (1)–(3). Equations 2–3 effectively predict the various parameters for standard emulsion paints. However, Equation 1 cannot because it is given by mean value.

4. The quality of paints produced by those using hybridized prime pigment and the control complied with the Nigerian Industrial Standard (NIS) and East African Standard (EAS) for standard emulsion paint.

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