Application of MATLAB – based Solar Dryer for Cocoa Drying.

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Abstract: - Solar energy is used directly for drying bulk of agriculture products in the country, especially cocoa beans. In this paper, research work identifies practical and technological ways by which the Crank – Nicolson equation is applied to heat equations using finite difference method to develop a green house type of solar dryer used in drying cocoa beans. The mathematical model of the extended Crank – Nicholson method for the general case of the 3-D (three-dimensional) conduction equation for green house effect type dryer has been derived and simulated using the Mathwork Matlab program. The performance of dryer was then determined, using drying cocoa beans from freshness with water content of about 50%,60% and 70% to dried beans with water content of about 7% of the weight. The results show that the green house effects dryer made of polythene sheeting produces temperatures of 50^0C to 60^0C and dries cocoa very well within seven days with water content of 50% to dried beans with 7% of water content of the weight. Compared to the traditional method of drying cocoa in Ghana, this method can be more technologically advance and better in producing the required dryness of cocoa beans in shorter time. Other advantages of this method include the more hygienic way of drying cocoa with less foreign materials. The overall aim of this research is to develop a MATLAB-based modeling and simulation to predict the air properties, air flow rate, equilibrium moisture content of the solar dryer technology for food crop drying especially cocoa and other cash crops.

Key-Words: - Crank-Nicholson, Parabolic Equations, Finite Differences, Psychometrics, Simulation, MATLAB.

1 Introduction

The colour of cocoa fruit is varied and rich, ranging from bright burnt orange to Provencal yellow. The pods length is essential to the breath of traditionally grown trees to ensure leaves don't burn in the sun. Drip irrigation is employed to help maintain the thin soils around the roots, keeping the dirt from drying out and eroding. It takes 3-4 years before a cocoa tree bears usable fruit. Less than 10 line flowers are successfully pollinated and become pods. Once pollinated, it takes 5-6 months for pods to reach maturity. During harvesting of cocoa pods a sharpened knife blade attached to a long rod, is used to carefully sever a ripe pod from the stem. The pods are gathered at a collection point, split open and the seeds removed from the surrounding thick, white, viscous pull. Fermentation is one of the initial processes applied before drying of cocoa beans. First**, t**he beans are sorted and any foreign matter; pieces of pod, are removed. Second, stocky mass is heaped into wooden bins and covered with plantain leaves to begin the process of fermentation. Once the fermentation process is complete, the beans are spread on large wooden trays and rolled into the sun to dry or scattered on a cement platform of a drying patio. Workers frequently turn the beans at night to protect them from moisture. Chemical activity diminishes as the moisture dries out. After about 5 or 6 days the beans have shrunken and become hard. It takes about two to three weeks to sun drying cocoa beans. Cocoa is dried mainly using direct sun drying method in Ghana. It is by far the most convenient and traditional way of doing things. However, with increase demand by our overseas customers for

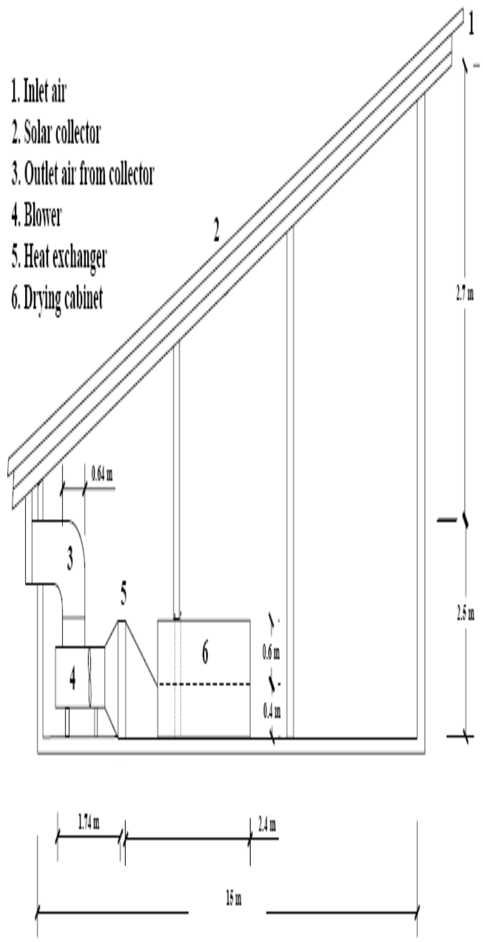
ISBN: 978-1-61804-084-8

improved quality of products and efficient way of doing things there is the need to improve the solar drying technology, hence the importance of this research work. The solar powered cocoa bean dryer has advantage over the traditional method of drying because it gives more hygienic way of drying cocoa beans in shorter time, with less foreign materials. The use of solar energy for drying has been very intensively studied for several decades. In this research work, the technological ways by which the green house type of solar dryer is used in drying cocoa beans is modeled and simulated using MATLAB computer programming. The software used for modeling and simulation was MATLAB version 10a. On a Pentium IV that had processor speed of 2.0 GHz, RAM of 1.O GB and hard disk drive of 40 GB. MATLAB was selected as the modeling and simulation software because it gives immediate access to high performance numerical computing. The functionality is extended with interactive graphical capability for creating plots, images, surfaces and volumetric representation. Further, toolbox algorithms enhance MATLAB functionality in domains such as signal and image processing, data analysis and statistics, mathematical modeling and control design. Technical computing with MATLAB allowed us to accelerate our research work, reduce development time, costs and deliver better products [4]. The overall aim of this research is to develop a MATLAB-based modeling and simulation to predict the air properties, air flow rate, equilibrium moisture content of the solar dryer technology for food crop drying especially cocoa and other cash crops.

2 Problem Formulation

The capacity of the dryer is 250kg which have a collector area of approx. $25m^2$. The dryer will consist of 5 separate units each with a transparent collector area of $4.77m^2$ and a capacity of approx 50kg. Small dc fans will be use to distribute air evenly over the drying bed. The fans of the dryer will be powered directly by PV – panels in order to make the dryer independent of an often unreliable, missing or expensive grid. The components of the solar dryer are: Solar Collector: Outer dimension is $4900 \times 1070mm^2$. Transparent area $4.77m^2$ cover by a 10mm double walled ribbed UV – stabilized polycarbonate. Absorber will be made up of felt mat, air intake at the back of the PV – panels at both ends and air outlet in the middle at the back. Blower Fan: $300m^2/h$ at 40 Pa 12V dc motor with power of 12W at 12V. PV will be 2 panels of 12V, 14 Wp. Inlet air duct between collectors and drying bed will be a metal ducting with the smallest cross section of $0.031m^2$. Drying Bed Cabinet: 5 trays made of plastic, $600 \times 400 \times 278\ mm^3$ of outer dimensions. Heat Exchanger: These will contain gravels overlaid with a perforated plate 5 mm diameter holes, 10mm apart to retain the heat to facilitate convective heat flow from the gravels onto the drying beans during the rest periods of the sun. The solar dryer with it measured parameters and the illustration of the main components is shown below.

Fig. 1. Green House Solar Dryer.



ISBN: 978-1-61804-084-8

2.1 Subsection

The system was assumed to be in a steady flow process and thus the mass flow rate of dry air remains constant during the entire process. Dry air and water vapor are ideal gases. The kinetic and potential energy changes are negligible. The emissivity and heat transfer coefficient are constant and uniform [3]. The numerical solution of Partial Differential Equations is a topic of great importance in science and engineering because of many applications. Finite Differences, Finite Volumes, Finite Elements, Boundary Elements are among the most valuable numerical tools that we can use in order to approximate the theoretical solution with a numerical one. Suppose that we have to solve the 1-D (one-dimensional) conduction equation.

$$\frac{\partial^2 f}{\partial x^2} = k\frac{\partial f}{\partial t} ------Eq\ 1$$

We consider the grid of the points $(i_1, i_2) \in Z^2$ as a discretization of the continuous space of x,t of R^2 where we have the function $f(i_1,i_2)$ that approximates the f(x,t). This finite difference scheme suffers from convergence problems, instability and errors, so another better method the so called Crank-Nicholson method is applied. The Crank-Nicholson method for the general case of the 3-D (three-dimensional) conduction equation is applied to the parabolic equation:

$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} = k\frac{\partial f}{\partial t} ----Eq\ 2$$

A point that does not belong to the grid of the points (i_1,i_2,i_3,i_4) is considered. It is the $(i_1, i_2, i_3, i_4 + \frac{1}{2})$ at this point we approximate to numerical scheme below:

$$\frac{1}{2}\left(\frac{f(i_1-1,i_2,i_3,i_4)+f(i_1+1,i_2,i_3,i_4)-2f(i_1,i_2,i_3,i_4)}{h_1^2}\right.$$
$$\left.+\frac{f(i_1-1,i_2,i_3,i_4)+f(i_1+1,i_2,i_3,i_4)-2f(i_1,i_2,i_3,i_4+1)}{h_1^2}\right)$$
$$+\frac{1}{2}\left(\frac{(i_1,i_2-1,i_3,i_4)+f(i_1,i_2+1,i_3,i_4)-2f(i_1,i_2,i_3,i_4)}{h_2^2}\right.$$
$$\left.+\frac{f(i_1,i_2-1,i_3,i_4+1)+f(i_1+1,i_2,i_3,i_4+1)-2f(i_1,i_2,i_3,i_4+1)}{h_2^2}\right)$$
$$+\frac{1}{2}\left(\frac{f(i_1,i_2,i_3-1,i_4)+f(i_1,i_2,i_3+1,i_4)-2f(i_1,i_2,i_3,i_4)}{h_3^2}\right.$$
$$\left.+\frac{f(i_1,i_2,i_3-1,i_4+1)+f(i_1,i_2,i_3+1,i_4+1)-2f(i_1,i_2,i_3,i_4+1)}{h_3^2}\right)$$
$$= k\frac{f(i_1,i_2,i_3,i_4+1)-f(i_1,i_2,i_3,i_4)}{\tau} ---Eq3$$

Where h_1,h_2,h_3 and τ are the steps of discretization with respect to x,y,z,t. The numerical scheme of equation 3 that is the Crank-Nicholson method of the 3-D conduction equation is an implicit numerical scheme because the values at the previous time step which are not readily available. This requires us to solve a set of simultaneous linear equations at each time step. The Crank-Nicholson method is superior to finite difference scheme, because of stability, convergence and accuracy [1]. The simulated graph of equation 3 is shown below in figure 1 and 2 explains the heat conduction mechanism during drying of the beans. The red arrows show the direction of heated air flow. The evaporated moisture is shown as pink and that of the equilibrium moisture is shown as blue and green respectively. The energy balance equation for the drying process is:

$$M_w \times L = M_a \times C(T_p - T_c) --Eq.4$$

Where M_w is the mass of water evaporated from the sample and absorbed by drying air of mass M_a; T_p and T_c are the initial and final temperatures of the drying air respectively. L = 2.43 MJ Kg^{-1} is the latent heat of vaporization for free water at 38°C, and C is the specific heat capacity of air [5]. The mass of water evaporated was calculated from the equation:

$$M_w = \frac{(M_o - M_f)}{(100 - M_f)} ---Eq.5$$

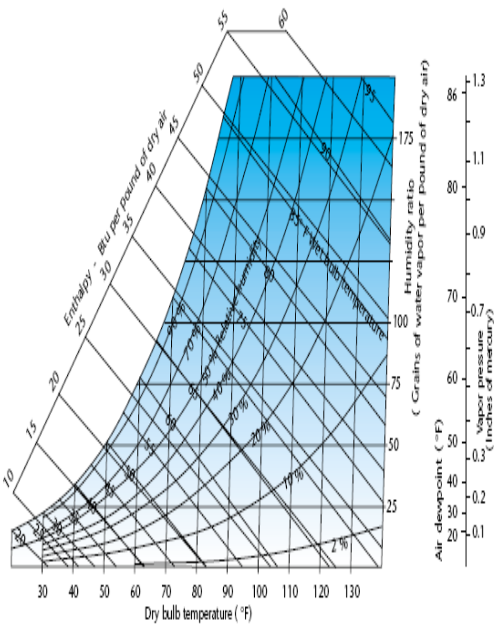
ISBN: 978-1-61804-084-8

Where M_f is the final or equilibrium moisture content and M_i is the initial mass of the air as received by sample. The total estimated time for drying is 84 hours and the air flow rate within the collector is $0.024m^3s^{-1}$, where assume. The volume of air for dehydration equation is:

$$V = \frac{M_a \times R \times T_c}{P} - - - Eq.6$$

From psychometric chart, the quantity of thermal energy required and the specific volume of dry air required for dehydration process was found [3].

Fig. 2. Psychometric Chart.



The dehydration curves and rate of drying can be represented by the general equations of the from:

$$M = M_o exp(-k \times t) - - - Eq.7$$

The drying constants k was assume to be 0.025 for the cocoa bean, $R = 2.9\times10^2$ $Jkg^{-1}K^{-1}$ and $P = 1.01\times10^5 Pa$. The equation for the pickup efficiency is given by:

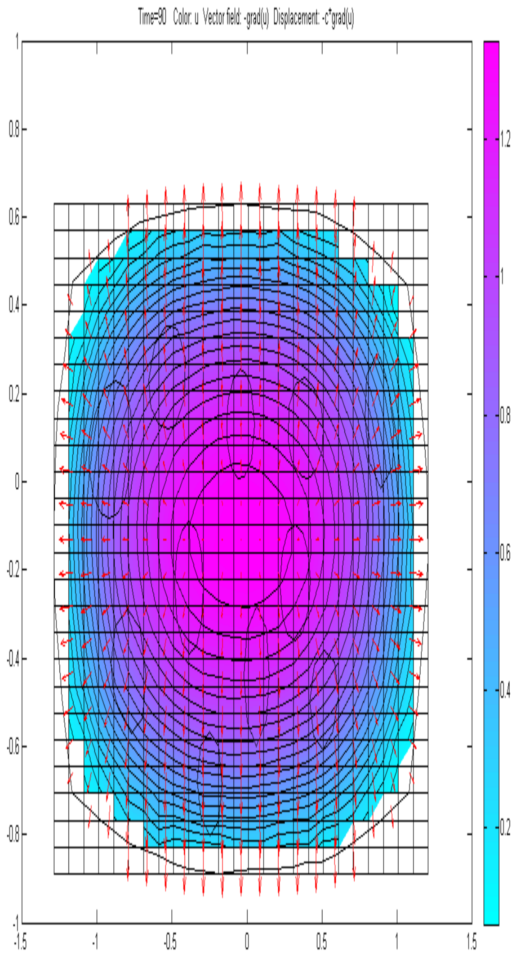
$$n = \frac{h_o - h_i}{h_a - h_i} - - - Eq.8$$

Where h_o is the absolute humidity of air leaving the drying chamber, h_i is the absolute humidity of air entering the drying chamber, h_a is adiabatic saturation humidity of the air entering the dryer. The results of the modeling and simulation using MATLAB is shown below.

3 Problem Solution

The partial differential equations (PDE) Toolbox within MATLAB was used to build system of equations to model heat conduction of drying cocoa beans from Crank-Nicholson method and obtaining numerical approximation for the solution and visualizing the results as shown in the figure 3 below.

Fig.3. Simulation in PDF Toolbox.



The parabolic graph of three-dimensional heat conduction simulation for drying cocoa beans in

ISBN: 978-1-61804-084-8

the dryer from the Crank-Nicholson method is shown in figure 4 below.

Fig. 4. Crank-Nicholson 3-D Dehydration of Cocoa Beans.

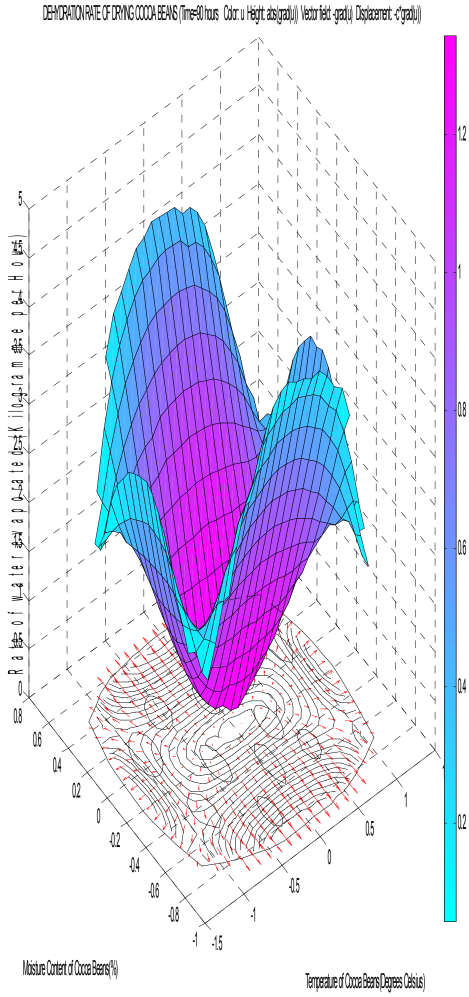
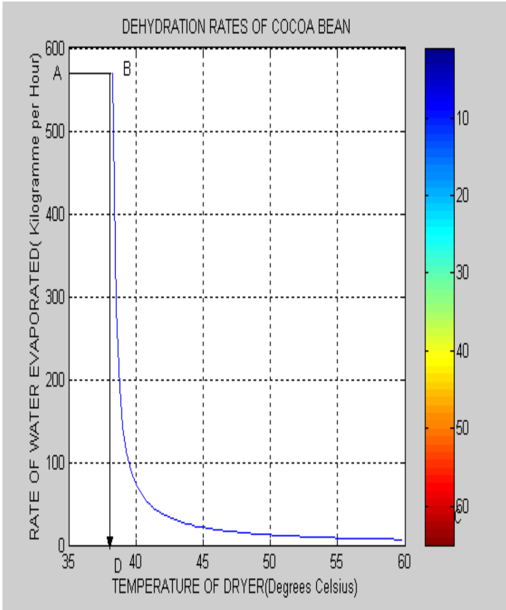


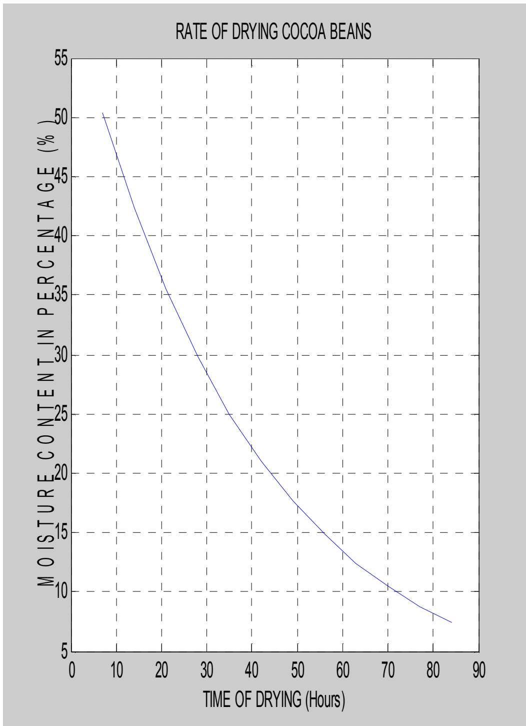
Figure 5 shows the dehydration curve for simulated cocoa beans drying. The sections with the straight line (A, B), represent the constant temperature till the latent heat of vaporization of water is reach. The falling curve (B, C), shows the rate of water evaporated with respect to temperature, to a corresponding critical moisture content of 7%. The relative humidity was found from the psychometric chart shown in figure 2 above, to be about 10% and humidity ratio of 11.5. The pickup efficiency was 47%, when the dry air was heated in the drying chamber to 60 °C.

Fig. 5. Dehydration Rates in Solar Dryer.



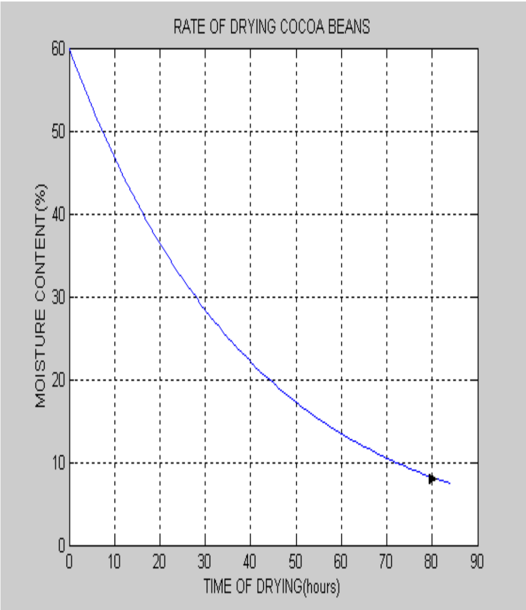
The simulated graph in figure 6 below shows the drying rate of the cocoa beans with initial moisture content of 50% to dried beans of moisture 7% of the weight.

Fig.6. Drying Rate from 50% to 7% Moisture.



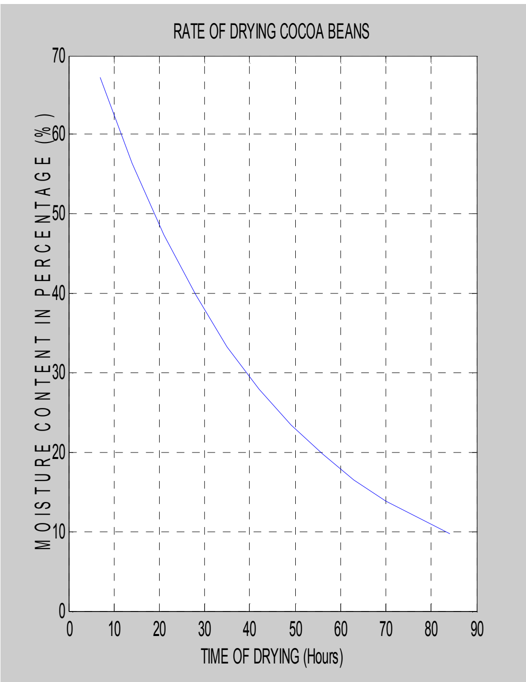
The simulated graph in figure 7 below shows the drying rate of the cocoa beans with initial moisture content of 60% to dried beans of moisture 7% of the weight.

Fig.7. Drying Rate from 60% to 8% Moisture.



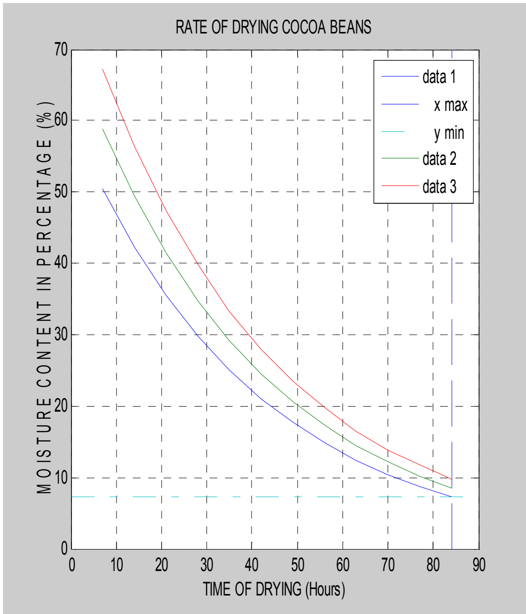
The simulated graph in figure 8 below shows the drying rate of the cocoa beans with initial moisture content of 70% to dried beans of moisture 7% of the weight.

Fig.8. Drying Rate from 70% to 10% Moisture.



The simulated graph in figure 9 below shows the combined drying rate of the cocoa beans with initial moisture content of 50%, 60% and 70% of the weight with the final time of drying at 84 hours. The simulated graph shown in red data3 indicated the initial moisture of 70% and final moisture of 10% of the weight after drying. The green data2 shows initial moisture of 60% to final moisture 8% of the weight after drying. The blue data1 shows 50% initial moisture and final moisture 7% of the weight after drying. X max shows the total time of drying of beans 84 hours. Y min shows the moisture at 7% of cocoa beans. This shows that the cocoa beans with moisture content of 50% are the perfect choice for this dryer. Hence the dryer performed at it optimal range and dried beans within 7 days to a moisture content of 7% to the weight of the beans.

Fig.9. The Combined Drying Rate of Cocoa Beans.



4. Conclusion.

The drying processes of greenhouse solar dryer were enhanced by the heated air at very low humidity. Figure 9 shows the combine rate of change of moisture content with time. A mass of 1000kg of cocoa bean with moisture content of 50% is passed through our model design dryer, and also solar radiation is intense for at least 12hours per day, then it will take cumulative, 84 hours to reduce the moisture content of the beans from 50% to 7% .Thus within 7 days the cocoa beans could be ready for bagging, compares very well with the 2 to 3 weeks drying time for direct sun drying.

Advantages of greenhouse solar dryer include: foreign materials like, stones and twines, will not be found in the dried cocoa beans, hence is the most hygienic way of drying, cocoa processing companies need not blow ambient air through beans to remove foreign materials. Hence reducing production cost, time and cocoa dried in the dryer would give cocoa of grades one and two which meet international standard. Modeling and simulation applied in cocoa bean drying has shown that drying time could be reduced from 2 to 3 weeks typically used for direct sun drying to one week using the model solar dryer. Further, we have shown that maximum efficiency is achieved at dryer chamber temperature of 60°C. The solar dryer modeled and simulated could be built and tested to validate and improve upon the operational efficiency and perhaps reduce further the time to reach 7% moisture content of the beans. Subsequently economic viability of solar cocoa bean dryers could be embarked on for optimum designed capacities.

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