

ENERGY AND EXERGY ANALYSIS DURING THE DEHYDRATION OF PRETREATED SWEET POTATO VIA A CONVENTIONAL AIR DRYER

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Abstract

The energy and exergy analysis during the dehydration of pretreated sweet potato via a conventional air dryer (Model: DHG-9023A, England) was investigated. Sweet potatoes were sliced and divided into three lots; first lot was pretreated in 0.5% sodium metabisulphite (SMB), second lot was water blanched (WAB) and the last lot was untreated (UNT). The samples were dried at varying drying temperatures (60°C, 70°C and 80°C) and constant air velocity of 1.5 ms⁻¹. Energy utilization (EU), Energy utilization ratio (EUR), heat transfer rate (Q_{evap}), exergy loss and exergy efficiency were estimated using standard equations. The results showed that the higher the temperature, the shorter the drying time irrespective of the treatment. However, WAB sweet potato slices takes longer time to dehydrate than SMB and UNT. The energy analysis showed that EU, EUR and Q_{evap} increases as temperature increased. WAB slices has the highest EU, EUR and Q_{evap} next to it was SMB and UNT had the least values. For exergy analysis, exergy loss and exergy efficiency increases with increased in drying temperatures. Comparing the drying temperatures, the highest and lowest exergy loss was obtained at 80°C and 60°C. The least exergy efficiency was obtained at 60°C, thus, drying at 70°C and pretreatment with SMB gave the most acceptable processing conditions base on effective moderate exergy loss (8.69 KJ/s) and exergy efficiency (0.38). However, it is recommended that process optimization should be done in further studies.

Keywords: energy, exergy, sweet potato, dehydration, conventional air dryer

1.0 Introduction

Sweet potato (*Ipomea batatas*) is an important vegetable in Nigeria. Nigeria is the largest producer in Africa and the second largest producer of sweet potato tubers in the world, after China [1]. It is a nutritious food crop with high potential use in human food system, though it is under-utilized [2, 3]. The tuber is rich in complex carbohydrates, dietary fibre, iron, calcium and vitamins [4]. Sweet potato tubers once harvested deteriorate rapidly, mainly due to physiological changes and mechanical damage during harvesting, transportation and handling. Besides, the tubers exhibit no dormancy and are susceptible to insect infestation [4]. The very short storage life after harvest has been recognised as a limitation to the cultivation of the crop [5]. As a result, growers prefer to convert the tubers into more stable forms such as chips and flours so as to prolong the shelf life. Sweet potato can be processed into sweet potato flour as a means of preserving it from post-harvest loss. Sweet potato flour can be used as ingredients in processed sweet potato products including soups, sauces, noodles and bread [6]. The process of producing sweet potato flour includes peeling, washing, slicing/dicing, cooking/blanching, drying, milling and packaging.

Prior to drying, most food products are usually subjected to some form of pre-treatments, among which are hot water blanching and sulphiting. Blanching helps to inactivate enzymes that may lead to quality degradation [7] and to improve the acceptability

of the final product [8]. Hot water blanching and the use of chemicals such as sulphur, methyl and ethyl ester emulsions or alkaline pre-treatment in aqueous solutions of sodium hydroxide, sodium chloride, potassium and sodium carbonate, calcium chloride have been applied to overcome the waxy or fibrous barrier on roots, fruits and vegetables [4, 9-11]. Energy is a major determinant in any production and drying was reported as an energy intensive unit operation [12] thus there is need to analysis the energy and exergy used during the drying of sweet potato. Energy analysis of solar dryers has been an interesting subject for researchers but, it should be noted that the energy analysis does not just show the quality of energy destruction. In the recent years, a new concept has been introduced and used in order to measure the ability of several types of energies to work, known as Exergy[13].

Exergy is the property of the system, which gives the maximum power that can be distracted from the system when it is brought to a thermodynamic equilibrium state from a reference state [13]. Using exergy analysis, based on the first and second laws of thermodynamics, it is possible to infer the true potential of different kinds of energies. Due to thermodynamic irreversibilities, the exergy efficiency of a process is often low in spite of high energy efficiency [14]. Exergy analysis, as is known, evaluates the available energy at different points in a system. [13] reported that in the design of a system, the exergy method provides the useful information to choose the appropriate component design and operation procedure. Exergy is not subject to a conservation law; rather, exergy is consumed or destroyed due to the irreversibility in any process. It is the measure of the potential of a stream to cause change, as a consequence of not being completely stable relative to the reference environment [13]. Quality of energy is evident from daily life experience. For example, heat has a lower energy quality (exergy) compared with work. For this reason, heat cannot be converted into work by 100% efficiency. On the other hand, electricity or mechanical work can be converted to heat completely. Thus, exergy can be calculated by product of energy and quality i.e. $\text{Exergy} = \text{Energy} * \text{Quality}$.

Energy and exergy analyses evaluate the available energy at different scenarios in a system and provide useful information required to choose appropriate variables and operating conditions in order to achieve the best performance of a system [15]. The increasing awareness of the fact that energy resources are limited has caused many countries to re-examine their energy policies and take drastic measures in eliminating waste [15]. It has also sparked interest in the scientific community to take a closer look at the energy conversion devices and to develop new techniques to better utilize the existing limited resources [16]. Previous works on dehydration have been focused on developing mathematical models and studying drying kinetics, which are useful in the design of equipment, and analysis of mass and heat transfer processes [15]. However, little insight is provided for optimization of energy and exergy analyses of the drying process [17]. In addition, documented literature is few on energy and exergy analyses during dehydration of sweet potato, a major unit operation production in sweet potato flour production. Therefore the aim of this research is to study the influence of pretreatments of energy and exergy analysis during the dehydration of sweet potato.

2.0 Materials and Methods

2.1 Source of Material and Experimental Location

The Sweet potatoes (*Ipomea Batatas*) for this experiment were obtained from the Jimeta Modern Market Yola, Adamawa State. The experiment was conducted in the Laboratories of the Department of Food Science and Technology, Modibbo Adama University of Technology, Yola, Adamawa State and the Department of Food Science and Engineering, Ladoke Akintola University of Technology, Ogbomosho, Oyo State.

2.2 Drying Method

Sweet potatoes were washed in a bowl with clean water and peeled with table knife under water. The peeled potatoes were sliced into uniform surface area 3 cm by 2 cm and thickness of 4 mm. The sliced sweet potatoes were divided into three portions; one portion was pretreated for 5 minute using 0.5% sodium metabisulphite (SMB) and weighed using a digital weighing balance. The second portion was water blanched (WAB) at 60°C for 5 minute and weighed while the last portion serves as control (UNT). After pre-treating, sweet potato samples were arranged in an oven tray and placed in the oven (Model: DHG-9023A Modified Equipment and Scientific England) adjusted to 60°C. After 30 minute, the inlet, outlet and ambient temperatures for the drying chamber were measured and recorded. Also the inlet, outlet and ambient temperatures for the dry bulb and wet bulb temperature were measured and recorded in order to obtain values for relative humidity using psychometric calculator. This procedure was repeated at 30 minute interval while recording masses and reintroducing the sample into the dryer until a constant weight is achieved. The drying time required to reach the equilibrium moisture content was 750 min, 840 min and 780 min for UNT, WAB and SMB respectively. The same procedure was repeated for 70°C and 80°C with the readings being accurately recorded. The drying time required to reach the equilibrium moisture content was 630 min, 720 min and 690 min at 70°C and 450 min, 510 min and 480 min at 80°C for UNT, WAB and SMB respectively. The initial moisture content of the fresh fruits was immediately determined according to [18] method (number 934.01), and found to be 54.10 ± 0.25 g water per 100 g sample.

2.3 Energy analysis

The enthalpies of dry air (h_{da}) and humidity ratios (w) were determined as described by [19] for inlet, outlet and ambient temperatures. Humidity ratios were obtained by using a psychometric calculator.

$$h_{da} = C_{pda}(T_i - T_{ref}) + (h_{fg} \times w) \quad (1)$$

Where: h_{da} = enthalpies of dry air (KJ/kg)
 C_{pda} = specific heat of dry air (kJ/ [kg K])
 T_i = initial temperature (°C)
 T_{ref} = reference temperature (°C)
 h_{fg} = latent heat of vaporization (kJ/kg)
 w = humidity ratio

The energy utilization (EU) and energy utilization ratio (EUR) of the drying chamber were estimated by applying the [20] equations:

$$EU = m_{da}(h_{dai} - h_{dao}) \quad (2)$$

$$EUR = \frac{m_{da}(h_{dai} - h_{dao})}{m_{da}(h_{dai} - h_{dae})} \quad (3)$$

Where: EU = energy utilization (KJ/s)
 EUR = energy utilization ratio
 m_{da} = mass flow rate of drying air (kg/s)
 h_{dai} = inlet enthalpy (KJ/kg)
 h_{dao} = outlet enthalpy (KJ/kg)
 h_{dae} = ambient enthalpy (KJ/kg)

The rate of heat transfer by evaporation Q_{evap} was determined using the equation [21], given as:

$$Q_{evap} = mw h_{fg} \quad (4)$$

Where: Q_{evap} = heat transfer by evaporation (KJ/s)
 m = mass flow rate (kg/s)

2.4 Exergy analysis

Based on the second law of thermodynamics, total exergy inflow, outflow and losses in the drying chamber was estimated by determining the exergy values at steady and unsteady states [22] [20]. The exergy values were calculated by using the characteristics of the working medium from a first law energy balance as described by [20].

$$\text{Exergy inlet} = m_{da}C_{pda} \left[(T_i - T_{ref}) - T_{ref} \ln \frac{T_i}{T_{ref}} \right] \quad (5)$$

$$\text{Exergy outlet} = m_{da}C_{pda} \left[(T_o - T_{ref}) - T_{ref} \ln \frac{T_o}{T_{ref}} \right] \quad (6)$$

The exergy loss and exergy efficiency were calculated as described by [22];

$$\text{Exergy loss} = \text{Exergy inflow} - \text{Exergy outflow} \quad (7)$$

$$\text{Exergy efficiency} = \frac{\text{Exergy inflow} - \text{Exergy loss}}{\text{Exergy inflow}} \quad (8)$$

2.5 Data analysis

The data obtained were analyzed by applying the thermodynamic principle of exergy and energy analysis and calculations were done on an excel sheet for convenience.

3.0 Results and Discussion

3.1 Drying characteristics of sweet potato

The change in moisture content (dry basis) with drying time (min) for untreated (UNT), sodium metabisulphite (SMB) pretreated and water blanched (WAB) sweet potato was showed in Figure 1. It was observed that the total drying time for UNT sweet potato was 750 min, 630 min and 450 min, WAB was 840 min, 720 min and 510 min and SMB was 780 min, 690 min and 480 min at drying temperature of 60, 70 and 80 °C respectively. It was observed that increase in drying temperature reduced the drying time and vice versa. The decrease in moisture content was faster at the initial stage of drying and then slower as drying continued. All curves showed a clear exponential tendency with moisture content decreasing as the drying time increased. The results agree with what was reported by [23]. It was observed that WAB sweet potato sample takes longer time to dry when compared with UNT and SMB samples due to the varying water absorption capacity in the samples. This indicates that pre-treatments also affect the drying time of sweet potato slices. Similar result was reported by [4]. The drying of sweet potato slices exhibited the characteristic moisture desorption behaviour noted for many tuber crops [24], which has been explained to be due to various forms in which water is present in food products. Therefore, it can be observed from the drying characteristic curves that temperature of drying air has a significant effect on the drying time.

3.2 Energy analysis of thin layer dried sweet potato

The energy analysis of thin layer drying process of sweet potato was performed by using data obtained from experiments to estimate the energy utilization (EU) and energy utilization ratios (EUR). Figure 2 shows the variation of energy utilization (EU) as a function of drying time for the sweet potato samples at different drying air temperature. The EU decreased with increasing the drying time. The EU was high at the initial stage of drying as a result of high moisture content of the samples whilst it decreased steadily as drying continued because of the reduction in moisture content of samples. Similar findings were reported for drying of Coroba slices in an oven dryer [8] and drying of pumpkin slices in convective type dryer [22, 25]. The analysis show that EU increased as temperature increased from 60 – 80°C for the sweet potato samples. Energy utilization obtained at 60°C varied from one pretreatment to other. The highest EU was obtained during the drying of WAB sweet potato

slices (157.20 KJ/s). This was followed by the value obtained for the SMB sample (156.30 KJ/s) while the least EU was obtained for the UNT sample (154.90 KJ/s). At 70°C, the same trend of result was obtained with the highest EU for the WAB sample (246.50 KJ/s), followed by EU for the SMB sample (245.70 KJ/s), whilst the least EU was obtained for the UNT sample (245.00 KJ/s). At 80°C, the highest EU was obtained for the WAB sample (470.80 KJ/s), next to this was for the SMB treated sample (450.50 KJ/s), while the least EU was obtained for the UNT sample (444.26 KJ/s). The result shows that irrespective of the drying temperature, the EU of water blanched sweet potato slices will be higher due to the high moisture ratio of the samples. The results agree with what was reported by [25] and [26].

Figure 3 shows the variation of energy utilization ratio (EUR) as a function of drying time for different air temperatures and samples. The values of EUR decreased with increasing drying time. Similar result was reported by [22 and 25]. Comparing the three temperatures, maximum value of EUR was obtained at 60°C, followed by that obtained at 70°C, with the least EUR obtained at 80°C. These values show that EURs of the drying chamber decreased with the increase in temperature of the drying air. Furthermore, it can be said that the moisture contents of the sweet potato samples affect the energy utilization ratio [22 and 25]. At 60°C, EUR obtained varies from sample to another. The highest EUR was obtained for the WAB sample (0.883), next to this was that obtained for the SMB sample (0.878) while the least EUR was obtained for UNT sample (0.870). The same trend of results was obtained for samples at 70 and 80°C, respectively. The result shows that the EU and EUR of water blanched sweet potato was higher than sulphite pretreated and untreated samples. The results agree with what reported by [25] and [27].

Figure 4 shows the heat transfer rate due to evaporation of the dryer (Q_{evap}) for the sweet potato samples as a function of drying time and different air temperatures. At 60°C, Q_{evap} varied for the three samples. The highest value was obtained for the WAB sample (1.82 KJ/s), next to this was the value for the SMB treated sample (1.67 KJ/s) whilst the least value was obtained for the UNT sample (1.53 KJ/s). At 70°C, the same trend of result was obtained with the highest Q_{evap} for the WAB sample (2.12 KJ/s), followed by the SMB treated sample (1.93 KJ/s), whilst the least Q_{evap} was obtained for the UNT sample (1.79 KJ/s). At 80°C, the highest Q_{evap} was obtained for the WAB sample (2.45 KJ/s), next to this was for the SMB treated sample (2.16 KJ/s), while the least Q_{evap} was obtained for the UNT sample (2.04 KJ/s). The results show that pre-treatments have an effect on the heat of evaporation of Sweet potato samples as the values of the pretreated samples (SMB and WAB) were higher than that of the UNT samples. The rate at which the moisture evaporated for the WAB sample was higher than that of the SMB treated sample. This is as a result of more exposure of the internal pores of Sweet potato samples by the boiling effect during blanching compared to that caused by sulphite thereby allowing easy penetration of heat and hence increasing the rate at which moisture was removed. The results agree with what reported by [28]. The Q_{evap} decreases as the surface moisture evaporates until the end of the drying process. This can be explained by the fact that the surface moisture evaporates very quickly due to high heat and mass transfer coefficients in the thin layer drying [28]. It can be pointed out that the drying rate was very high at the initial drying stage but decreased exponentially with time when all surface moisture evaporates as heat diffuses into the material. The analysis showed that the value of Q_{evap} increased with increasing air temperature. Comparing the three temperatures, maximum value of Q_{evap} was obtained at 80°C (water blanched samples), next to this value was that obtained for the same sample at 70°C whilst the least value was obtained for untreated Sweet potato slices at 60°C [22 and 25].

3.3 Exergy analysis of thin layer dried sweet potato

The exergy analysis of thin layer drying process of sweet potato was performed by using data obtained from experiments to estimate the exergy loss and exergy efficiency. Figure 5 shows exergy loss as a function of drying time for the samples at different drying air temperatures. At 60°C, exergy loss varied with the highest value obtained for the WAB sample (6.00 KJ/s), next to this was the value for the SMB treated sample (5.76 KJ/s) whilst the least value was obtained for the UNT sample (5.51 KJ/s). At 70°C, the same trend of result was obtained with the highest exergy loss for the WAB sample (9.02 KJ/s), followed by the SMB treated sample (8.69 KJ/s), whilst the least exergy loss was obtained for the UNT sample (8.34 KJ/s). At 80°C, the highest exergy loss was obtained for the WAB sample (14.39 KJ/s), next to this was for the SMB treated sample (13.72 KJ/s), while the least exergy loss was obtained for the UNT sample (13.36 KJ/s). This shows that the values of exergy loss increased with decreasing drying time and increasing temperature. Comparing the three temperatures, the highest exergy loss was obtained at 80°C while the least value was obtained at 60°C. The results agree with what was reported by [29] [20] [26].

Figure 6 show variation of exergy efficiency as a function of drying time for sweet potato dried at different drying air temperatures. At 60°C, exergy efficiency varied with the highest value obtained for the UNT samples (0.31), next to this was the value for the SMB treated sample (0.29) whilst the least value was obtained for the WAB sample (0.25). At 70°C, the same trend of result was obtained with the highest exergy efficiency for the UNT sample (0.40), followed by the SMB treated sample (0.38), whilst the least exergy efficiency was obtained for the WAB sample (0.35). At 80°C, the highest exergy efficiency was obtained for the UNT sample (0.44), next to this was for the SMB treated sample (0.42), while the least exergy loss was obtained for the WAB sample (0.39). This shows that the value of exergy efficiency decreased with increasing drying time and decreasing temperature. Comparing the three drying air temperatures, maximum exergy efficiency was obtained at 80°C while the least was obtained at 60°C. Higher exergy loss and low exergy efficiency simply means that actual energy was not effectively utilized [22], thus there is need to adopt a processing condition that have low exergy loss and higher exergy efficiency. With respect to the results obtained from this study, UNT samples shows highest exergy efficiency with low exergy, however to prevent enzymatic browning that use to occur in sweet potato, it is imperative to consider SMB samples due to its high exergy efficiency and its tendency to eliminate enzymatic browning reaction that do occur in UNT. Therefore, SMB gave the most acceptable processing conditions base on effective minimum exergy loss (8.69 KJ/s), moderate exergy efficiency (0.38) and good colour outlook.

4.0 Conclusion

This research work provided useful information on the influence of pretreatments on energy and exergy analysis in dehydration of sweet potato slices for instant sweet potato flour. Energy and exergy analysis of sweet potato slices is influence by drying temperature and pretreatment used. Drying at high temperature increases the energy utilization, exergy efficiency and exergy loss. Higher exergy loss and low exergy efficiency simply means that actual energy was not effectively utilized. Thus there is need to adopt a processing condition that have low exergy loss and higher exergy efficiency. With respect to the results obtained, drying at temperature of 70°C and pretreatment of sweet potato slices using SMB gave the most acceptable processing conditions base on effective energy utilization, exergy loss, exergy efficiency and ability to prevent enzymatic browning reaction.

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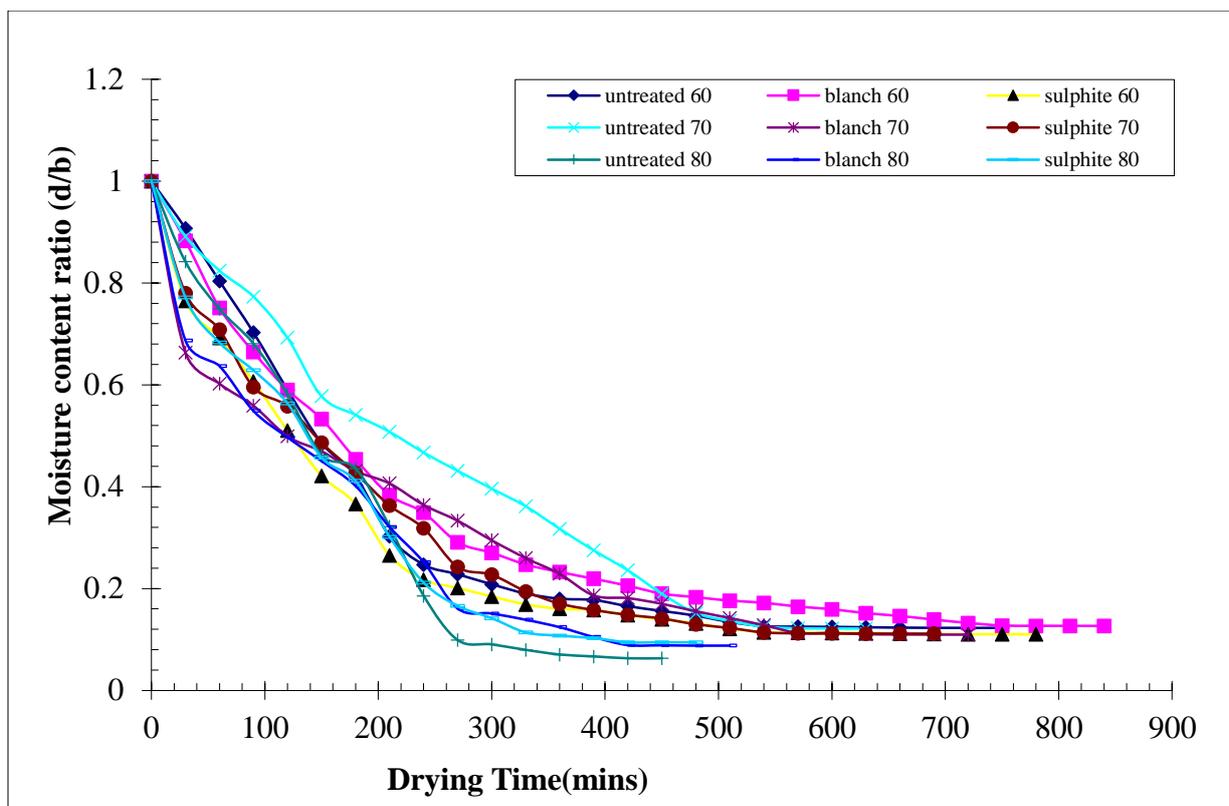


Figure 1: Variation in moisture content (dry basis) with drying time (min) for sweet potato samples at 60°C, 70°C and 80°C

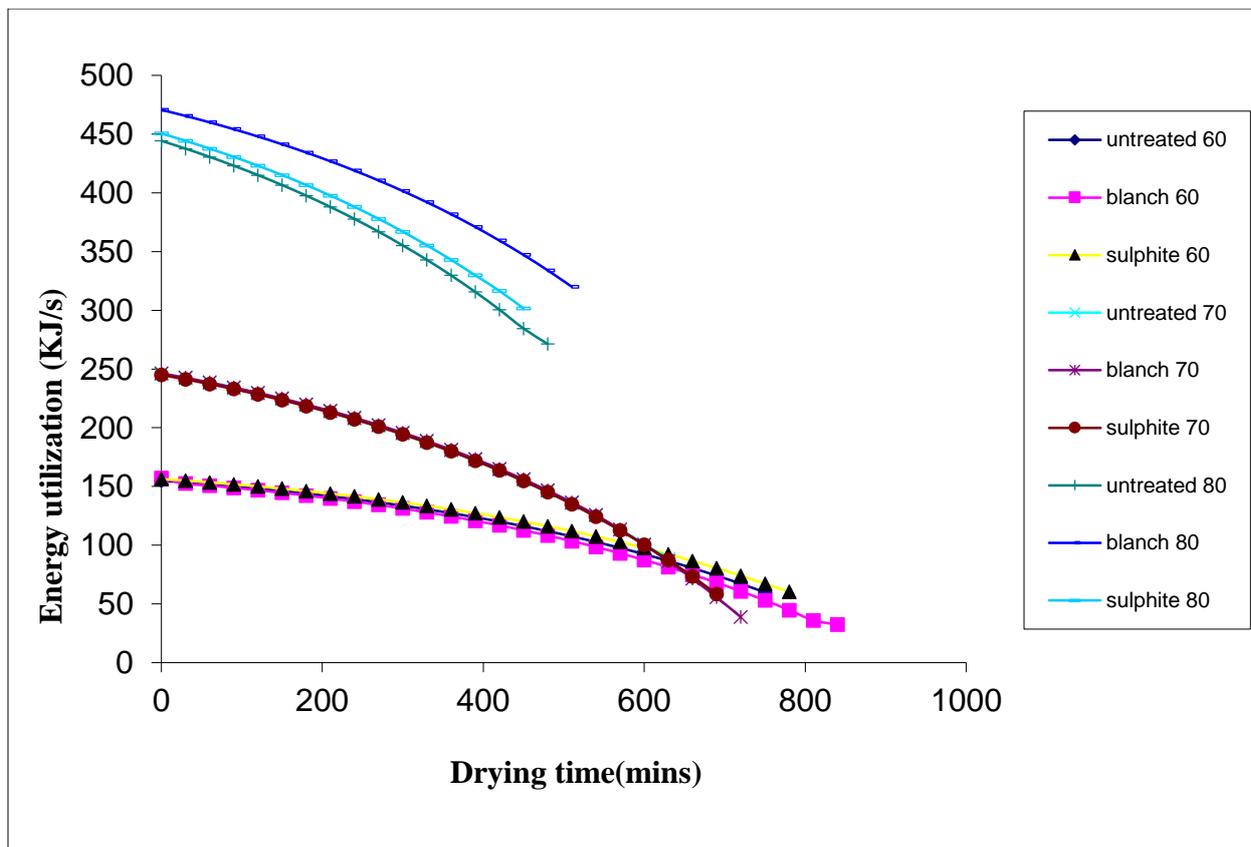


Figure 2: Variation of energy utilization with drying time for sweet potato samples at 60°C, 70°C and 80°C

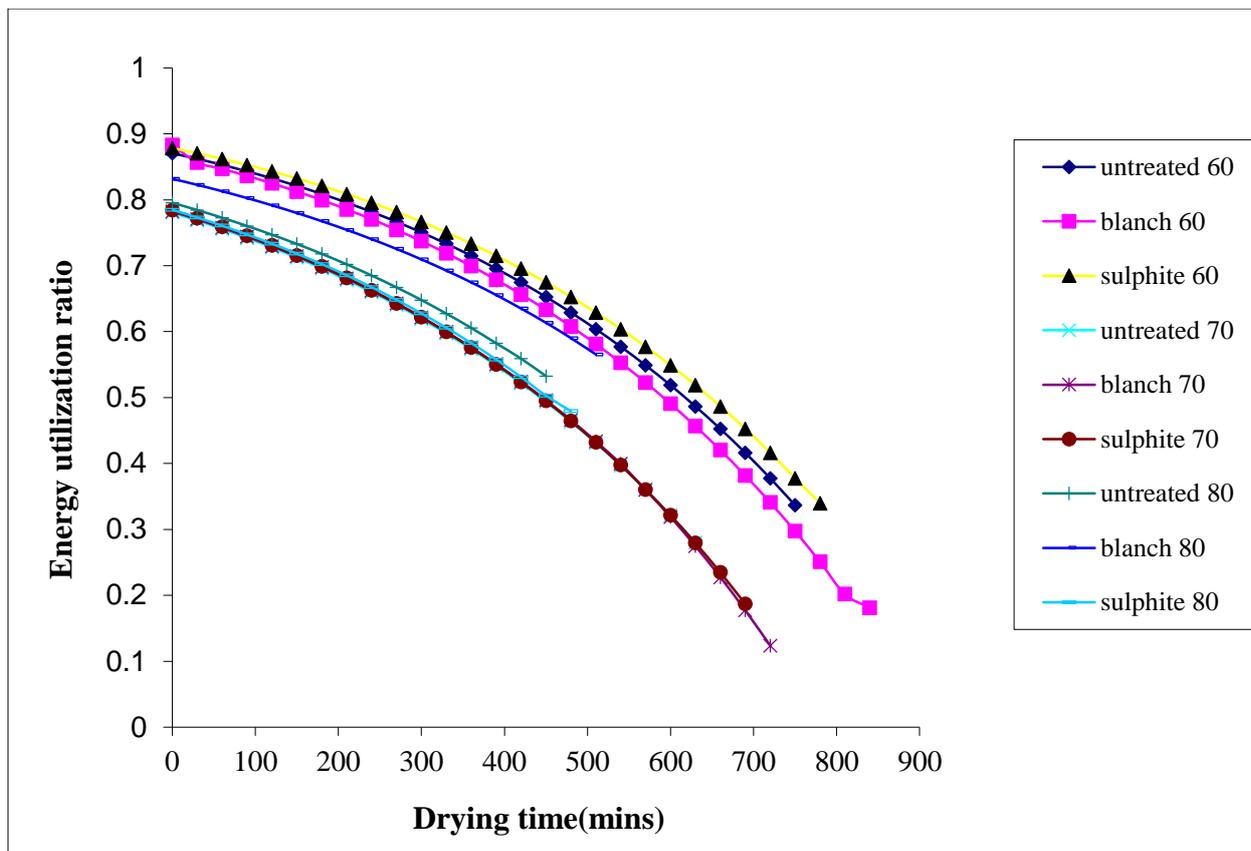


Table 3: Variation of energy utilization ratio with drying time for sweet potato samples at 60°C, 70°C and 80°C

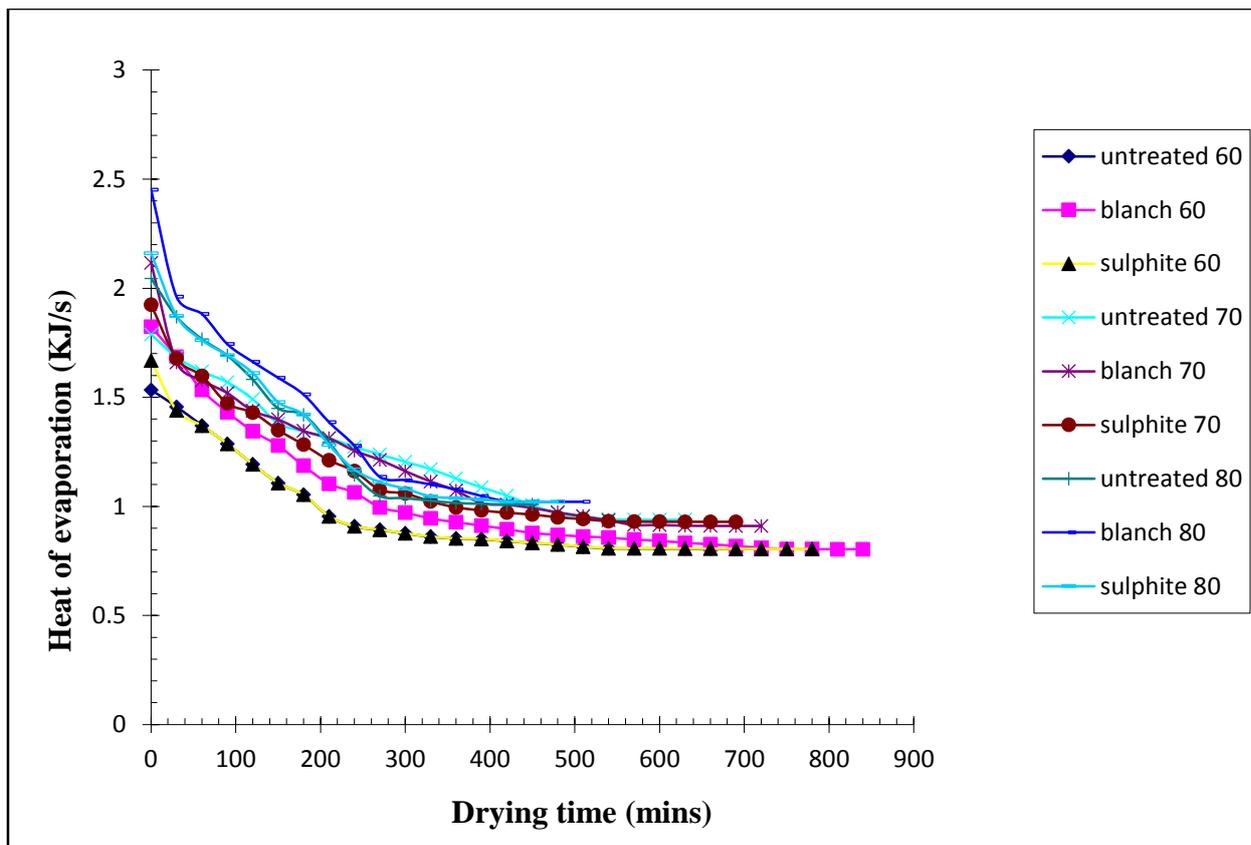


Figure 4: Variation of heat of evaporation with drying time for sweet potato samples at 60°C, 70°C and 80°C.

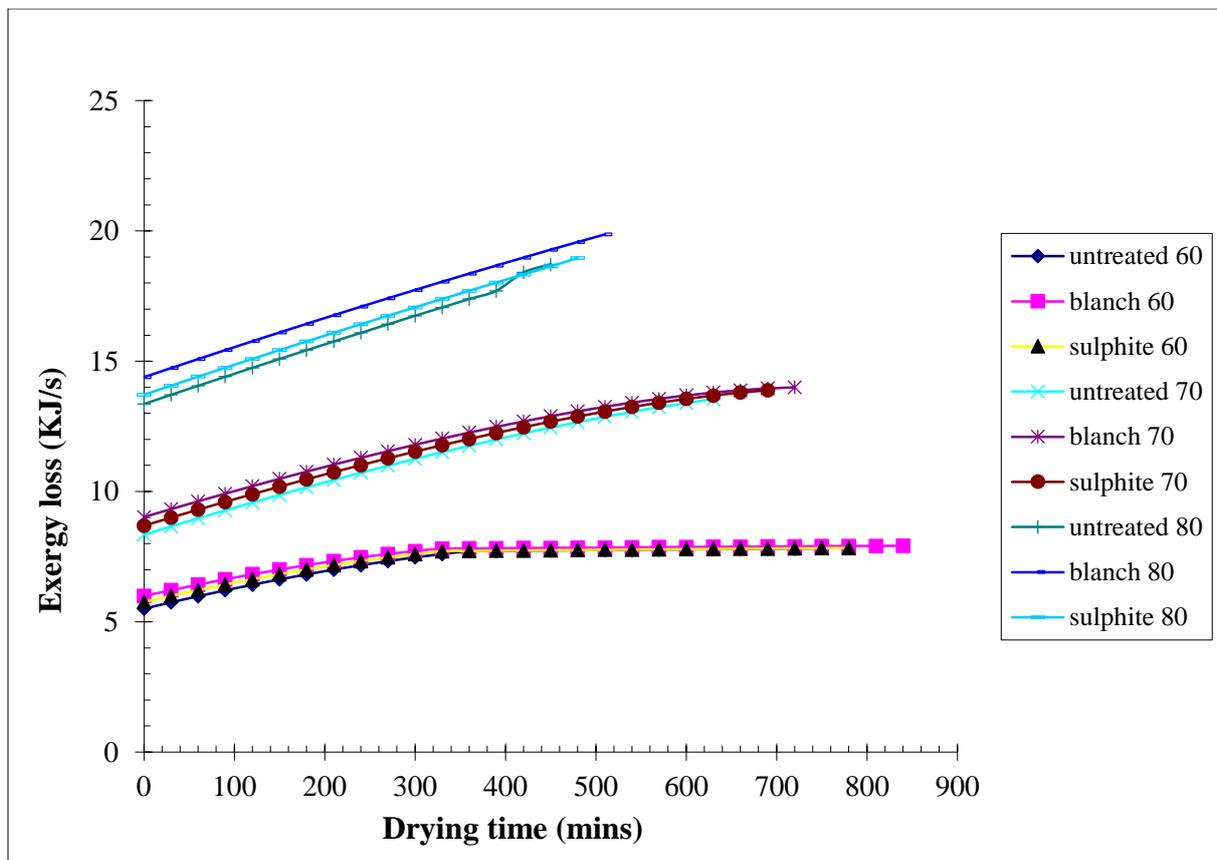


Figure 5: Variation of exergy loss with drying time for sweet potato samples at 60°C, 70°C and 80°C

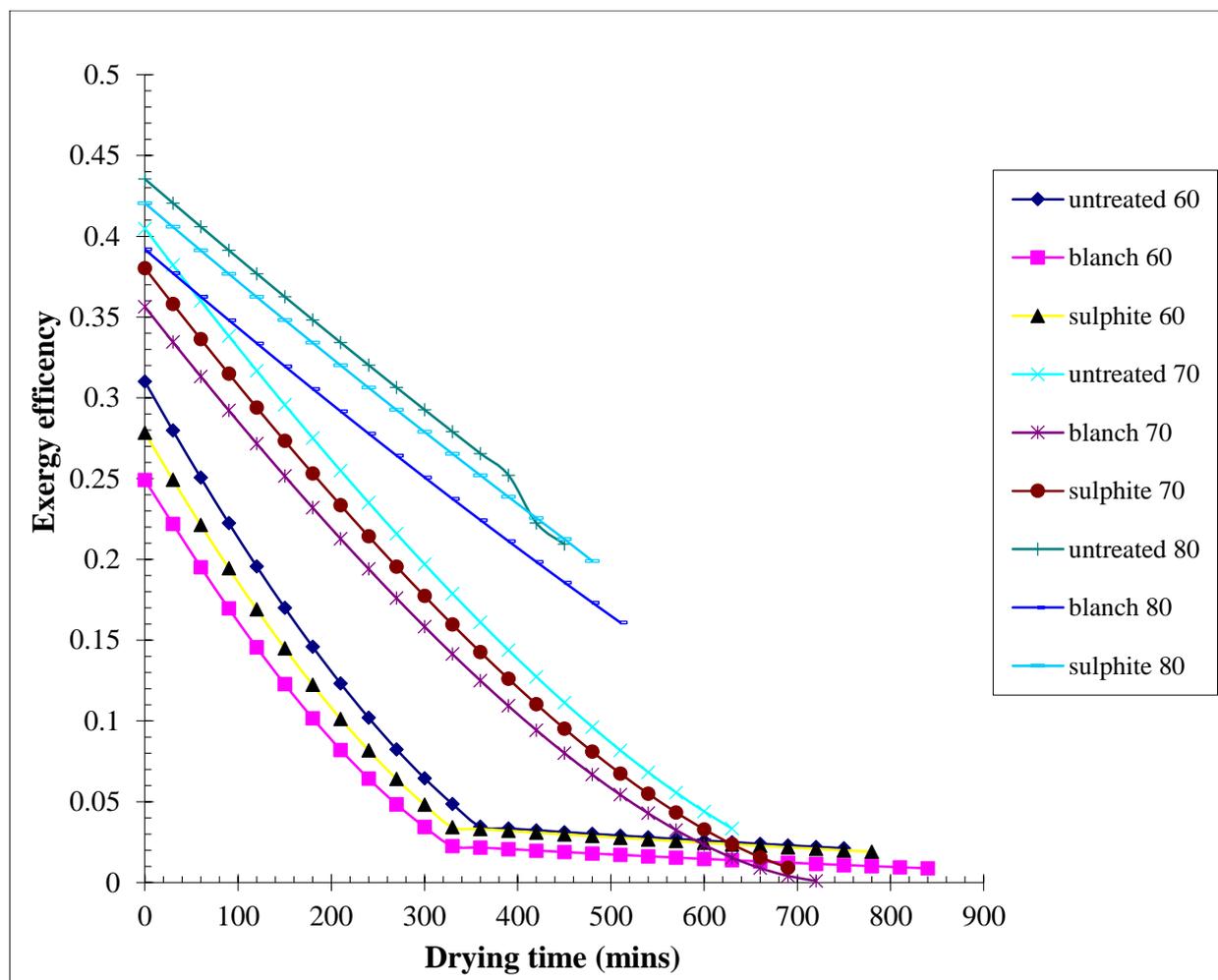


Figure 6: Variation of exergy efficiency with drying time for sweet potato samples at 60°C, 70°C and 80°C.