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Influence of Roof Material and Angle of Tilt on Quantity of Harvested Rainwater: Modeling and Optimization

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Abstract: Rainwater harvesting is an approach which provides loads of benefits to plants, animals and human lives for survival. On this basis, a small-scale rainwater harvesting structure was constructed at the Adeleke University Teaching and Research Farm Ede, Osun-State. This study investigated the influence roof material and angle of tilt on the volume of harvested rainwater. Four mini-structures were constructed with different roof materials (Aluminum, Fiber, Asbestos and Biomass based materials) and each roof material was constructed with an adjuster to set the roof surface to three major tilt angles (35, 40 and 45^0). The volume of harvested rainwater harvested was measured for various samples. The statistical analysis showed that all the variables affect the volume of harvested rainwater. Modeling result gave the optimal condition of 45^o tilt angle and biomass based roof material which gave 5.27 litres of water. The model developed developed has a R^2 value of 97% which showed a good agreement. More concerted efforts should be geared towards public sensitisation for an increased public interest to harvest more rainwater for domestic uses like irrigation farming and other farm operations especially in places with water scarcity areas where there is low annual rainfall.

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1. Introduction

Water is essential for every living organism on earth. It is a life-giving liquid for all living organisms (Brainly, 2017; Achadu *et al.,* 2013) which can be used for many activities such as cleaning, washing, cooking, drinking and irrigation. The dimensions of the global water crisis are massive for instance, some 2.2 billion people globally do not have access to safe drinking water, 4.2 billion people do not have access to safely managed sanitation services and 3 billion lack basic water availability for hand-washing facilities (WHO, 2019). At least 3-4 million people dies yearly of water related diseases, a large portion of them which are children (Rehydration Project, 2020). Water is a natural and environmental resource which is very important and indispensable (Chang *et al.,* 2014), it is in high demand (Aderogba, 2005) and it represented a unique characteristic for drinking, washing, sanitation, farming, recreation and industrial processes in every settlement.

Globally, people are searching for solutions to water shortages and in many ways the harvesting of rainwater offers a main way out of the water scarcity. Depending on the situation there are several different ways to collect rainwater, it may be collected from building roofs in many regions of the world, and stored in tanks above or below ground (Benjamen *et al.,* 2019) and in certain areas where geological characteristics do not support the use of wells/boreholes, extracting rainwater may also be a realistic alternative in dealing with an increasing population and the consequent rise in per capita water consumption in Nigeria (Biplob and Bablu, 2014). The most common method however is to harvest rainwater from tops which has a direct influence on both the quantity and quality of the water collected. This study examined the effect of roof materials and tilt angle on the quantity of harvested rainwater and also developed an empirical model to predict the relationship between the roof materials, angle of tilt and the volume of harvested rainwater.

2. Material and Methods

2.1 Study Area

The experiment was carried out at Adeleke University Teaching and Research Farm, Ede, Osun State, Nigeria. The study area was located between Longitude 4°43’0” and 4°59’0” E and Latitude

7°43’0” and 7°50’0” N with an elevation of 353 m above sea level. The average rainfall of study area over the years is about 1,500 mm whereas the daily minimum temperature varied from 20-22 °C and maximum temperature varied from 27 and 35°C.

2.2 Experimental Design

The experimental set up is presented in Table 1, it was conducted in a 4 × 3 completely randomized block design with three replicates. The roof materials used are aluminium, fiber, asbestos and biomass-based materials while the tilt angle are 35, 40 and 45^0. This implies that each roof material was tilted three times based on the selected angles of tilt.

Table 1: Experimental design of rainwater harvest using randomized block design (RBD)

1_{30}	1_{40}	1_{45}
2_{30}	2_{40}	2_{45}
3_{30}	3_{40}	3_{45}
4_{30}	4_{40}	4_{45}

(1 – Aluminum roof; 2 – Fibre roof; 3 – Asbestos roof; and 4 – Biomass based *roof material; subscripts are the angles of tilt 30º*, 40º and 45º).

2.3 Experimental Procedures

The experiment was designed in such a way that four (4) mini-structures were constructed with different roof materials (Aluminum, Fiber, Asbestos and Biomass based materials); they placed in the open field and rainwater was collected over each roof material directly into a close container. Each of the mini structure was constructed with an adjuster to set the roof surface to three major tilt angles (35, 40 and 45^0). The mini-structure measures 1.0x0.50. Roof gutters were connected to the edge of each roof to harvest the rainwater coming from the roofing sheets and a 5.0 liter plastic bucket was used to collect the rainwater separately from each roof. An extra bucket that served as control was placed on the open field to harvest rain water directly from the sky. The volume of water harvested was measured using an electronic weighing machine.

2.4 Data Analysis

In setting constraints for optimization of the volume of harvested rainwater, the independent variables were set at the range of levels used for the experiment while the volume of water harvested was maximised. In order to correlate the response variable to the independent variables, empirical models were developed. The empirical data was used to predict the relationship between the independent and dependent variables by applying multiple linear regressions. Six different models (mean, linear, two factorial interactions, quadratic models, cubic and quartic) were used to represent relationship between roof materials, angle of tilt and the corresponding volume of harvested rainwater. The global predictive equation from which specific solution may be derived is presented in Equation 1 (Ogunlade and Aremu, 2019):

$$Y = \beta_o + \sum_{i=1}^{k} \beta_i X_i + \sum_{i<} \sum_{j=3}^{k} \beta_{ij} X_i X_j X_k + \sum_{i=1} \sum_{j=1}^{k} \delta_{ij} X_i X_j X_k + \boldsymbol{\varepsilon} \quad (1)$$

where: Y is the measured system response (water quantity and quality)

β_o is the model intercept,

$\sum_{i=1}^{k} \beta_i X_i$ characterises the main linear effects of individual process variables (roof materials and angle of tilt)

$\sum_{i<} \sum_{j=2}^{k} \beta_{ij} X_i X_j$ incorporates the interaction effects between variables $\sum_{i=1} \sum_{j=1}^{k} \delta_{ij} X_i X_j$ represents the main quadratic effects of the variables

$\boldsymbol{\varepsilon}$ is the random error of experimentation,

X_{ijk} represents the matrix of the encoded process variables

The determination of the unknown coefficients of $\boldsymbol{\beta}_o$, $\boldsymbol{\beta}_i$, $\boldsymbol{\beta}_{ij}$ and $\boldsymbol{\delta}_{ij}$ is accomplished via regression analysis implemented on the statistical analysis software Design Expert Version 10.0.1 using empirical data recorded from experimentations. For statistical analysis, the variables X_i (i= 1, 2, 3) were coded A, B, and C. The determination of unknown coefficients applies design matrix formulated by judicious transformation of the actual values of the independent variables at various levels over which the experiments were executed to their coded equivalents using -1 and +1 notations to designate low and high level factor setting (Ogunlade and Aremu, 2020). It has been shown that working with the coded variables enhances matrix transformation and helps in result analyses (Uzoh and Okechukwu, 2016).

3. Results

The results from the effect of roof materials and tilt angle on the volume of harvested rainwater is presented in Table 1. The volume of harvested rainwater from the roof materials ranged from 3.57 to 6.97 liters with an average value of 4.77 (± 1.05) liters.

It was observed that roof materials and angle of tilt had significant influence on the volume of harvested rainwater as shown in Table 2 and an increase in the angle of tilt caused an increase in volume of water harvested. The highest volume of water harvested was obtained on biomass-based roof material followed by the Asbestos roof, fiber roof and Aluminium roof. The volume of water harvested is dependent on the friction on each roof surface that restricts movement of water, the rough surface nature of Aluminium might be the reason behind the low volume of water harvested. The angle of tilt at 45^o gave the maximum volume of harvested water on the four roof materials considered, a similar finding was reported by Evans et al. (2006). Quadratic model was suggested to represent the relationship between roof materials, angle of tilt and the volume of harvested rainwater. In Table 2, p-values less than 0.0500 indicate model terms are significant. In this case A, B, AB, B^2 are significant model terms and values greater than 0.1000 indicate the model terms are not significant.

Table 1: Experimental Data for Influence of Roof Material and Angle of Tilt on the volume of harvested rainwater

Samples	Roof Mat	Angle of tilt	Vh
1	1	30	4.65
2	1	40	3.66
3	1	45	4.68
4	2	30	4.40
5	2	40	4.03
6	2	45	5.61
7	3	30	3.57
8	3	40	4.59
9	3	45	6.34
10	4	30	3.98
11	4	40	4.75
12	4	45	6.97

(Roof materials: 1 – Aluminium roof; 2 – Fiber roof; 3 – Asbestos roof; and 4 – Biomass based roof material)

Table 2: Analysis of Variance (ANOVA) for the Volume of harvested water

Source	**Sum of Square**	**df**	**Mean**	**F val**	**P val**	
Model	11.71971	5	2.343943	43.03731	0.000127	Significant
A-Roof material	0.770647	1	0.770647	14.14991	0.00938	Significant
B-Angle of tilt	6.125	1	6.125	112.4616	4.14E-05	Significant
AB	2.79222	1	2.79222	51.26817	0.000374	Significant
A^2	0.001875	1	0.001875	0.034427	0.858915	Not Significant
B^2	2.884716	1	2.884716	52.96649	0.000343	Significant
Residual	0.326778	6	0.054463			
Cor Total	12.04649	11				

A-Roof material, B- angle of tilt, AB – interactions between roof material and angle of tilt

Equation 1 shows the developed model representing the relationship between roof materials, angle of tilt and the volume of harvested rainwater, the Model F-value of 43.04 implies the model is significant and there is only a 0.01% chance that an F-value this large could occur due to noise. The predicted R^2 of 0.8455 is in reasonable agreement with the Adjusted R^2 of 0.9503; i.e. the difference is less than 0.2. the positive terms in the equation represents a direct relationship between such independent variable and interaction with the volume of harvested rainwater (i.e. increase in such variable conduces increase in the corresponding volume of water), while negative terms represent an inverse relationship between the response and independent variable (indicating a decrease in volume of harvested rainwater value when the value of that independent variable is increased).

$$V_w = 35.22446 - 2.42829\,R_m - 1.64505\,A_t + 0.069186\,R_m.A_t + 0.0125\,{R_m}^2 + 0.021185\,{A_t}^2 \quad (1)$$

(S.D = 0.233, Mean = 4.77, R^2 = 0.97, Adjusted R^2 = 0.95, Predicted R^2 = 0.84, Adeq Precision = 20.4)

Where: Vw is the volume of harvested rainwater (liters), Rm is the roof material, At is the angle of tilt (degrees), S. D. is the standard deviation value

Figure 1 shows the response of the volume of harvested rainwater to changes in roof materials and angle of tilt, the figure shows that the volume of harvested rainwater decreases from 4 kg to 3.7kg at 30 - 36° angle of tilt and increase again to around 5.7kg from 36 to 45° angle of tilt while a linear increase was observed between the roof material with natural roof material giving the highest volume of harvested rainwater. Figure 2 shows the predicted volume of water and actual volume of harvested rainwater values. The volume of harvested rainwater harvested was measured for various samples. The statistical analysis showed that all the variables affect the volume of harvested rainwater. Modeling result gave the optimal condition of 45° tilt angle and biomass based roof material which gave 5.27 litres of water.

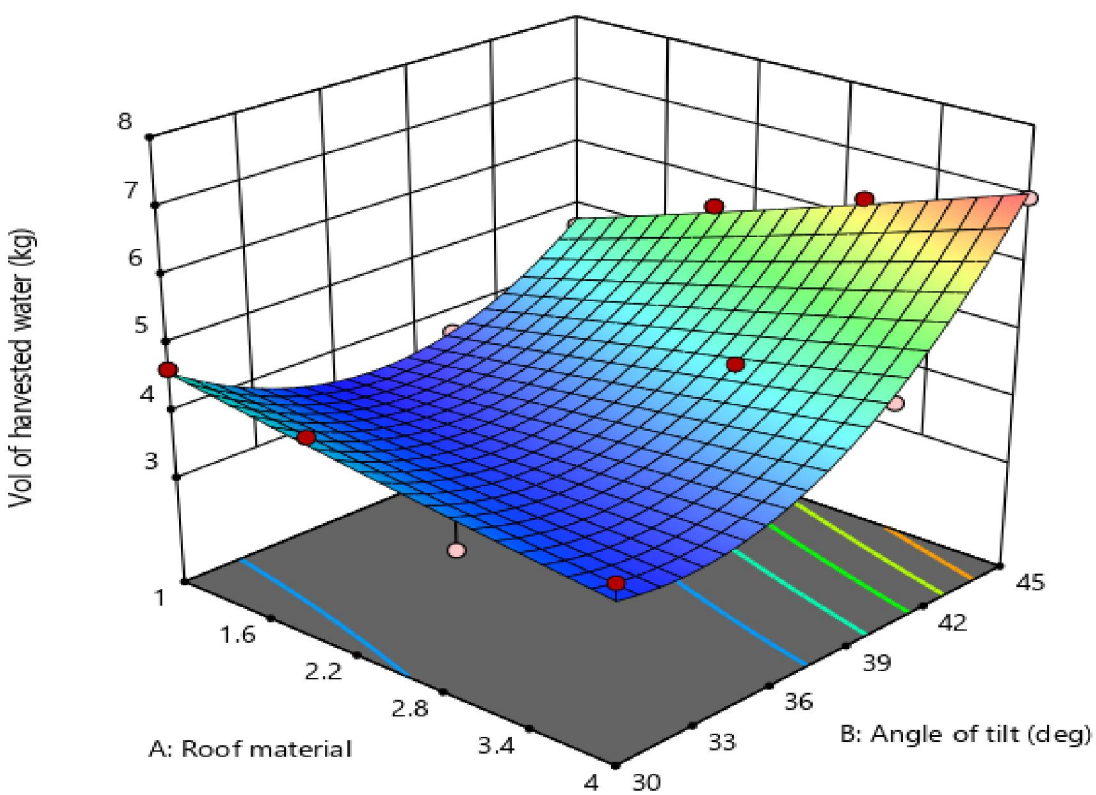

Figure 1: Influence of Roof Material and Angle of Tilt on the Volume of Harvested Rainwater

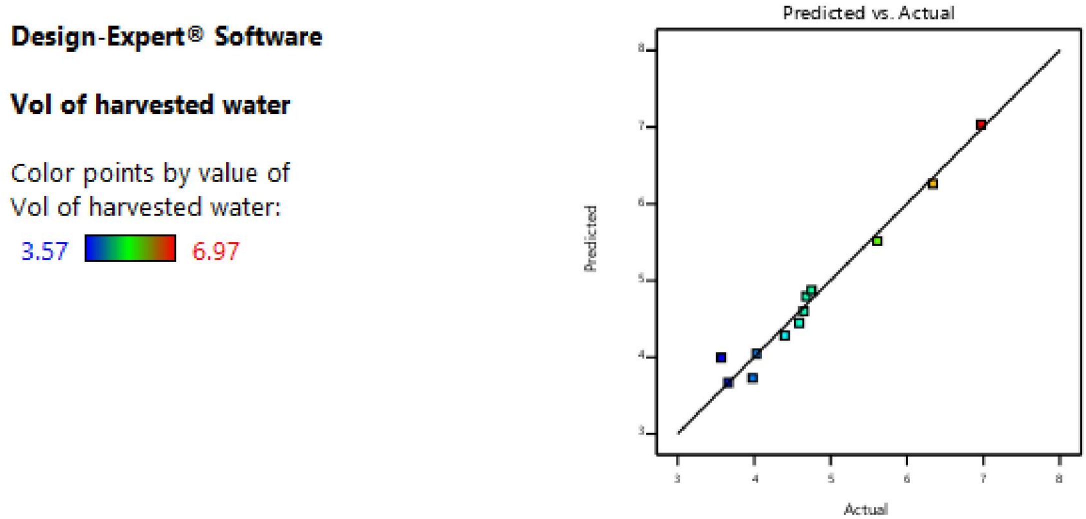

Figure 2: Predicted vs Actual Volume of Harvested Rainwater

4. Conclusion

This study investigated the influence roof material and angle of tilt on the volume of harvested rainwater. The volume of water harvested on the specially constructed mini structures was influenced by the angle of tilt and roof materials used. The highest volume of water harvested was obtained on biomass-based roof material followed by the Asbestos roof, fiber roof and Aluminium roof. The volume of water harvested is dependent on the friction on each roof surface that restricts movement of water, the rough surface nature of Aluminium might be the reason behind the low volume of water harvested. The model developed developed has a R^2 value of 97% which showed a good agreement. More concerted efforts should be geared towards public sensitisation for an increased public interest to harvest more rainwater for domestic uses like irrigation farming and other farm operations especially in places with water scarcity areas where there is low annual rainfall.

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