Journal of Chemical, Environmental and Biological Engineering
2023; 7(2): 44-56
http://www.sciencepublishinggroup.com/j/jcebe
doi: 10.11648/j.jcebe.20230702.11
ISSN: 2640-2645 (Print); ISSN: 2640-267X (Online)

Influence of Solar-Exhaust Gas Greenhouse Drying Modes on Viability of Black Nightshade Seeds

George Onyango Orido[1, 2, *], Erick Kiplangat Ronoh[1], Patrick Ochuodho Ajwang[1], Benson Baari Gathitu[1]

[1]Agricultural and Biosystems Engineering Department, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya
[2]Agricultural Engineering Department, Egerton University, Nakuru, Kenya

Email address:

george.orido@egerton.ac.ke (George Onyango Orido), ronoh@jkuat.ac.ke (Erick Kiplangat Ronoh), ajwang@agr.jkuat.ac.ke (Patrick Ochuodho Ajwang), bbgathitu@jkuat.ac.ke (Benson Baari Gathitu)
[*]Corresponding author

To cite this article:

George Onyango Orido, Erick Kiplangat Ronoh, Patrick Ochuodho Ajwang, Benson Baari Gathitu. Influence of Solar-Exhaust Gas Greenhouse Drying Modes on Viability of Black Nightshade Seeds. *Journal of Chemical, Environmental and Biological Engineering*. Vol. 7, No. 2, 2023, pp. 44-56. doi: 10.11648/j.jcebe.20230702.11

Received: June 27, 2023; **Accepted**: July 12, 2023; **Published**: July 27, 2023

Abstract: In this study, three distinct and unique modes of greenhouse drying are introduced: solar, solar-exhaust gas, and exhaust gas modes of drying. The effect of drying black nightshade seeds in the three modes was studied, using germinability as a measure of quality. In solar mode, seeds were dried from a moisture content of 89.34% (db) to 7.13% (db) with the greenhouse dryer room air temperature range of 14.82-58.46°C and relative humidity of 9.40-88.03%. In solar-exhaust gas mode drying was performed from 92.57% (db) to 6.07% (db) within a temperature range of 34.49-61.97°C and relative humidity of 7.10-39.27%. In exhaust gas mode black nightshade seeds were dried from an initial moisture content of 88.84% (db) to a final one of 9.42% (db) when the greenhouse dryer room air temperature ranged from 25.75 to 30.77°C and relative humidity inside the dryer was between 51.88 and 83.98%. The results show that exhaust gas drying mode had a difference of 12.5% when its mean germination percentage was compared to solar mode of drying. Moreover, a 16.2% difference in means of germination percentage was recorded when solar-exhaust gas mode of drying was compared to exhaust gas mode. The highest mean germination percentage was recorded at 89% for exhaust gas drying mode because black nightshade seeds were subjected to temperatures ranging from 25.75 to 30.77°C. Modified Giner's model predicted germination changes of black nightshade seeds more accurately than modified Sharp's model due to the higher coefficient of determination (0.6896 > 0.6853) and lower root mean squared error (6.1554 < 6.4519). The activation energy in the modified Giner's model was found to be 7.034×10^{33} Joule/mole through model fitting to experimental data. In conclusion, it is recommended that the feasibility of exhaust gas energy use in drying be expanded to seeds of other African vegetable crops.

Keywords: Black Nightshade Seeds Viability, Solar-Exhaust Gas Greenhouse Dryer, Exhaust Gas Energy

1. Introduction

Seeds are the reproductive units of higher plants, and they have a significant place in agriculture and plant diversity maintenance [1]. Moreover, investigating how seed germination of multiple species in an ecosystem responds to environmental conditions is crucial for understanding the mechanisms for community structure and biodiversity maintenance [2]. It is important for seed scientists to be aware of areas on which to focus their research to support the work of the genebanks in conserving and making available plant genetic resources [3]. Bakhtavar *et al*. [4] have recommended that seed must be dried to safe moisture limits before storage and the dryness should be maintained throughout the supply chain. Previous studies have been undertaken to examine the effect of drying on viability, the water absorption pattern, laboratory and field germination and seedling growth on seeds of three citrus species, one of its allied genus and a hybrid [5]. In vegetable crops like black nightshade, high yield and growth are primarily associated with seedling health and early emergence which induces a potential to cope with various biotic and abiotic stresses [6]. As long as the soil moisture requirements are met, germination can be achieved in one day and rainfall rather than temperature will be extremely limiting for seed germination in future climate scenarios [7]. Important parameters that influence seeds' germination and seedlings' emergence consist of environmental factors such as soil temperature, soil water potential, exposure to light, fluctuating temperatures, nitrates concentration, soil pH, and the gaseous environment of the soil [8].

One of the traditional and economical drying methods for seeds is to leave them in the field to be dried and another is to extract the seeds as proposed by Degwale *et al.* [9] then expose them to direct sunlight through open sun drying. In the present work, three methods of drying: solar, solar-exhaust gas, and exhaust gas have been introduced in a greenhouse dryer. Greenhouse drying has significant advantages over in-field and open sun drying such as early harvesting options, yield and quality benefits, and reduced threat of weather damage [10]. It is for these reasons that the three modes of drying were studied for black nightshade seeds. Seed quality is characterized by germination percentage and physical purity. Determination of key traits in seeds such as dormancy and viability is important, therefore, researchers like Krichen *et al.* [11] have introduced a modelling approach to identify the cardinal temperature of germination of needle grass, considering dormancy and viability after exposure to salinity and drought, conditions experienced in North Africa due to desertification. A state-of-the-art multichannel imaging method introduced by ElMasry *et al.* [12] has been recommended for monitoring germination and vigour in actual growing environments; and its applicability was reported to be critically important in identifying vigorous seeds that can tolerate abiotic and biotic stress under different conditions of the environment. According to Reed *et al.* [13], elevated temperature during seed development can delay germination and reduce seed vigour in crops such as cereals, legumes, and vegetable crops (black nightshade). Reed *et al.* [13] have argued that in the coming decades, maintaining a steady food supply for the increasing world population will require high yielding crop plants which can be productive under increasingly variable conditions. Black nightshade vegetable crop has been reported to have the ability to withstand the potential impact of climate change in addition to combatting malnutrition and contributing to Africa's food supply [14, 15]. However, some authors have treated it as one of the worst weeds in crop fields [16] while others have promoted its cultivation through improved seeds germination by priming treatments [17] because of its economic and medicinal importance [14]. Khaeim *et al.* [18] have conducted a study that provides essential information regarding germination requirements and investigates tolerance to a range of environmental temperatures and drought stresses. The authors in their conclusion declared that dry weight could indicate seedling development, because dry matter accumulation is consistent with the physical measurement of seedling growth. Furthermore, Khaeim *et al.* [18], affirmed that different seed and seedling densities present no significant difference; thus, using a lower seed density is recommended for lab examination.

To inhibit microorganisms and prevent germination during storage, seeds must be dried to safe moisture level. In the agriculture sector, low black nightshade seeds quality due to delayed or improper drying is a problem to farmers [14]. Chao *et al.* [19] have also shown a literature gap and reported that currently, the effects of different drying methods on bioactive compounds, antioxidant capacity and antityrosinase activity of seed-used pumpkin by-products are not clear, therefore, this influenced their selection for an optimal drying method to acquire particularly anticipated quality for dehydrated seed-used pumpkin by-products. A study on lentils by Najib *et al.* [20] revealed a knowledge gap on preparation of plant-based ingredients from germinated lentils using microwave-assisted infrared drying process. Lack of reported data necessitated Najib *et al.* [20] to carry out a comprehensive comparison of three lentil varieties in hydration, germination, and dehydration behaviour. Huang *et al.* [21] aimed to determine the optimum drying temperature for rice seeds according to their initial moisture content, and to elucidate the mechanism mediating the effects of drying temperature and initial moisture content on seed vigor of rice. The authors reported that drying temperature, drying rate, and seed temperature showed extremely significant negative correlations with germination energy, germination rate, germination index, and vigor index [21]. For a single seed population of each of four species of grain legume studied by Covell *et al.* [22], positive linear relationships were shown between temperature and rate of germination for different fractions of each population, from a base temperature, at which germination rate was zero, to an optimum temperature, at which germination rate was maximal. Subsequently, Ellis *et al.* [23] reported that a screening procedure which required information on the progress of germination at only four temperatures was able to define the response of the rate of seed germination to sub- and supra-optimal temperatures for whole seed populations of each of five bean genotypes. Aflakpui *et al.* [24] have also reported that positive linear relationships were established between the rate (reciprocal of time taken) of germination of 90% of the final germination percentage and temperature up to the respective optimal temperatures.

In a recent study, Ismaili *et al.* [25] have determined optimal germination conditions for *stachys mouretti* an endemic species of Morocco considered rare and threatened. The researchers aimed to conserve and valorized the plant whose seeds were collected then subjected to alternating temperatures which had a significant effect on germination capacity. A recent methodology used to investigate the impact of temperature on germination of perennial ryegrass has been reported by Javaid *et al.* [26] and in their study, twenty seeds were placed uniformly in a Petri plate, lined with filter paper beneath the seed moistened with distilled water of three millilitres and then retained in an incubator at constant temperatures of 20, 25, 30 and 35°C for fifteen days. Javaid *et* *al*. [26] concluded that temperature had a significant impact on seed germination of perennial ryegrass with optimum temperature for its germination as 25°C. Xie *et al*. [27] explored the suitability of radio frequency combined hot air drying and found that the technique reduced germination rate by 27.8% as compared to pulsed vacuum drying which maintained good germination rates when peanut pods used for seeds was dried. Coradi *et al*. [28] in a study aimed at evaluating the associations of drying temperature with storage systems and conditions as a strategy for preserving the quality of maize grain postharvest on laboratory and field scales; reported that an increase in temperature accelerated the reduction in grain moisture but increased deterioration. Baskin *et al*. [29] have pointed out the mistakes made in seed germination ecology, problems in determining the kind of dormancy and in extrapolating data to the field situation. The authors emphasized that even if treatments that seeds might experience in nature are effective in promoting germination, it is not safe to assume that they play an important role in nature [29]. In a study to determine the influences of temperatures on seed germination rate in Himalayan elm, the thermal time both at sub and supra-optimal temperatures increased linearly as the values of the percentile germination increased in all three seed sources but the seeds germinated at supra-optimal temperatures required less thermal time to germinate than at sub-optimal temperatures [30].

Maturity of seeds, dryer design, drying time, moisture content, and species or variety are the factors which affect seeds response to hot air drying [10]. High quality seeds tolerate stressful planting conditions and result in uniform stand which allows better secondary tillage operations, therefore, there is a need to maintain the quality through new methods of drying to ensure germinability [31]. In order to ensure that a seed lot of good quality (high seed viability) reaches the storage facilities, standard practices must be followed starting from seed collection and during postharvest seed management, prior to storing seeds [32]. De Vitis *et al*. [32] have documented a compendium of best practices, tools, and standards for the steps between postharvest seed handling and seed storage, for applications in restoration. Restoration studies by Budelsky and Galatowitsch [33] have shown particular interest in the potential influence of storage condition and duration (seed history) on seed response to different germination conditions with uniqueness in considering the effects of storage condition, storage duration, germination temperature, and germination moisture simultaneously for *carex* seeds to determine the optimum treatment combination for maintaining viability and stimulating germination. The proximate implications of the research by Budelsky and Galatowitsch [33] include recommendations for seed producers regarding the best storage conditions for maintaining seed viability after collection, the efficacy of short-term stratification on germination of stored seed, optimum conditions for growth chamber or greenhouse germination, and timing of seed dispersal in restorations and creations. Harrington [34] in a summary pointed out that seeds reach a peak of vigor and germination at the moment of full maturity and that man can only attempt to keep them as close to this peak as possible by proper harvesting and milling and by drying seed to safe moisture levels for storage until needed.

From the above reviewed literature and to the best of the authors knowledge it is evident that published studies on use of exhaust gas energy to dry black nightshade seeds are limited with no clear consensus on recommended temperatures and drying methods' influence on viability of black nightshade seeds. In addition, knowledge of seed germination response of species to environmental conditions is still scarce at the community level [2]. The present study, therefore, focused on drying behaviour and germination of black nightshade seeds subjected to solar, solar-exhaust gas and exhaust gas modes of drying in a greenhouse dryer. Drying experiments and standard germination tests were conducted to generate data to be fitted to two commonly used germination models to allow for selection of the best model to describe germination experimental data. The hypothesis proposed for this research was that germination percentage for the three drying modes was the same. The overall goal of this research was to determine the influence of the drying modes on the viability of black night shade seeds. Specifically, the authors asked the question: how will the drying modes influence viability of black nightshade seeds?

2. Materials and Methods

2.1. Description of Study Site

Field experiments were set up at the Department of Agricultural and Biosystems Engineering, Jomo Kenyatta University of Agriculture and Technology (JKUAT), Kenya. The latitude and longitude angles of the University are $1^{\circ}5'20.8''$S and $37^{\circ}0'30''$E, while the altitude is 1527 m above the sea level. The mean annual temperature is 19.85°C with a mean annual maximum temperature of 24.91°C and a mean annual minimum temperature of 14.79°C. The relative humidities range from 15-80%. The climate for the study site is considered warm and temperate with an annual bimodal rainfall of 1014 mm characterized by cold rainy seasons occurring from April to August and October to December each year.

2.2. Experimental Set Up

The solar-exhaust gas greenhouse dryer used in this study is shown in Figure 1 (outside view). The measurements of the dryer were 8 m long, 4 m wide, and 2.6 m high. Figure 2 shows the hybrid recuperative heat exchanger designed and developed to harvest exhaust gas heat energy from a diesel engine inside the dryer [35]. The diesel engine was capable of utilizing both diesel and biodiesel fuels as explained in the methodology of Orido *et al*. [36]. Four drying trays, two on the right and two on the left were fabricated inside the dryer to measure 6 m long by 1 m wide with a spacing of 0.3 m between the two levels of drying. The heat exchanger was placed below the drying trays and food-grade plastic mesh screen held the drying products in position during the thin layer drying experiment as presented in Figure 3.

Figure 1. Outside view of the solar-exhaust gas greenhouse dryer (reproduced from [14]).

Figure 2. Recuperative heat exchanger in the solar-exhaust gas greenhouse dryer (reproduced from [35]).

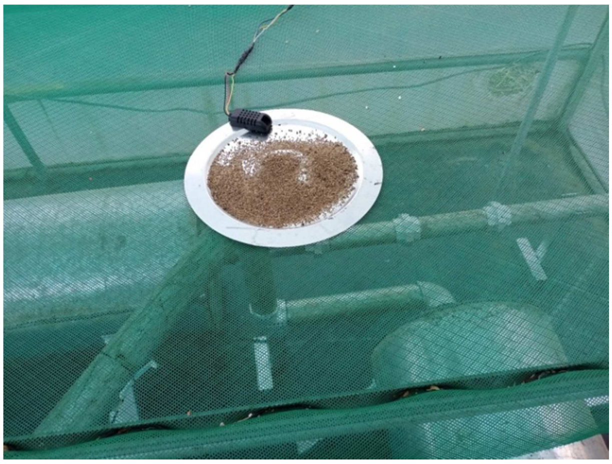

Figure 3. Thin layer drying of black nightshade seeds on a drying tray (reproduced from [14]).

2.3. Instrumentation and Data Acquisition

To study the variation of temperature and relative humidity profiles inside and outside the solar-exhaust gas greenhouse dryer, twenty-six (AM2301A, China) temperature and relative humidity composite sensors with calibrated digital signal output were used. Twenty-four of the sensors were placed at the desired locations inside the dryer while one RH sensor and another temperature sensor were placed outside the dryer. Surface temperatures of connectors and tubes of the heat exchanger were measured using twelve (DS18B20, China) programmable resolution 1-wire digital thermometers with operating temperature range of -55°C to +125°C ($\pm$0.1). The sensors (AM2301A, China), and (DS18B20, China), were programmed to record data in a microcontroller (ATmega2560, Italy). The Arduino Mega microcontroller was equipped with a 2 GB microSD card for data storage of the experiments.

2.4. Germination Modelling

To predict the percentage viability of seeds during storage after a given period of time, the relationship between temperature, moisture content and mean viability is used as given in (1) [37].

$$log\, p_{50} = K_v - C_1M - C_2T \quad (1)$$

In (1), p_{50} is mean viability period in days (time taken for 50% of the seeds to die), M is moisture content (% db), T is temperature (°C), K_v, C_1 and C_2 are constants. Equation (2) [38, 39] is used to model the effect of time, temperature, and moisture content on the storage life of seeds.

$$t_v = (K_i - v)10^{(C_1 - C_2 logM - C_3T - C_4T^2)} \quad (2)$$

In (2), t_v is storage time in days for the percentage viability to fall to v, C_1, C_2, C_3, and C_4 are constants which vary for different crops and are independent of initial seed quality. K_i is a constant specific to each seed lot and is a measure of initial seed quality. The change in seed germination which is a function of the resultant temperature from heat balance and moisture content for any time step is estimated using the modified Sharp's model presented in (3) [10].

$$G_t = G_0 - \frac{t}{10^{(C_0 - C_1 logM_i - C_2T - C_3T^2)}} \quad (3)$$

In (3), G_t is germination of seed after t hours of exposure (%), G_0 is initial germination of seed lot (%), M_i is initial moisture content of seeds (% db), T is temperature (°C), C_0, C_1, C_2, and C_3 are constants. Equation (4) is the modified Giner's model [40] and is used to estimate germination (G_t) of seeds with initial germination (G_0) after an exposure time (t), during which grain moisture (M_i) and absolute temperature (T_a) are kept constant.

$$\frac{G_t}{G_0} = exp\left[-\left(exp\left(-\frac{E_a}{RT_a} + Z_1 + Z_2M_i\right)\right)t\right] \quad (4)$$

To fit experimental data over a succession of time intervals (Δt), (5) [40] is used with grain moisture and temperature deemed constant.

$$\frac{G_{t+\Delta t}}{G_t} = exp\left[-\left(exp\left(-\frac{E_a}{RT_{am}} + Z_1 + Z_2M_m\right)\right)\Delta t\right] \quad (5)$$

In (5), G_t is germination percentage at time t, $G_{t+\Delta t}$ is germination percentage at time $t + \Delta t$, M_m is mean grain moisture content during the interval Δt (db, decimal), T_{am} is absolute temperature during the interval Δt (K), E_a is activation energy corresponding to viability loss (Joule/mole), R is gas constant, and Z_1 and Z_2 are constants of the model. Equation (6) [41] which is a polynomial relationship between stress cracks and germination of seeds is used to find germination percentage of seeds.

$$G = -0.0211c_r^2 + 2.051C_r + 48.577 \quad (6)$$

In (6), G is germination percentage of seed and C_r is proportion of seeds having transverse or vertical stress cracks (%).

Model validation was a necessary step to examine the developed and fitted models. Firstly, the coefficient was defined by (7), where P_i were the predicted values of the variable, O_i were the observed values, $\hat{P}_i$ was an estimate of the average response, $\hat{O}_i$ was the average of observations made and n was the number of elements of data from the experiment.

$$R^2 = \frac{\sum_{i=1}^{n}(P_i - \bar{P}_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O}_i)^2} \quad (7)$$

Secondly, the performance of the model was measured in terms of RMSE (root mean squared error) as given in (8), where n was the number of observations available for analysis, P_i were the predicted values of the variable and O_i were the observed values.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \quad (8)$$

Finally, plotting of the residuals against the independent variable was done as a standard through which the regression model could be validated statistically because it was used as a measure of the distribution of errors.

2.5. Sampling Procedure

The technique adopted in selecting black nightshade berries, for diameter and seeds number determination as quantitative parameter and qualitative variable, respectively, involved the sample design and size. A finite type of accessible population was considered with Western Kenya as the geographical sampling unit. To represent the accessible population under study, comprehensively and reliably, the sampling frame was defined as the source list composed of mature black nightshade berries from the vegetable crops within Western Kenya. The berries were deemed mature for harvesting when they were still held by the plant and their colour had turned orange from green to signify that they had ripened. In this study, diameter of black nightshade berries was treated as a quantitative parameter characteristic to the accessible black nightshade berries' population and seeds number in a berry was a qualitative variable dependent on the diameter and characteristic to the sample of black nightshade berries drawn from the accessible population. To denote the number of black nightshade berries to be selected from the accessible population to constitute a sample, an optimum sample size that fulfilled the requirements of representativeness, reliability and flexibility was used. The sample procedure constituting the sample design was chosen to result in the smallest sampling error. The disproportionate sampling design was used as expressed in (9).

$$\frac{n_1}{N_1\sigma_1} = \frac{n_2}{N_2\sigma_2} = \frac{n_3}{N_3\sigma_3} = \cdots \dots \dots \dots = \frac{n_k}{N_k\sigma_k} \quad (9)$$

In (9), n_1, n_2, n_3,…., n_k denote the sample sizes of k strata; N_1 , N_2 , N_3 ,…., N_k denote the accessible black nightshade berries' population sizes of k strata; and σ_1, σ_2, σ_3 ,…., σ_k denote the standard deviations of the berries' diameters of k strata. From (9), the allocation of the subsample sizes for each stratum was computed as expressed in (10).

$$n_i = \frac{nN_i\sigma_i}{N_1\sigma_1 + N_2\sigma_2 + N_3\sigma_3 + \cdots \dots\dots + N_k\sigma_k} \quad (10)$$

The confidence interval for the accessible black nightshade berries' population mean (μ), was given by (11).

$$\mu \geq \bar{X} \pm Z\frac{\sigma}{\sqrt{n}} \quad (11)$$

In (11), $\bar{X}$ is the sample mean, Z is the value of the standard variate at a given confidence level, n is the sample size and σ is the population standard deviation. The difference between the population mean (μ), and the sample mean ($\bar{X}$), was termed the acceptable error (E), which was computed as expressed in (12).

$$E = \left(Z\frac{\sigma}{\sqrt{n}}\right)\sqrt{\frac{(N-n)}{(N-1)}} \quad (12)$$

In (12), N is the size of the finite accessible black nightshade berries' population and other terms are as defined previously in (11). Ripe black nightshade berries were plucked from buds of mature plants and placed in a sealed container. Plucking was done by the action of fingers to prevent unnecessary physical damage to the ripen berries that would have led to loss of seeds. A micrometer screw gauge was used to measure the diameter of the round berries. In order to measure the diameter, berries were placed between the jaws of the micrometer screw gauge and the thimble was rotated using a ratchet until each berry was secured. To read the results from the micrometer screw gauge, the first significant figure was taken from the last graduation showing on the sleeve directly to the left of the revolving thimble. An additional half scale division of 0.5 mm was included if the mark below the main scale was visible between the thimble and the main scale division on the sleeve. The remaining two significant figures—hundredths of a millimeter—were taken directly from the thimble opposite the main scale. The thimble had to line up with the main scale for the hundredths of a millimeter reading to be taken. To count the number of seeds within a berry, a sample of black nightshade berry was placed on a spot in the middle of a circular absorbent paper and with the application of thumb pressure, it was smashed to extract the seeds from the concentration of soluble solids contained in the berry fruit. The pulp and skin of the black nightshade berry were then separated from the seeds, to allow the latter to be counted. A sample of 40 berries were evaluated in this manner. The data was used in an analysis to determine the relationship between black nightshade berry seed count and size across the largest diameter to the nearest 0.01 mm with a micrometer screw gauge.

2.6. Standard Germination Test

Experiments were conducted in order to accomplish the proposed objective of this study. The experiments involved seed sample collection, drying experiments, seeds quality tests and models fitting. Black nightshade seeds originated from Western Kenya and were dried under solar, solar-exhaust gas, and exhaust gas drying modes so that the influence of the drying conditions on the seed viability could be determined. A standard germination test for viability was conducted for the samples collected from the drying experiments. The objective was to determine the seed quality in terms of germination percentage (the percentage of seeds that develop into normal seedlings) under normal environmental planting conditions within a period of time. Seed samples were kept in aluminium containers under ambient conditions overnight to be in equilibrium with ambient temperature and reduce seeds stress. The standard germination test was conducted by placing seed samples on moist soil. Six replications of 30 seeds were performed for each drying mode. The seeds that had root and shoots longer than 2 mm were considered as germinated seeds and were counted after 7 days. Thereafter, the numbers obtained were converted to percentages.

3. Results and Discussion

3.1. Sampling Results

The results of accessible population of black nightshade berries comprised of four strata such that: $N_1 = 50$, $N_2 = 100$, $N_3 = 150$ and $N_4 = 200$. The respective standard deviations of the diameters of the berries were: $\sigma_1 = 0.6815\,mm$, $\sigma_2 = 0.6994\,mm$, $\sigma_3 = 0.7223\,mm$ and $\sigma_4 = 0.8200\,mm$. A desirable sample size of 40 black nightshade berries was optimally allocated to the four strata using disproportionate sampling design as: $n_1 = 4$, $n_2 = 7$, $n_3 = 12$ and $n_4 = 17$ with a 99% precision of $E_1 = 0.24\,mm$, $E_2 = 0.18\,mm$, $E_3 = 0.16$ mm and $E_4 = 0.17\,mm$. The accessible berries' population mean diameter was, $\mu = 6.83\,mm$ with a standard deviation of, $\sigma = 0.7552\,mm$. The mean number of seeds in a berry in this study were 54 seeds—comparable with a study done by Schippers [42] where seed count in a berry was reported to be between 20-60 seeds. Figure 4 shows a scatter plot of the variations of seeds count with berries diameter. It reveals a linear relationship with a coefficient of determination, $R^2 = 0.8328$. The size in diameter of black nightshade berries was found to be directly related to the number of seeds in a berry at harvest on maturity. The maximum berry size in diameter was reported as 7.99 mm from an accessible population of 500 berries. From the same population the minimum size in the form of diameter was recorded at 5.28 mm.

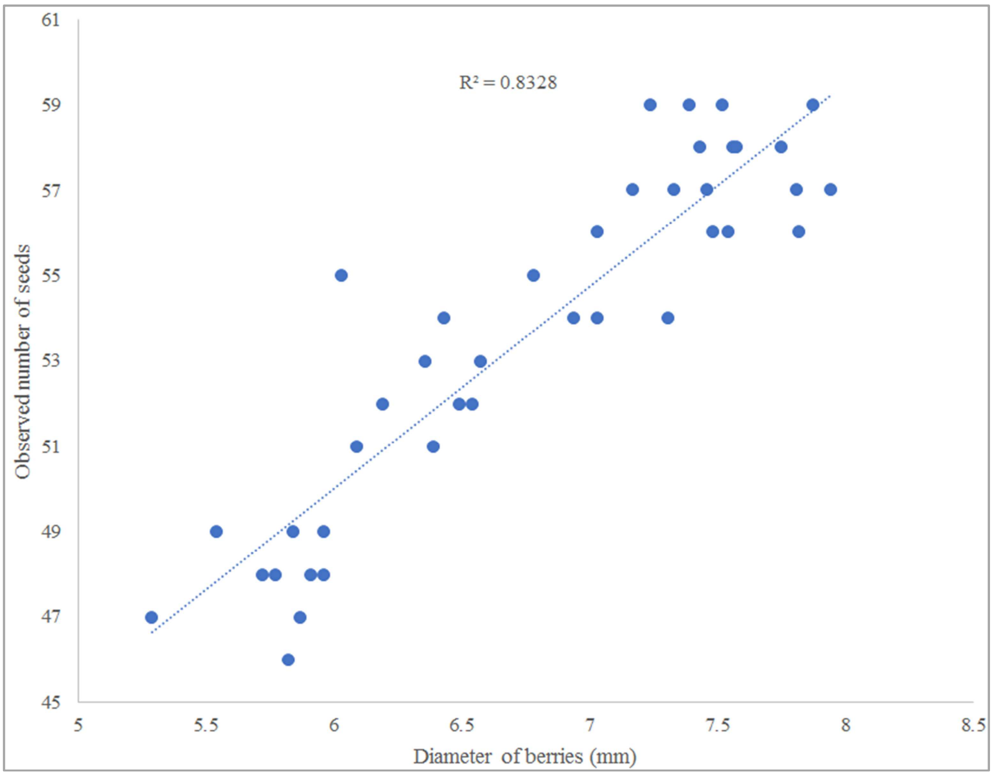

Figure 4. *Scatter plot of seeds' count variation with berries' diameter.*

Results of regression analysis revealed that the number of seeds (N_s) on the y-axis was positively correlated with the diameter of berries (D_b) on the x-axis. A linear regression model was developed from the data and is presented in (13) which is applicable for diameters ranging from 5 to 8 mm.

$$N_s = 21.5207 + 4.7469 D_b \qquad (13)$$

In (13), N_s is the number of seeds in a berry, 21.5207 is the intercept (a_0), of the model, 4.7469 is the slope (a_1), of the regression model, D_b is the diameter of a berry. From the coefficient of determination, over 83% of the total variability in seed count was accounted for by the model, showing that, there exists a strong positive linear relationship between the number of seeds in a berry and the diameter of black nightshade berries. This implied that the number of seeds could be estimated from a berry's diameter ranging from 5 to 8 mm with reasonable certainty. The t-distribution similar to the t-test was used as the test statistic for the regression model's intercept and slope. Making statistical inferences at the 0.05 level of significance ($\alpha = 0.05$), it was concluded that the true value of the intercept of the regression model lied in the interval 19.1191 to 23.9223 and similarly the true slope lied in the interval 4.4032 to 5.0905. The value of the t-distribution calculated from the data was more than the critical value of the t-distribution for a two tailed test with $\alpha = 0.05$: ($t_{calc} = 18.6082$, $t_{crit} = 2.074$) for the intercept and ($t_{calc} = 27.9584$, $t_{crit} = 2.074$) for the slope. Thus, there was enough evidence to reject the null hypotheses that the intercept and slope were equal to zero and it was concluded with 95% confidence that berries diameter is useful in predicting the number of seeds in a berry of black nightshade. The RMSE for the seed count model was 2 seeds. A plot of the residuals against the independent variable (berries' diameter) is shown in Figure 5.

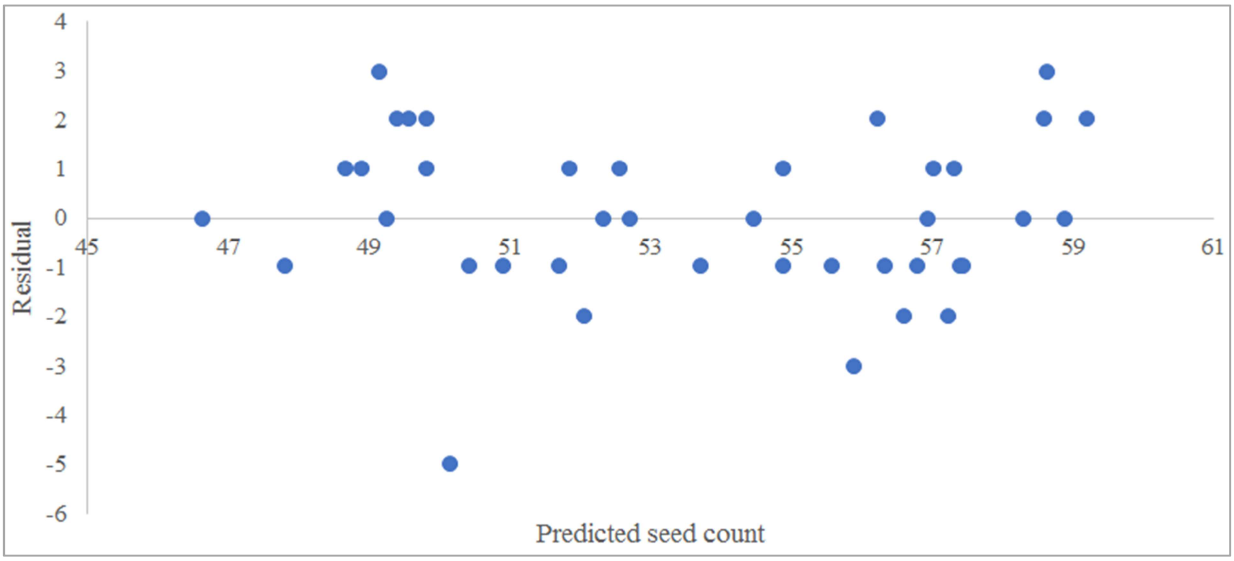

Figure 5. *Residual plot of seed count data for black nightshade berries.*

It was observed from Figure 5 that the seed count model gave a scattered residual plot, and this led to a conclusion that the model was able to explain the variation in the experimental data. The covariance was constant with a band width of most values at ± 2.

3.2. Standard Germination Test Results

The results of standard germination test are presented in Figure 6. The ANOVA results showed that at 0.05 level of significance $F_{cal} = 17 > F_{crit} = 3.68$. Thus, at least one of the drying modes was significantly different from the other. Fishers least significant difference (LSD) was determined as 5.1%. The difference between the means of germination percentage of solar drying mode compared to solar-exhaust gas mode of drying were not significantly different at 3.7%. Exhaust gas drying mode had a difference of 12.5% when its mean germination percentage was compared to solar mode of drying. Moreover, a 16.2% difference in means of germination percentage was recorded when solar-exhaust gas mode of drying was compared to exhaust gas mode. The highest mean germination percentage was recorded at 89% for exhaust gas drying mode because black nightshade seeds were subjected to temperatures ranging from 25.75 to 30.77°C. These temperatures were lower when compared to those of the other two modes of drying: solar (14.82-58.46°C) and solar-exhaust gas (34.49-61.97°C). A number of authors have recommended low drying temperatures for seeds. Moreno *et al.* [15] have recommended 35-40°C for drying amaranth seeds in order to ensure viability. The authors reported an unacceptable decrease in amaranth seeds germination rate from 85 to 23% due to increased drying temperatures in microwave drying and forced convection drying using hot air in an electric oven. A slight decrease of germinability was observed in beech seeds dried at 30°C when Pukacka and Wójkiewicz [43] dried the seeds at 15 and 30°C. The previous study reviewed 15-20°C as the recommended temperature of drying beech seeds and contrasted broadleaved species to conifers specifically on their inability to withstand high drying temperatures. Xie *et al.* [27] have reported germination rates of up to 88% while drying peanut pods used for seeds through hot air drying technique. Soares *et al*. [44] in a study aimed at evaluating the drying kinetics of barley grains in conventional and intermittent drying methods reported that drying at 40°C resulted in the highest values of germination energy and germination index.

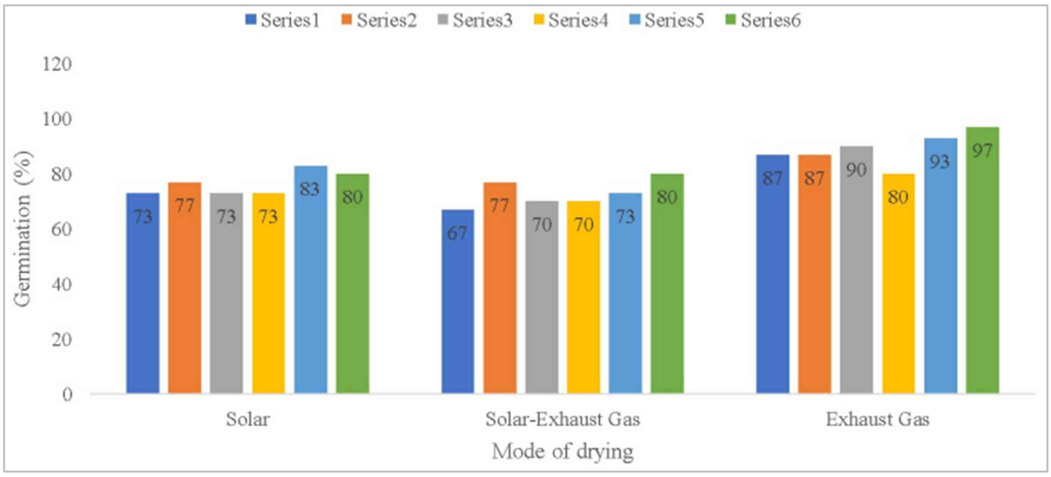

Figure 6. *Six replications of germination tests on black nightshade seeds' viability.*

3.3. Germination Models Fitting

Modified Sharp's model and modified Giner's model have been commonly used in predicting germination percentage of seeds during drying process. Consequently, in the present study, experimental data of standard germination test were used to fit the two models using data collected from exhaust gas mode of drying. This mode of drying was chosen because black nightshade seeds dried under it had the highest germination percentages The patterns from Sharp's model and Giner's model were used in R statistical software (*mosaic* collection of packages) to obtain the values of RMSEs, and constants as presented in Table 1.

Table 1. *Germination models' parameters.*

Model	R^2	RMSE	Constants
Modified Sharp's Model $G_t = G_0 - \frac{t}{10^{(C_0 - C_1 log M_i - C_2 T - C_3 T^2)}}$	0.6853	6.4519	$C_0 = 30.874$ $C_1 = 0.0163$ $C_2 = 0.0229$ $C_3 = 0.0101$
Modified Giner's Model $\frac{G_t}{G_0} = exp\left[-\left(exp\left(-\frac{E_a}{RT_a} + Z_1 + Z_2 M_i\right)\right)t\right]$	0.6896	6.1554	$E_a = 7.034 \times 10^{33}$ $Z_1 = 2.64 \times 10^{28}$ $Z_2 = 1.88 \times 10^{28}$

Figure 7 shows the performance of modified Sharp's model against experimental germination data. Figure 8 is a correlation between the observed and predicted germination percentages when modified Sharp's model was used. Figure 9 is a plot of residuals resulting from the predictions of modified Sharp's model.

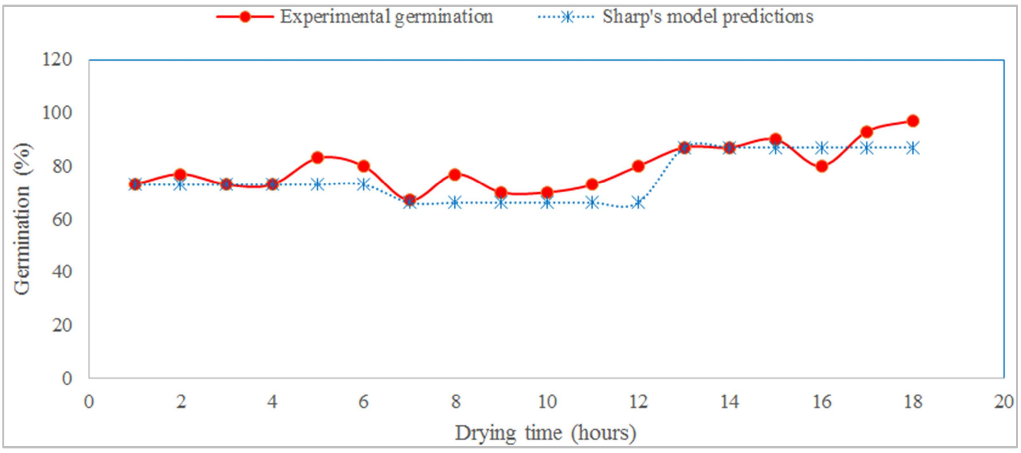

Figure 7. *Modified Sharp's model performance compared to experimental data.*

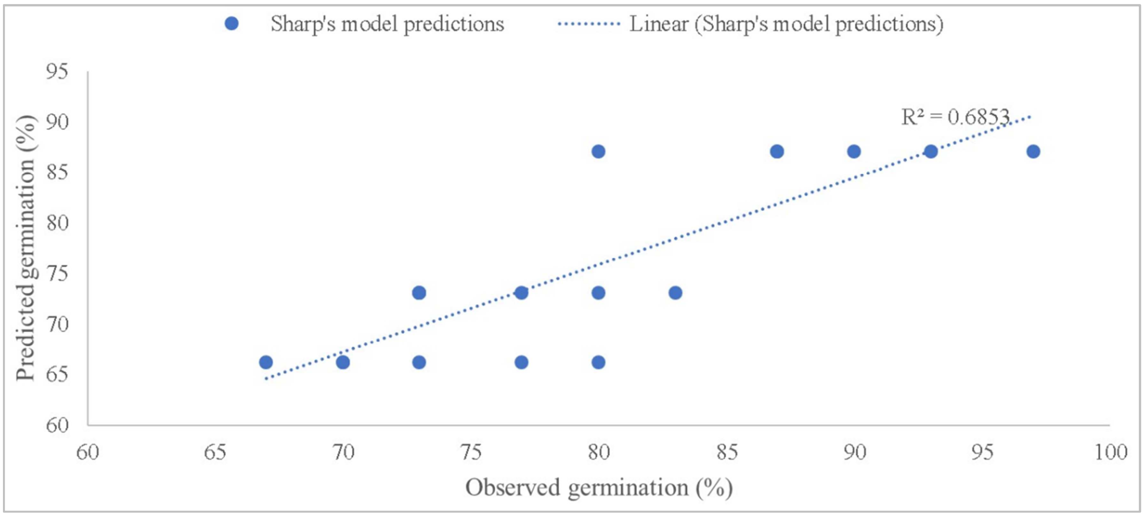

Figure 8. *Correlation between observed and predicted germination percentages using modified Sharp's model.*

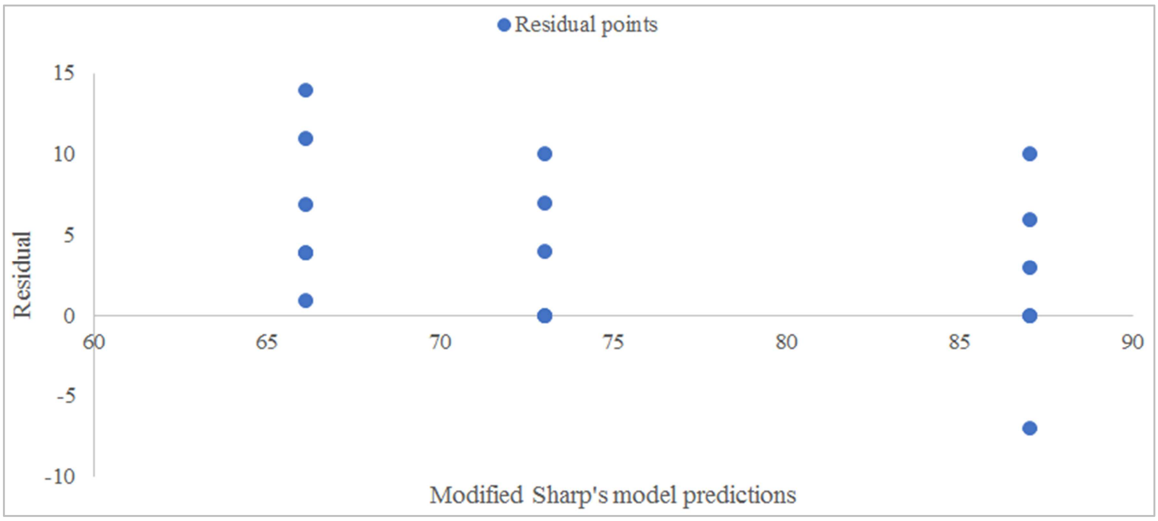

Figure 9. *Residual plots of modified Sharp's model predictions.*

Figure 10 shows the performance of modified Giner's model against experimental germination data. Figure 11 is correlation between the observed and predicted germination percentages when modified Giner's model was used. Figure 12 is a plot of residuals resulting from the predictions of modified Giner's model.

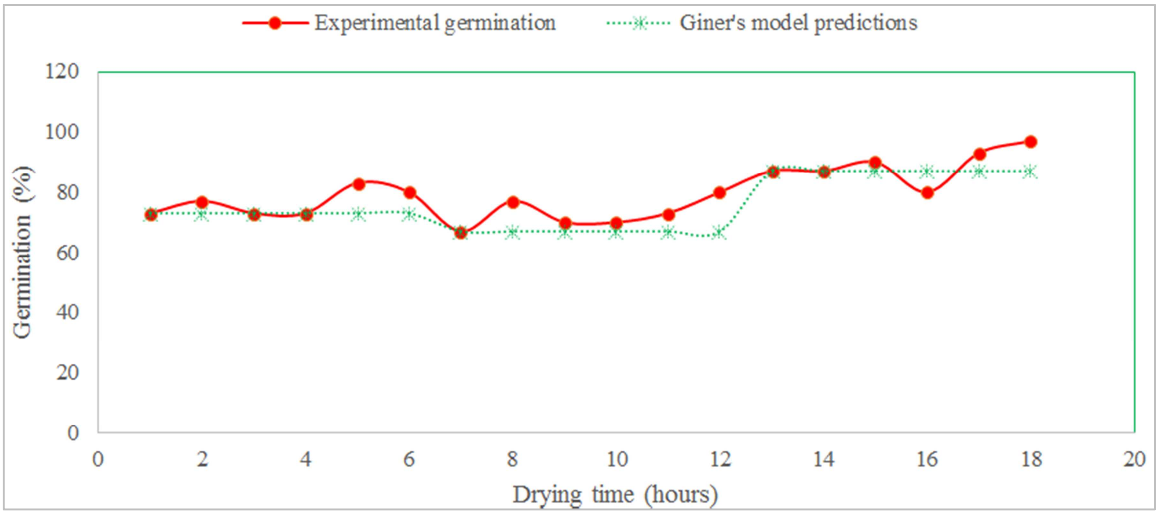

Figure 10. *Modified Giner's model performance compared to experimental data.*

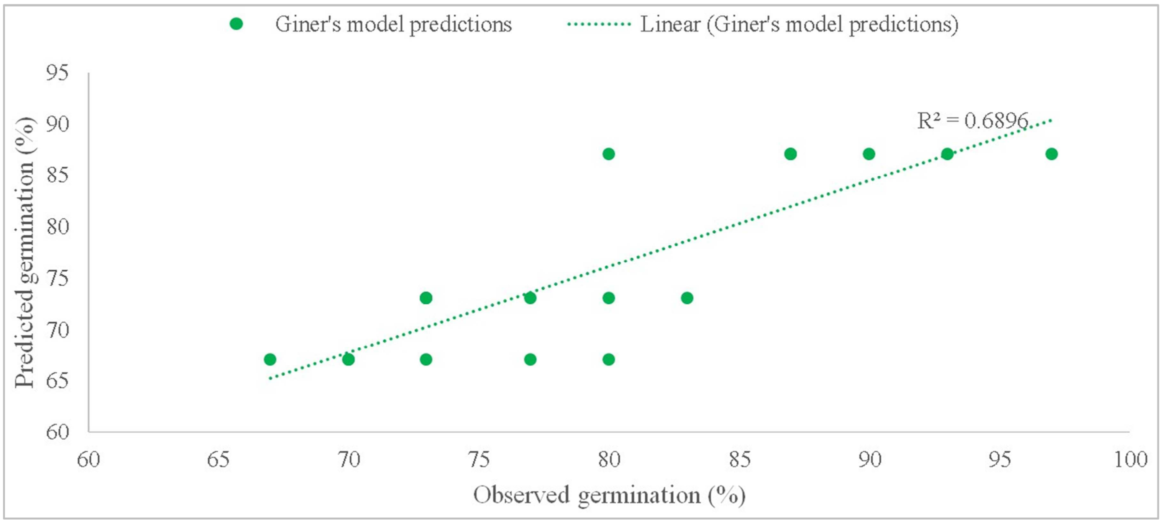

Figure 11. *Correlation between observed and predicted germination percentages using modified Giner's model.*

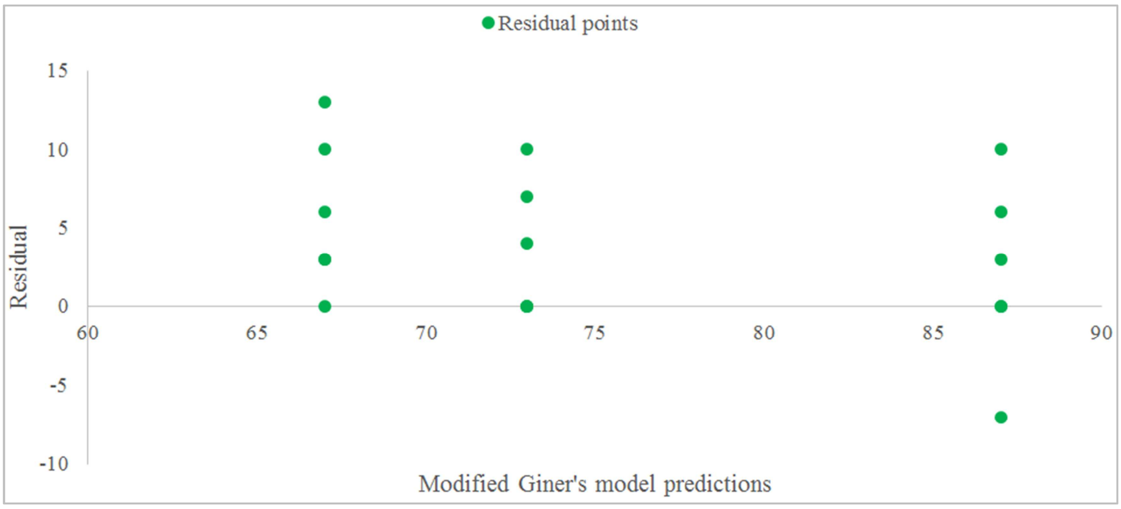

Figure 12. *Residual plots of modified Giner's model predictions.*

Modified Giner's model predicted germination changes of black nightshade seeds more accurately than modified Sharp's model due to the higher coefficient of determination (0.6896 > 0.6853) and lower root mean squared error (6.1554 < 6.4519). The survival analysis procedures with life tables, logistic regression, and accelerated failure are the most informative analyses for seed germination studies [45]. In this regard, the statistical procedure selected to evaluate the models' parameters shown in Table 1 best tested the hypothesis posed by the experiments in the current study to provide as much ancillary information as possible. Graphical evaluation of percent germination shown in Figures 7 to 12 was a useful step in analysis to promote stand establishment through the use of exhaust gas energy to dry black nightshade seeds.

4. Conclusions

In this study, three modes of drying in a greenhouse dryer (solar, solar-exhaust gas, and exhaust gas modes) were applied to black nightshade seeds. The viability of black nightshade seeds samples collected during drying experiments was assessed by standard germination test. Exhaust gas mode of drying was recommended as the most suitable mode of drying black nightshade seeds because it produced the highest mean germination rate of 89%. The models described in this study have potential use as seeds management protocols in quantifying seeds in berries and assessing germination. Modified Giner's model predicted germination changes of black nightshade seeds more accurately than modified Sharp's model due to the higher coefficient of determination (0.6896 > 0.6853) and lower root mean squared error (6.1554 < 6.4519). The activation energy in the modified Giner's model was found to be 7.034×10^{33} Joule/mole through model fitting to experimental data. It is recommended that the feasibility of exhaust gas energy use in drying be expanded to seeds of other African vegetable crops. There is need for research to be conducted on moisture sorption isotherms of black nightshade seeds for equilibrium moisture content evaluation. The effect of volumetric shrinkage, moisture diffusivity and geometric changes on heat and mass transfer in black nightshade seeds drying needs determination.

Conflict of Interest and Authorship Conformation Form

1. All authors have participated in conception, design, analysis, and interpretation of the data; drafting the article, revising it critically for important intellectual content; and approval of the final version.
2. This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.
3. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

Nomenclature

C_r	Proportion of seeds having transverse or vertical stress cracks (%)
C_0 to C_4	Constants
D_b	Diameter of a berries
E	Precision (acceptable error)
E_a	Activation energy corresponding to viability loss (Joule/mole)
G_0	Initial germination of seed lot (%)
G_t	Germination after exposure time t hours (%)
$G_{t+\Delta t}$	Germination percentage at time $t+\Delta t$
K_v	Constant
K_i	Constant
M	Moisture content (% db)
M_m	Mean grain moisture content during the interval Δt (db, decimal)
N	Population
N_s	Number of seeds in a berry
n	Sample size
N_{so}	Observed number of seeds in a berry
N_{sp}	Predicted number of seeds in a berry
O_i	Observed values
$\hat{O}_i$	Average of observed values
P_i	Predicted values
$\hat{P}_i$	Average of predicted values
p_{50}	Mean viability period of seeds in days
R	Gas constant = 8.315 Joule/mole K
R^2	Coefficient of determination
T	Temperature (°C)
T_a	Absolute temperature (K)
T_{am}	Absolute temperature during the interval Δt (K)
t_v	Storage time in days for the percentage viability to fall to v
$\bar{X}$	Sample mean
Z	Standard variate value
Z_1 and Z_2	Constants
μ	Population mean
σ	Standard deviation
AfDB	African Development Bank
JKUAT	Jomo Kenyatta University of Agriculture and Technology
RMSE	Root mean square error

Acknowledgements

The authors would like to acknowledge the Japan International Cooperation Agency (JICA) through the AFRICA-ai-JAPAN Project Phase II (2022-2023) for the financial support of this work.

References

[1] El-Maarouf-Bouteau, H. (2022). The Seed and the metabolism regulation. Biology, 11 (2), 168.

[2] Yi, F., Wang, Z., Baskin, C. C., Baskin, J. M., Ye, R., Sun, H.,... & Huang, Z. (2019). Seed germination responses to seasonal temperature and drought stress are species-specific but not related to seed size in a desert steppe: Implications for effect of climate change on community structure. Ecology and Evolution, 9 (4), 2149-2159.

[3] Whitehouse, K. J., Hay, F. R., & Lusty, C. (2020). Why seed physiology is important for genebanking. Plants, 9 (5), 584.

[4] Bakhtavar, M. A., Afzal, I., & Basra, S. M. A. (2019). Moisture adsorption isotherms and quality of seeds stored in conventional packaging materials and hermetic Super Bag. Plos One, 14 (2), e0207569.

[5] Saipari, E., Goswami, A. M., & Dadlani, M. (1998). Effect of seed drying on germination behaviour in citrus. Scientia Horticulturae, 73 (2-3), 185-190.

[6] Waqas, M., Korres, N. E., Khan, M. D., Nizami, A. S., Deeba, F., Ali, I., & Hussain, H. (2019). Advances in the concept and methods of seed priming. Priming and pretreatment of seeds and seedlings: Implication in plant stress tolerance and enhancing productivity in crop plants, 11-41.

[7] Dantas, B. F., Moura, M. S., Pelacani, C. R., Angelotti, F., Taura, T. A., Oliveira, G. M.,... & Seal, C. E. (2020). Rainfall, not soil temperature, will limit the seed germination of dry forest species with climate change. Oecologia, 192 (2), 529-541.

[8] Travlos, I., Gazoulis, I., Kanatas, P., Tsekoura, A., Zannopoulos, S., & Papastylianou, P. (2020). Key factors affecting weed seeds' germination, weed emergence, and their possible role for the efficacy of false seedbed technique as weed management practice. Frontiers in Agronomy, 2, 1.

[9] Degwale, A., Tesfa, T., Meseret, B., & Fantaw, S. (2023). Seed extraction methods affect the physiological quality of tomato seed and developing seedlings. International Journal of Vegetable Science, 29 (1), 16-24.

[10] Jittanit, W., Srzednicki, G., & Driscoll, R. (2009). Germination models for seeds dried in fluidised and spouted bed dryers. Seed Science and Technology, 37 (1), 180-191.

[11] Krichen, K., Ghorbel, M. A., & Chaieb, M. (2023). Modeling the influence of temperature, salt and osmotic stresses on seed germination and survival capacity of Stipa tenacissima L. Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology, (just-accepted), 1-21.

[12] ElMasry, G., Mandour, N., Ejeez, Y., Demilly, D., Al-Rejaie, S., Verdier, J.,... & Rousseau, D. (2022). Multichannel imaging for monitoring chemical composition and germination capacity of cowpea (Vigna unguiculata) seeds during development and maturation. The Crop Journal, 10 (5), 1399-1411.

[13] Reed, R. C., Bradford, K. J., & Khanday, I. (2022). Seed germination and vigor: ensuring crop sustainability in a changing climate. Heredity, 128 (6), 450-459.

[14] Orido, G. O., Ronoh, E. K., Ajwang, P. O., & Gathitu, B. B. (2023a). Evaluation of Thin Layer Models for Simulating Drying Kinetics of Black Nightshade Seeds in a Solar-Exhaust Gas Greenhouse Dryer. Bioprocess Engineering, 7 (1), 10-31.

[15] Moreno, Á. H., Aguirre, Á. J., Maqueda, R. H., Jiménez, G. J., & Miño, C. T. (2022). Effect of temperature on the microwave drying process and the viability of amaranth seeds. Biosystems Engineering, 215, 49-66.

[16] Ma, Z., Huang, H., Huang, Z., Guo, D., Saeed, M., Jiang, C.,... & Wei, S. (2021). Germination response of black nightshade (Solanum nigrum) to temperature and the establishment of a thermal time model. Weed Science, 69 (6), 695-703.

[17] Poovizhi, M., & Sujatha, K. (2020). Improvement in seed germination by priming treatments in Black nightshade (Solanum nigrum L.). Journal of Applied and Natural Science, 12 (2), 8.

[18] Khaeim, H., Kende, Z., Jolánkai, M., Kovács, G. P., Gyuricza, C., & Tarnawa, Á. (2022). Impact of temperature and water on seed germination and seedling growth of maize (Zea mays L.). Agronomy, 12 (2), 397.

[19] Chao, E., Tian, J., Fan, L., & Zhang, T. (2022). Drying methods influence the physicochemical and functional properties of seed-used pumpkin. Food Chemistry, 369, 130937.

[20] Najib, T., Heydari, M. M., & Meda, V. (2022). Combination of germination and innovative microwave-assisted infrared drying of lentils: effect of physicochemical properties of different varieties on water uptake, germination, and drying kinetics. Applied Food Research, 2 (1), 100040.

[21] Huang, Y. T., Wu, W., Zou, W. X., Wu, H. P., & Cao, D. D. (2020). Drying temperature affects rice seed vigor via gibberellin, abscisic acid, and antioxidant enzyme metabolism. Journal of Zhejiang University. Science. B, 21 (10), 796.

[22] Covell, S., Ellis, R. H., Roberts, E. H., & Summerfield, R. J. (1986). The influence of temperature on seed germination rate in grain legumes: I. A comparison of chickpea, lentil, soyabean and cowpea at constant temperatures. Journal of Experimental Botany, 37 (5), 705-715.

[23] Ellis, R. H., Simon, G., & Covell, S. (1987). The influence of temperature on seed germination rate in grain legumes: III. A comparison of five faba bean genotypes at constant temperatures using a new screening method. Journal of Experimental Botany, 38 (6), 1033-1043.

[24] Aflakpui, G. K., Gregory, P. J., & Froud-Williams, R. J. (1998). Effect of temperature on seed germination rate of Striga hermonthica (Del.) Benth. Crop Protection, 17 (2), 129-133.

[25] Ismaili, S. E., Maurady, A., Lachkar, M., Britel, M. R., & Bakali, A. H. (2023). Effect of temperature and different pre-treatments on seed germination of Stachys mouretii Batt. & Pit. Journal of Applied Research on Medicinal and Aromatic Plants, 32, 100438.

[26] Javaid, M. M., Mahmood, A., Alshaya, D. S., AlKahtani, M. D., Waheed, H., Wasaya, A.,... & Fiaz, S. (2022). Influence of environmental factors on seed germination and seedling characteristics of perennial ryegrass (Lolium perenne L.). Scientific Reports, 12 (1), 9522.

[27] Xie, Y., Lin, Y., Li, X., Yang, H., Han, J., Shang, C.,... & Lu, F. (2022). Peanut drying: Effects of various drying methods on drying kinetic models, physicochemical properties, germination characteristics, and microstructure. Information Processing in Agriculture.

[28] Coradi, P. C., Maldaner, V., Lutz, É., da Silva Daí, P. V., & Teodoro, P. E. (2020). Influences of drying temperature and storage conditions for preserving the quality of maize postharvest on laboratory and field scales. Scientific reports, 10 (1), 22006.

[29] Baskin, C. C., Thompson, K., & Baskin, J. M. (2006). Mistakes in germination ecology and how to avoid them. Seed Science Research, 16 (3), 165-168.

[30] Phartyal, S. S., Thapliyal, R. C., Nayal, J. S., Rawat, M. M. S., & Joshi, G. (2003). The influences of temperatures on seed germination rate in Himalayan elm (Ulmus wallichiana). Seed Science and technology, 31 (1), 83-93.

[31] Orido, G., Njue, M., & Ngunjiri, G. (2017a). Grain Drying Simulation in a GT-380 Dryer using Energy Recovered from ICE Exhaust. IOSR Journal of Agriculture and Veterinary Science, 10 (6), 01-06.

[32] De Vitis, M., Hay, F. R., Dickie, J. B., Trivedi, C., Choi, J., & Fiegener, R. (2020). Seed storage: maintaining seed viability and vigor for restoration use. Restoration Ecology, 28, S249-S255.

[33] Budelsky, R. A., & Galatowitsch, S. M. (1999). Effects of moisture, temperature, and time on seed germination of five wetland Carices: implications for restoration. Restoration ecology, 7 (1), 86-97.

[34] Harrington, J. F. (1959). Drying, storage, and packaging seed to maintain germination and vigor.

[35] Orido, G. O., Ronoh, E. K., Ajwang, P. O., & Gathitu, B. B. (2023b). Performance Assessment of Hybrid Recuperative Heat Exchanger for Diesel Engine Generated Exhaust Gas. International Journal of Thermofluids, 100392.

[36] Orido, G., Ngunjiri, G., & Njue, M. (2017b). Comparison of Thermal Energy Lost through Exhaust Gases at Various Engine Speeds and Torque Loads for Diesel and Biodiesel Fuels. IOSR Journal of Mechanical and Civil Engineering, 14 (3), 08-12.

[37] Roberts, E. H. (1972). Storage environment and the control of viability. Viability of seeds, 14-58.

[38] Ellis, R. H., & Roberts, E. H. (1980). Improved equations for the prediction of seed longevity. Annals of botany, 45 (1), 13-30.

[39] Sharp, J. R. (1982). A review of low temperature drying simulation models. Journal of Agricultural Engineering Research, 27 (3), 169-190.

[40] Giner, S. A., Lupano, C. E., & Anon, M. C. (1991). A model for estimating loss of wheat seed viability during hot-air drying. Cereal chemistry.

[41] Thuy, N. X., Choudhary, M. A., & Hampton, J. G. (1999). The effects of high drying temperature and tempering on development of stress cracks and germination of maize seed (Zea mays L.). Seed science and technology, 27 (2), 507-515.

[42] Schippers, R. (1998). Notes on huckleberry, Solanum scabrum and related black nightshade species. Natural Resource Institute, University of Greenwich. http://www. dfid. gov. uk/r4d/pdf/outputs/R6964a. pdf. Accessed on, 20/11/2021.

[43] Pukacka, S., & Wójkiewicz, E. (2003). The effect of the temperature of drying on viability and some factors affecting storability of Fagus sylvatica seeds. Acta Physiologiae Plantarum, 25, 163-169.

[44] Soares, M. A. B., Jorge, L. M. D. M., & Montanuci, F. D. (2016). Drying kinetics of barley grains and effects on the germination index. Food Science and Technology, 36, 638-645.

[45] Scott, S. J., Jones, R. A., & Williams, W. (1984). Review of data analysis methods for seed germination 1. Crop science, 24 (6), 1192-1199.