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Energy and Mass Balance in Storing Seed Potato Tubers Using a Para-Para System

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Abstract:- This research aims to analyze heat and mass transfer when storing seed potatoes using a para-para system. The research treatments were: Natural Aeration Without Sunlight (NANSL), Natural Aeration With Sunlight (NASL), Forced Aeration Without Sunlight (ANSL), and Forced Aeration With Sunlight (ASL). The para-para has dimensions of 90 cm wide and 225 cm high and consists of 6 shelves; the distance between the shelves is 30 cm. Potato tubers are stored in plastic baskets with a capacity of 10 kg and placed on shelves. Aeration uses air flow exhaled by a blower with a flow rate of 3.14 m3/sec. The variables observed included air temperature, potato tuber temperature, air humidity, light intensity, potato tuber weight loss, and the number of tubers growing apically. The total heat of respiration of storage treatments with NANSL, NASL, ANSL, and ASL were, respectively, 0.89 ± 0.08, 0.73 ± 0.06, 11.43 ± 0.2, and 11.2 ± 0.3 kJ/kg. The heat used to evaporate water from potato tubers is 0.17–0.42, 010-0.37, 0.03-0.15, and 0.02-0.11 kJ/kg. Average heat to raise the air temperature is 0.160±0.04, 0.136±0.02, 0.409±0.03, and 0.379±0.05 kJ/kg. Total heat lost to the environment for treatments NANSL, NASL, ANSL, and ASL is 0.89 kJ/kg, 0.73 kJ/kg, 11.43 kJ/kg, and 11.2 kJ/kg. The average amount of water vapor in the air in the NANSL, NASL, ANSL, and ASL storage treatments is: 0.0133±0.0008, 0.0133±0.0001, 0.0134±0.0005, and 0.0134±0.0005 kg/kg. Storing potato tubers on granola G3 variety seeds using the para-para model was able to produce quality seeds with seed damage of 2.47–10.28% and weight loss of 1.78–1.86%. The ANSL treatment produced seed potatoes with the best growth quality of 94.7 ± 1.1%.

Keywords: *Seed of potatoes, Storage, Energy and mass balance, Aeration, Para-para system*

1. Introduction

Potato tubers contain 12% carbohydrates, 3% protein, 3.5% energy, and 7% fiber; therefore, according to Visser et al. [1], potatoes are the fourth most important food in the world. Potatoes are grown in the highlands 1000–2000 m asl in almost all countries in the world; this has an impact on the need for continuous and quality potato seeds [2]. The continuous availability of quality seeds requires support from both the cultivation process and the process of storing potato seeds.

The process of storing potato tubers for seeds is still a problem because farmers store seed potato tubers using the traditional method (TSR) without controlling temperature, humidity, and lighting in the storage room [3]. Therefore, the number of rotten tubers when stored using the TSR method reaches 30–70% [4]. The TRS storage method used by farmers is spreading potato tubers on the floor with a thickness of ± 40 cm or storing them in plastic baskets with a capacity of 40 kg or a height of ± 40 cm. The conditions in the storage room for the TSR method are: air temperature 27–29 °C, air humidity 80–90%, and light intensity is not controlled [2].

Increasing the storage room temperature and increasing the air humidity using the TSR method are respectively 3-5°C and 10-15% [5]. The storage temperature of seed potato tubers is more than 25°C, and a humidity of 90% has an impact on increasing microbial activity, which causes damage to stored potato tubers and increases their respiratory activity. Damage to potato tubers using the TSR method is quite large as a result: room temperature is more than 26°C and humidity is above 85% [6]. Seed potato tubers have been exposed to disease before storage, and the respiration process is rapid. Potato seeding in open fields still produces disease-affected potato tubers (NST), potato diseases originating from bacteria and viruses [7].

According to Murlidhar et al. [8] and Muthoni et al. [9], potato dormancy is inversely proportional to shelf life. The dormancy period for potatoes is 3-5 months. Dormancy in potatoes is influenced by: the type of cultivar [10], age and weight of tubers at harvest, tuber water content, temperature and humidity of the storage room [11], and intensity of light in the storage room [12]. During this dormancy period, the potato tuber still has a respiration process, which produces heat, and an evaporation process, which produces water vapor. Heat and water vapor increase the temperature and humidity of the air around the tuber [13].

Storage temperature affects healing and wound healing processes, disease spread, and respiration. The optimal temperature for storing potato tubers is 8–20°C, and the optimal humidity is 85% [6]. However, Martin et al. [14] stated that storage of potato tubers can be done at a temperature of 18–28°C and RH 70–90%. Temperature setting at 21–25°C and humidity at 80–90%, with an airflow rate of 24 m3/minute if the room temperature is 40°C and humidity less than 35%. Storage of seed potato tubers using the TSR method can be carried out for 5 months [14].

Storing potato tuber seeds using the diffuse light storage (DLS) method is better than using the TSR method [15]. Applying the aeration method to stored potato tubers is very effective in reducing tuber weight loss and tuber damage. Heat from the respiration process is removed from the storage space by air flow due to the aeration system, and the dormancy period is regulated by regulating temperature, relative air humidity (RH), and incoming light [4]. In low-temperature storage conditions, respiration is also low. In this condition, the potato tubers are in a dormant state and do not need much oxygen for the respiration process.

The size of the storage space, the amount of light penetrating the stack of stored potato tubers, and air circulation must be controlled. Therefore, modifications to the TSR storage model by controlling temperature, humidity, and incoming light need to be carried out so that the dormancy period for potato tubers lasts 3-5 months and the tubers grow apical buds perfectly [16].

Air circulation and regulation of light diffusion in the storage room are the main factors in the success of storing potato tubers for seeds until apical shoots grow. These two factors have an impact on the availability of oxygen for the respiration process and the apical bud growth process [6]. Aeration aims to remove heat and water vapor that arise from the respiration process in potato tubers. Another impact of the aeration process in the storage room is to control temperature, humidity, and oxygen availability during the potato tuber dormancy process.

The dynamics of temperature and humidity in the potato storage room need special attention so that the needs for potato seeds are continuously met. An empiric model has been developed by Whitney and Potterfield [13] to approach temperature dynamics in piles of agricultural materials; Setiyo et al. [17] developed a mathematical model to approach the temperature and humidity of apples in cartons; and Meneghetti et al. [18] developed empirical models of horticultural storage. This empiric model has the potential to be developed to make it easier to control temperature and humidity in para-para potato storage rooms.

The storage method applies an aeration system and low light diffusion. This can be done using a para-model storage system. In fact, this system has been widely applied by Indonesian farmers for seeding corn, shallots, or other commodities. The para-para is built on a stove in the farmer's kitchen, and due to the flow of smoke through the commodity in the para-para, the water content of the material becomes low. Besides that, the temperature and humidity of the air are controlled. Several layers of agricultural commodities are placed on the para-par, which is stored.

The aim of the research is to analyze the metabolic processes of potato tubers stored in para-para with energy balance and mass balance due to aeration and lighting treatments to control temperature and air humidity in the storage room.

2. Materials and method

2.1 Materials

The main ingredient in this research is seed potato tubers of the G3-group granola variety. The characteristics of seed potato tubers are: harvest age of 3 months; roundness of 0.84 ± 0.016; water content of 80% wb; specific gravity of 1.05 ± 0.02 g/cc; and average weight of 40 ± 2.0 g/tuber [19].

The main tool is a para-para with dimensions of 3 m long, 0.9 m wide, and 2.1 m high, consisting of 6 shelves. Para-para with dimensions of 3 m long, 0.9 m wide, and 2.25 m high, or consisting of 6 shelves. The distance between shelves is 30 cm, 10 cm for plastic shelves filled with potato tubers, and 20 cm for air spaces. Para-para has a wooden main frame with dimensions of 5 cm by 7 cm and shelves made of wood with dimensions of 2 cm by 3 cm. Supporting equipment is a plastic basket with a capacity of 10 kg of potato tubers, a blower, an analytical scale, a lux meter, a hygrometer, and a thermometer.

The research treatments were: Natural Aeration Without Sunlight (NANSL), Natural Aeration With Sunlight (NASL), Forced Aeration Without Sunlight (ANSL), and Forced Aeration With Sunlight (ASL). Aeration naturally occurs due to differences in air pressure between parts of the storage room, so that air naturally flows with a discharge of 0.023 m3/sec. Forced air flow through the pile of potato tubers occurs due to the rotation of the blower. The blower is installed on the outside of the para-para and flows air through the pile of potato tubers in the para-para. The air flow for forced aeration is 3.14 m3/sec. Each unit of the potato tuber storage experiment was repeated three times. The NANSL treatment is para-para without a blower and the walls are covered with black paranet; the NASL treatment is para-para without a blower but the walls are covered with transparent UV plastic; the ANSL treatment is para-para equipped with a blower and the walls are covered with colored paranet black; and the ASL treatment is para-para equipped with a blower and the walls are covered with transparent UV plastic.

2.3. Research procedure

Potato tubers are sorted based on the following criteria: (1) have a smooth surface without black spots; roundness of more than 80%; specific gravity ± 0.93-0.99 g/cc; weight 40 ± 2 g/tuber; and water content > 80% wb [19, 20]. Next, the sorted potato tubers are stored in plastic baskets and placed on the shelf. The thickness of the pile of potato tubers in each plastic basket is 10 cm, or 4 layers of potato tubers (the basket capacity is 10 kg). One shelf is filled with 18 baskets, or baskets with a capacity of ±1000 kg of potato tubers. Potato tuber seeds are stored for 16 weeks at room temperature (20–26 °C), room humidity (70–85%), and incoming light intensity (100–200 lux) for treatment where there is light in the para-para.

2.4. Observation variables

Storage process variables include potato tuber temperature, air temperature, air humidity, and light intensity, repeated three times for each shelf. Observation points are taken randomly; the time taken is 09.00 WITA. Meanwhile, potato tuber quality variables include the specific gravity of potato tubers, the weight loss of potato tubers, and the number of tubers that grow apical buds. Observations of all parameters from 20 potato tuber samples were carried out every two weeks.

2.5. A theoretical approach to heat transfer and mass transfer for potato storage

The respiration process in stored seed potato tubers requires oxygen to convert starch into sugar. Stored potato tuber cells oxidize glucose into the nutrients the tuber needs to stay alive, producing water, carbon dioxide, and heat. The chemical reaction of the respiration process is written in Eqn 1.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy [21]} \quad (1)$$

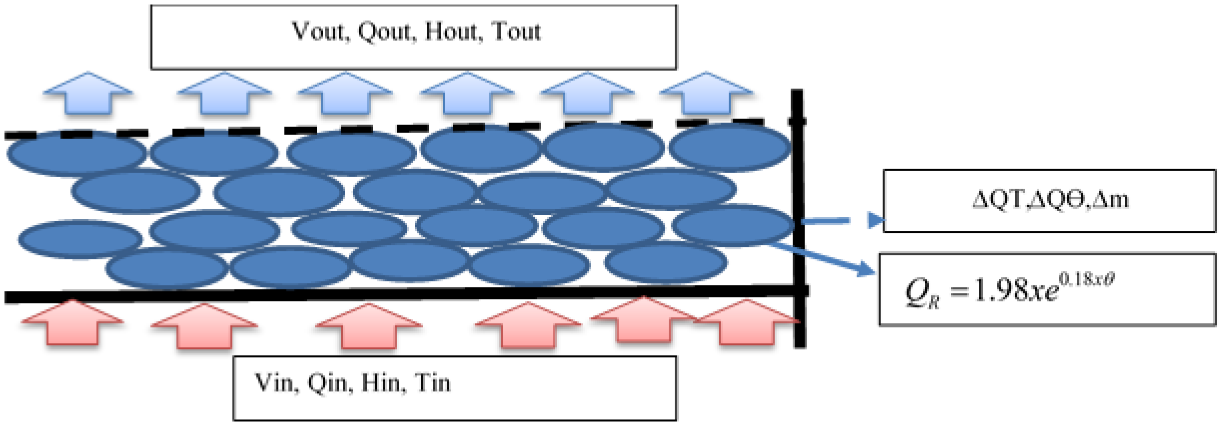

Figure 1. Sketch of the development of a mathematical approach to heat transfer and mass transfer

The mathematical model of heat and mass transfer for storing bulk seed potatoes in para-para was developed from the mathematical models of Whitney and Poterfield [13], Lerew [22], and Setiyo et al. [23]. Mathematical models are developed for the cases of one-dimensional boundary value problems and transient conduction. In a pile of potato tubers in a plastic basket, there is an inflow of air, an outflow of air, the respiration process, changes in the water content of the potato tubers due to the evaporation process, changes in the temperature of the potato tubers and the air around them, and changes in the humidity of the air around the tubers.

2.5.1. Energy balance

The energy balance in storing potato tubers in the para-para model is a function of the heat of respiration, heat to increase the temperature of the material and air temperature, heat to evaporate water, and heat lost to the environment. Eqn 2 is a heat balance approach model [24].

$$Q_R = Q_\theta + Q_T + Q_U + Q_L \quad (2)$$

QR = heat respiration, J/kg
QΘ = the heat to increase potato temperature, J/kg
QT = heat for increased air temperature, J/kg
QU = heat for water evaporated from potatoes to the environment, J/kg
QL = heat loss from potato to the environment, J/kg

The heat of respiration is a function of potato tuber temperature [25] and is calculated using Eqn 3.

$$Q_R = 1.98xe^{0.18x\theta} \quad (3)$$

Θ = potato temperature, °C
The heat needed to increase the temperature of the material is a function of the mass of the potato tuber, the specific heat of the potato tuber, the specific heat of the air, the air mass around the potato tuber, and changes in the temperature of the tuber and air. The value of heat to increase air temperature and potato tuber temperature is formulated in Eqn 4 and 5.

$$Q_T = \rho_U x V_U x C_{PU} x \Delta T \quad (4)$$

ρU = air mass density, kg/m3
VU = air volume, m3
CPU = specific heat of air, J/kg-°C
ΔT = change in air temperature,°C

$$Q_\theta = m_k x C_{Pk} x \Delta\theta \quad (5)$$

Mk = mass of potato tubers, kg
CPk = specific heat of potato tubers, J/kg-°C
□Θ = change in temperature of potato tubers, °C
The specific heat value of potato tubers is a function of the water content of the material, and for storage above the freezing point of water, it is formulated as in Eqn 6. [25]

$$C_{Pk} = 33.47 xM + 837 \frac{J}{kg-{}^{0}C} \quad (6)$$

M = water content of potato tubers, % (wb)

The heat to evaporate water from potato tubers into the surrounding air is a function of the mass of water evaporated and the latent heat of evaporation, Eqn 7 is formulated:

$$Q_U = m_{Uk} x h_{fg} \quad (7)$$

muk = mass of water evaporated, kg

hfg = latent heat of vaporization, J

The heat lost to the environment from the para-para model storage is a function of the convection heat transfer coefficient, surface area of the para-para and the difference in air temperature in the para-para with the temperature outside the para-para, or written in Eqn 8.

$$Q_L = hxAx\Delta T \quad (8)$$

h = convection heat transfer coefficient, J/m2-°C

A = surface area, m2

The value of the heat transfer coefficient by natural convection for near-spherical materials is a function of the Nusselt number, air thermal conductivity, and material diameter, which is written according to Eqn 9.

$$hp= (Nu.x\ ku)/D \quad (9)$$

Nu = Nusselt number

ku = conduction heat transfer coefficient in air, J/m-ºC

D = material diameter, m

$$Nu = 0.8 x \mathrm{Re}^{0.7} x \mathrm{Pr}^{0.33} \quad (10)$$

Re = Renold's number

Pr = Prank number

$$Re=(Va.)/\eta \ \ x \ \rho u \ \ x \ D \quad (11)$$

ρU = air mass density, kg/m3

Va = air speed, m/sec

$$Pr = 0.7\text{-}1.0 \quad (12)$$

2.5.2. Mass balance

Water vapor in the air in the storage room is the result of evaporation, and evaporation occurs due to the difference in water vapor pressure in the potato tubers and water vapor pressure in the air. When the water vapor from potato tubers is accumulated in dry air, it changes the humidity of the air, and the water vapor is carried out of the storage room. The mass balance for storing potato tubers in para-para is formulated in Eqn 13.

$$H_{in} + \Delta M = H_{out} + \Delta H \quad (13)$$

ΔH = change in air humidity, kg

ΔM = change in water content of potato tubers, kg

Hin = water vapor entering the storage room, kg

Hout = water vapor coming out of the storage room, kg

2.5.3. Mathematical calculations of para-para construction

Based on Eqn 3, the amount of respiratory heat produced per 1 kg of potato tubers if the storage temperature is 23–28°C is 1.3–2.5 kJ. The heat of respiration causes an increase in the temperature of potato tubers which is approximated by Eqn 4, the heat of respiration is 0.008-0.018 kJ/kg potato tubers with a temperature increase of 0.001-0.003°C. The heat of respiration to increase air temperature (Eqn 4) is 0.4-1.4 kJ/kg potato tubers or increases air temperature 0.05-0.35°C/kg potato tubers/day.

Based on statements no. 1, 2 and 3, the heat of respiration and the increase in air temperature and potato tuber temperature must be controlled so that the optimal storage temperature for seed potatoes remains below 25°C, the amount of heat that must be removed is calculated using Eqn 7 or is 1.2–1.9 kJ/kg potato tubers.

Based on considerations 1–5, seed potato tuber storage platforms were designed with specifications: capacity 1000 kg or 167 kg per shelf, number of shelves 6 with each shelf air volume: potato volume = 2:1 (distance between shelves 30 cm) , the air flow rate for aeration produced by the blower is 3.14 m3/sec.

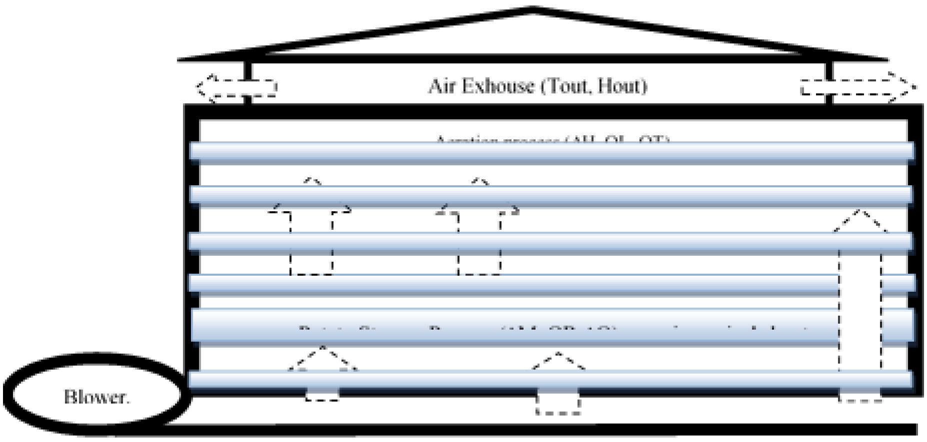

Figure 2. Para-para sketch

2.6. Data analysis

The data was subjected to regression analysis as well as quantitative and qualitative descriptive analysis by displaying graphs of the relationship between temperature, heat of respiration, heat to increase the temperature, heat of water evaporation, heat lost to the environment, weight loss and growth quality with storage time.

3. Results

3.1 Energy balance in the potato storage para-para system

3.1.1. Heat of respiration in potato tubers

Figure 3 shows that there is a similar trend in the relationship between storage time and respiration heat, but there are differences in the amount of respiration heat produced each week during the storage of potato tubers. The heat of respiration of potato tubers produced for the NANSL, NASL, ANSL, and ASL treatments was 1.3-2.09, 1.3-1.96, 1.3-1.75, and 1.3-1.66 kJ/kg, respectively [24]. Peak respiration occurred at week 6, and the respiration heat values for the four treatments were: 1.69 ± 0.1, 1.66 ± 0.08, 1.41 ± 0.09, and 1.36 ± 0.1 kJ/kg.

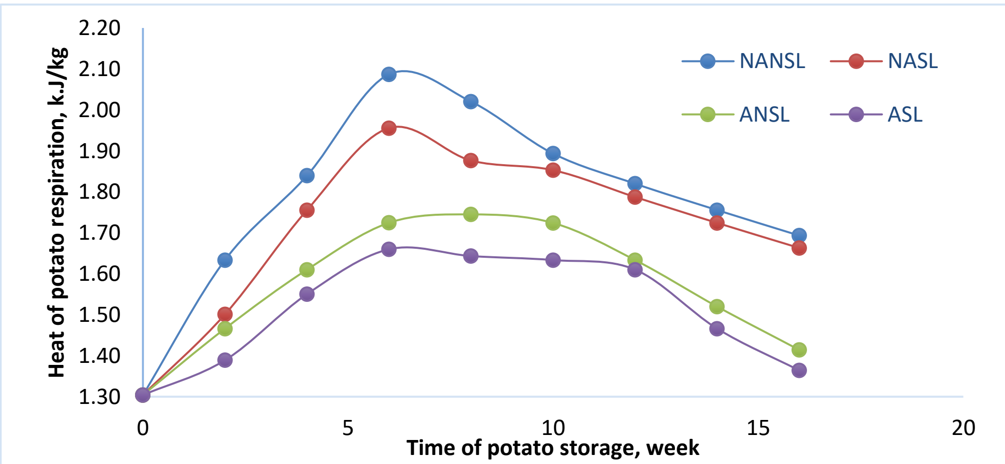

Figure 3. Heat of respiration of potato tubers during storage

3.1.2 Heat to change the temperature of potato tubers

The heat is used to increase the temperature of potato tubers during storage, as shown in Figure 4. The heat to increase the temperature of potato tubers in the NANSL, NASL, ANSL, and ASL storage treatments in containers with a capacity of 1000 kg is respectively 0.005-0.01, 0.005-0.0055, 0.0015-0.005, and 0.005-0.006 kJ/kg/day.

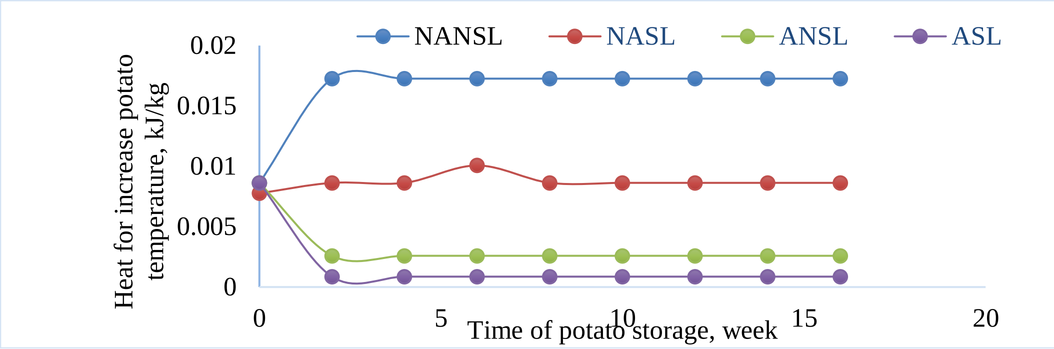

Figure 4. Heat to increase the temperature of potato tubers during storage

3.1.3. Heat for changes in air temperature around the potato tuber

Figure 5 shows the relationship between storage time and the increase in air temperature around the potato tubers, but there are differences in the amount of heat needed to increase the air temperature in each storage treatment. the total heat of respiration used to increase the temperature of potato tubers and the surrounding air during 16 weeks of storage for the NANSL, NASL, ANSL, and ASL treatments was 1.44 ± 0.2, 1.23 ± 0.12, 3.68 ± 0.08, and 3.41 ± 0.1 kJ/kg respectively**.**

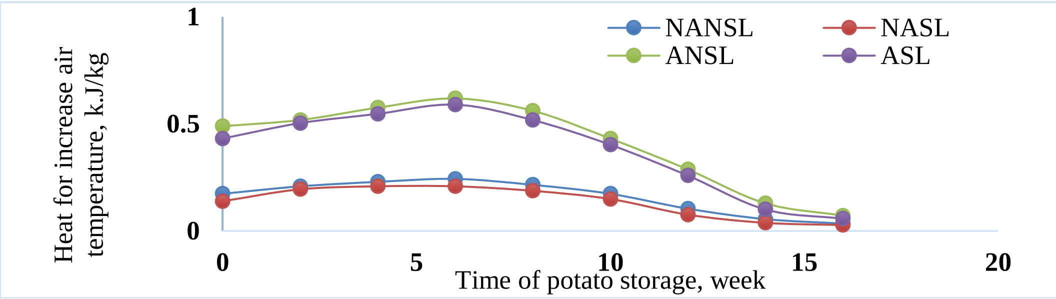

Figure 5. Heat to increase the temperature of the surrounding air in the storage room

3.1.4. Evaporation heat

Figure 8 shows the same trend in the relationship between storage time and heat of evaporation, but there are differences in the amount of heat of evaporation between treatments during storage. Respiration heat is used to evaporate water from potato tubers into the environment for treatment. NANSL, NASL, ANSL, and ASL were 0.17–0.42, 010-0.37, 0.03-0.15, and 0.02-0.11 kJ/kg, respectively.

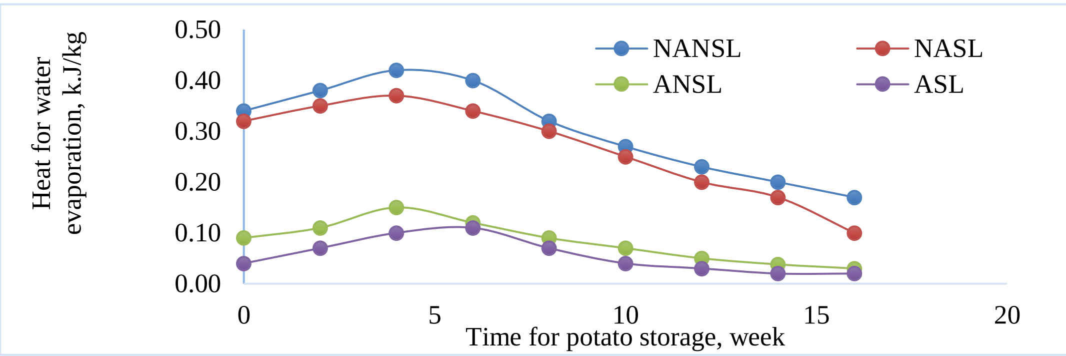

Figure 8. Heat of evaporation of water from potato tubers stored in para-para

3.1.5. Heat is lost to the environment from the potato tuber storage space in the para-para system

Figure 9a shows the same trend in the relationship between storage time and heat lost to the environment from a para-para model storage system without aeration. However, the NANSL treatment experienced higher heat loss than NASL. Figure 9b also shows the same trend in the relationship between storage time and heat lost to the environment from a para-para model storage system with aeration. However, ANSL experiences higher heat loss than ASL. The total amount of heat lost to the environment during storage of potato tubers in the para-para carried by the air flow for the NANSL, NASL, ANSL, and ASL treatments, respectively, is 0.89 ± 0.05, 0.73 ± 0.02, 11.43 ± 0.05, and 11.2 ± 0.1 kJ/kg. The average respiratory heat released to the environment in the para-para storage system with this treatment is 5.52 ± 0.22 %, 4.71 ± 0.1 %, 80.83 ± 0.8 %, and 82.01 ± 0.8 %.

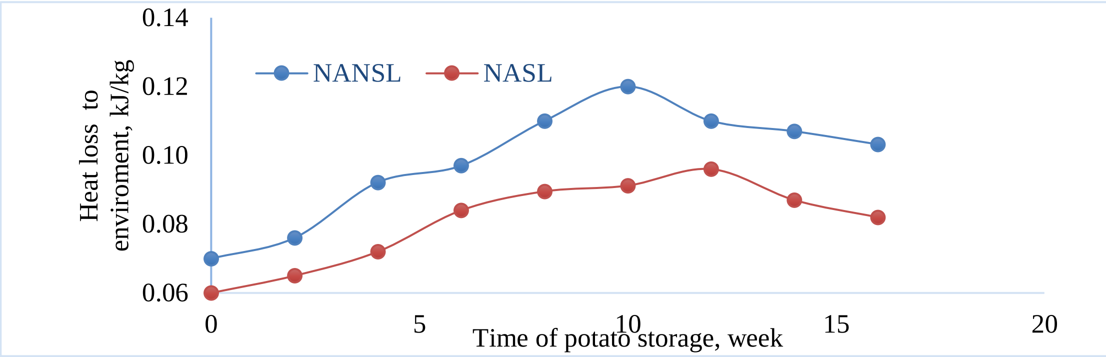

Figure 9a. Heat is lost to the environment in the treatment without aeration

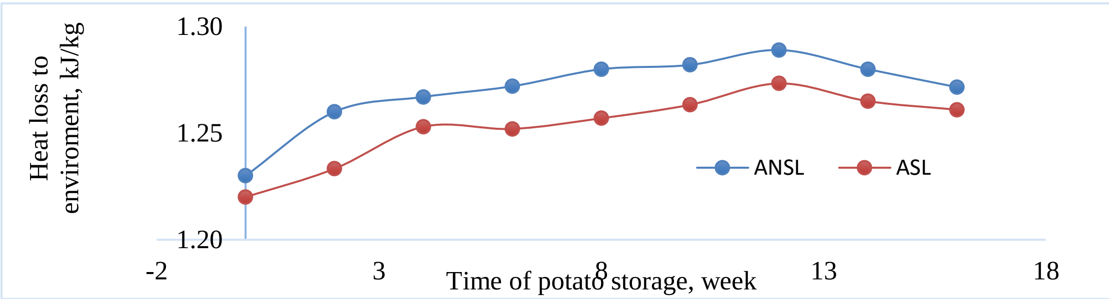

Figure 9b. Heat lost to the environment in aeration treatment

3.1.6. Storage air temperature

An illustration of the air temperature around potato tubers in relation to shelf height and storage time is shown in Figures 10 and 11. The average air temperature around seed potato tubers from shelf 1 to shelf 6 for treatment with aeration with a flow rate of 3.14 m^3/sec is between 23.25 and 24.63°C, while the air temperature for treatment with natural air flow aeration with a discharge of 0.023 m^3/sec is between 23.25 and 25.86°C.

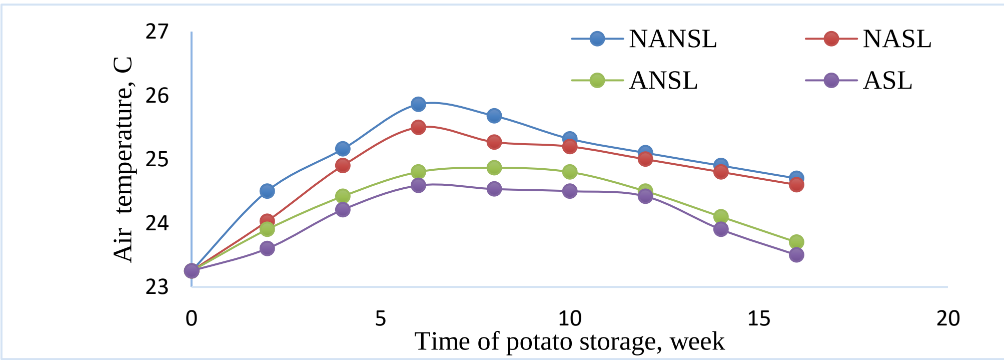

Figure 10. Air temperature around potato tubers stored in para-para

3.2. Mass balance in the storage of potato tubers in the para-para system

3.2.1. Evaporation

Figure 11 shows the same trend in the relationship between storage time and weight loss of potato tubers from the para-para model storage system, but there are differences in potato tuber weight loss between treatments during storage.

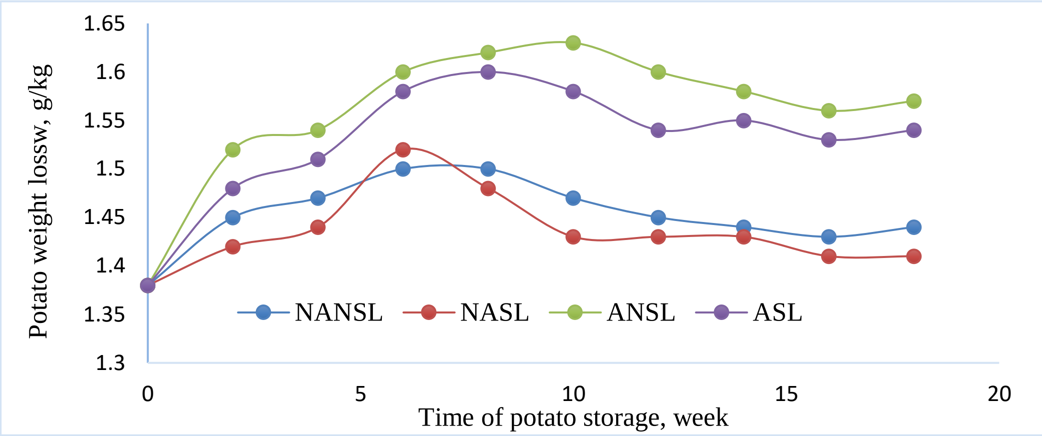

Figure 11. Relationship between storage time and weight loss of potato tubers

3.2.2. Humidity

The results of the evaporation of water from potato tubers are received by the air, and to increase the amount of water vapor in the air, initially store the amount of water vapor in the air at a temperature of 23.5°C and air humidity of 72% at 0.012 kg water vapor/kg dry air, and at the end of storage, this value changes. The average amount of water vapor in the air in the para-para for the NANSL, NASL, ANSL, and AS storage treatments is 0.0133±0.0008, 0.0133±0.0001, 0.0134±0.0005, and 0.0134±0.0005 kg water vapor/kg dry air.

3.3. Quality of seed potato tubers stored in para-para

Figure 12 shows the same trend in the relationship between storage time and the percentage of growth of apical shoots of potato tubers from the para-para model storage system; however, there are differences in the percentage of growth of apical shoots of potato tubers between treatments during storage. The lowest growth percentage occurred in the ASL treatment, while the highest was in the NANSL treatment.

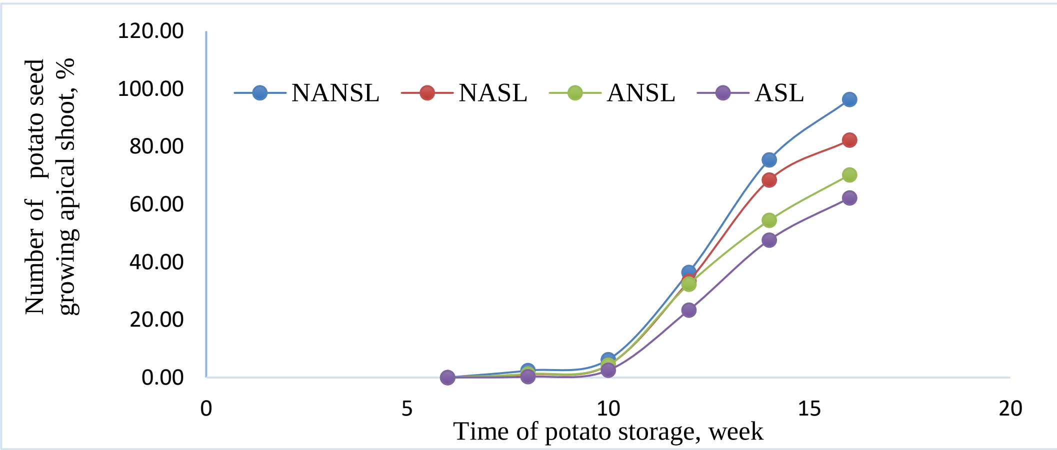

Figure 12. Percentage of potato tubers that grow apical shoots after 4 months of storage in para-para

4. Discussion

4.1. Energy balance in the potato storage para-para system

4.1.1. Heat of respiration in potato tubers

Potato tubers, from the beginning of storage until the 6th week, have good physical, chemical, and rheological properties, so this has an impact on the peak of respiration in the 6th week, and the hardening of the tuber skin and increasing the dormancy period also have an impact on decreasing the respiration process and reducing the environmental temperature [10, 24].

The respiration rate of potato tubers is influenced by the chemical composition of the tubers, the temperature of the storage room, and the oxygen concentration in the storage room [26]. The respiration rate in stored potato tubers influences the breakdown of starch into simple sugars [26]. At the beginning of storage (weeks 0–8), the breakdown of starch into simple sugars takes place more quickly than after potato tubers have been stored for more than 8 weeks (dormancy period) [27]. Apart from that, the higher the air temperature in the storage room, the greater the process of respiration and breakdown of carbohydrates in the form of starch into sugar [28]. This is in accordance with Eqn 2 [25]. At a temperature of 10–30°C, the respiration rate becomes 2–2.5 times faster for every 10 °C increase.

Potato tuber storage treatment with natural air flow (NANSL and NASL) has a higher heat of respiration than the heat of respiration for storage treatment with forced air flow (ANSL and ASL). Based on Eqn 2, apart from the concentration of starch in potato tubers, the amount of respiratory heat is more influenced by the availability of oxygen around the potato tubers or the speed of air flow for aeration. However, in this study, the para-para design has a volume of space for potato tubers of 1.62 m^3, while the space filled with air is 3.78 m^3. This ratio between the volume of potato tubers and air means that oxygen is still available for the respiration process even though the air flows naturally. The difference in the amount of heat of respiration between the storage treatment with natural air flow and the forced air flow treatment was 0.11-0.36 kJ/kg, with an average of 0.21±0.09 kJ/kg.

The light factor in the respiration process of potato tubers stored in para-paras inhibits the process, so that the heat of respiration of potato tubers in the presence of incoming light is lower than if there was no light. The difference in heat of respiration between storage treatments with light entering and without light entering the storage room is 0.05-0.14 kJ/kg, with an average of 0.09 ± 0.02 kJ/kg potato tubers [24, 29, 30].

According to Eqn 1, the availability of oxygen for the metabolic process of breaking down starch into simple sugars is sufficient around potato tubers from all treatments; aeration functions more as a heat dissipation process and regulates the temperature and humidity of the air around the tubers [28, 29]. The lowest respiration heat of potato tubers occurs in the ASL treatment, so this treatment is the best treatment for storing seed potatoes.

4.1.2. Heat to change the temperature of potato tubers

Heat is used to increase the temperature of potato tubers during storage, as shown in Figure 4, because more of the heat produced by the respiration process is released into the surrounding air or to increase the air temperature. This happens because the mass of the potato tuber is greater than the mass of the air around the tuber, and the specific heat of the potato tuber is also greater than the specific heat of the air [2, 4].

Natural or forced air flow around the stored potato tubers carries more heat from respiration to be immediately released into the environment, so that the heat of respiration used to increase the temperature of the potato tubers is very small. This shows that a para-para design with a ratio of potato volume to surrounding air volume of 1 to 2 is ideal for controlling the increase in temperature of potato tubers [6].

4.1.3. Heat for changes in air temperature around the potato tuber

Respiration heat is partly used to change the temperature on each shelf containing potato tubers. The heat of respiration for changes in air temperature and potato tubers is approximated using Eqn 4. The specific heat value of air is 1.05 kJ/kg-°C; the amount of heat needed to increase the air temperature for the NANSL, NASL, ANSL, and ASL treatments is 0.035–0.245, 0.027–19.95, 0.07–2.06, and 0.057–0.196 kJ/kg. The average heat to increase air temperature for each treatment was: 0.160 ± 0.07, 0.136 ± 0.02, 0.409 ± 0.03, and 0.379 ± 0.02 kJ/kg.

Based on Eqn 4, heat value changes in air temperature as a function of the air mass around the potato tuber, the specific heat of the air, and the change in temperature. The air mass of the aeration treatment with a discharge of 3.14 m^3/sec (forced air flow treatment) is definitely greater than the natural air flow aeration treatment (flow of 0.023 m^3/sec) [2, 4, 6]. In addition, the average change in air temperature in the forced aeration treatment (0.135 ± 0.01°C/day) is much smaller than the average change in air temperature in the natural aeration treatment (0.21 ± 0.02°C/day), so the total heat for temperature changes in potato storage for the forced air flow treatment is greater than the total heat for natural temperature changes in the air flow (Figure 5).

Based on the total heat data to increase the air around the potato tubers, the para-para storage system design with an air flow rate of 3.14 m^3/sec is able to control the increase in air temperature around the potato tubers by 0.15 ± 0.01°C/day. Storage treatment in the presence of light and no light was only able to control temperature changes of 0.04 ± 0.002 °C/day, or storage treatment of potato tubers without light, the total heat to increase air temperature was greater than the total heat to increase air temperature in the treatment without light (0.235 ± 0.002 kJ/kg).

Figure 5 shows the relationship between storage time and the increase in air temperature around the potato tubers, but there are differences in the amount of heat needed to increase the air temperature in each storage treatment. As previously mentioned, aeration with forced air flow is more likely to remove heat from respiration, so the heat to increase air temperature using forced air flow is higher than the heat to increase air temperature with natural air flow [28, 29]. . The highest amount of heat to increase air temperature occurs in the ANSL treatment, so this treatment is the best treatment for storing seed potatoes because the heat resulting from respiration is quickly released into the environment.

The availability of oxygen is more supportive of the perfect metabolic process of respiration than the intensity of light hitting potato tubers, so this has an impact on the amount of respiration heat and the amount of heat for changes in the temperature of the tubers and the surrounding air [16]. This is also supported by the height of the pile of potatoes, which is only 10 cm in each plastic basket, and the availability of air space that is twice as high as the pile of potatoes.

4.1.4. Evaporation heat

Air aeration with a flow rate of 3.14 m^3/sec over the stored potato tubers is able to control the air temperature at 23.25–24.64°C and the air humidity at 72% [5]. At an air temperature of 23.25–24.64°C and an air humidity of 72–80%, the heat of vaporization of water (hfg) is 47.5 kJ/kg of water vapor. Based on the equation for the evaporation of water from potato tubers into the environment, Equation 7, the relationship between storage time and the respiratory heat used to evaporate water is as shown in Figure 8.

The average heat of respiration used to evaporate water from potato tubers for each of these treatments from the heat of respiration produced was 17.1 ± 0.12, 15.5 ± 0.22, 5.3 ± 0.07, and 3.7 ± 0.12%. Based on the amount of heat needed to evaporate water from stored potato tubers into the environment (Figure 8), aeration treatment with forced air flow was able to reduce the average heat needed to evaporate water by 1.94 ± 0.03 kJ/kg during the storage process.

The heat resulting from respiration received by potato tubers is used to evaporate water. This occurs because the water vapor pressure in the potato tubers increases so that the water vapor pressure in the potato tubers is greater than the water vapor pressure in the air. Respiratory heat in potato tubers influences tuber weight loss, the dormancy period of potato tubers, and the growth of apical shoots [31]. The increase in air temperature and the temperature of potato tubers during storage have an impact on increasing the evaporation of water from the tubers into the environment; this occurs due to the increasing water vapor pressure deficit between the potato tubers and the air [16].

A decrease in water content in potato tubers results in an increase in sugar content, so that the apical growth process occurs due to increased sugar mobilization and respiration. Breaking of dormancy occurs when 80 ± 2% of the potatoes have grown buds, and the potato tubers grow apical buds at a water content of around 75% [32]. In the process of shoot growth, the role of the cytokinin hormone is very important [33].

When storing NANSL, NASL, ANSL, and ASL potatoes in para-para, there is still a respiration process that is consistent with the evaporation of water from the material into the environment, as shown in Figure 3. The peak rate of water evaporation from the material into the environment reaches its peak in the 12th week or during the germination period. Apical shoots begin to grow in the potato tuber, so at this time the dormancy period of the tuber begins to be broken because the carbohydrate and water content in the tuber is more supportive of the apical shoot growth process [34].

Figure 8 shows the same trend in the relationship between storage time and heat of evaporation, but there are differences in the amount of heat of evaporation between treatments during storage. As previously mentioned, aeration with forced air flow is more likely to remove heat from respiration, so that the heat to increase air temperature using forced air flow is higher than the heat to increase air temperature with natural air flow [16, 28, 34]. ASL treatment is a treatment that requires the lowest amount of heat to evaporate, so this treatment is the best treatment for storing seed potatoes because the heat resulting from respiration is quickly released into the environment.

4.1.5. Heat is lost to the environment from the potato tuber storage space in the para-para system

Forced air flow at a speed of 3.14 m^3/sec can reduce the air temperature around potato tubers by an average of 1.68 ± 0.2°C. Natural air flow with a flow of 0.023 m^3/sec can reduce the air temperature around the potato tubers on average to 0.82 ± 0.21°C. The values of the Renolt (Eqn 11) and Nuselt (Eqn 10) numbers for forced convection are 3200 and 300, and in natural air flow, the values of these two numbers are 38.5 and 220–253. The prank number is 0.8. Forced air flow includes transitional air flow, while natural air flow includes laminar flow. Based on the values of Nu, Re, and Pr, the value of the convection heat transfer coefficient between the surface of the potato tuber and the air is calculated using Eqn 9. The h value for natural air flow and forced air flow is 1.2 watt/m^2-°C, respectively, and 6.8–7.8 watt/m^2-°C.

Based on Equation 8, the heat lost to the environment due to air flow from the space in the para-para to the environment is illustrated in Figure 9a (heat lost to the environment in the natural air flow treatment) and Figure 9b (heat lost to the environment in the forced air flow treatment).

The total amount of heat lost to the environment during storage of potato tubers in the para-para carried by the air flow for the NANSL, NASL, ANSL, and ASL treatments, respectively, is 0.89 ± 0.05, 0.73 ± 0.02, 11.43 ± 0.05, and 11.2 ± 0.1 kJ/kg. The average respiratory heat released to the environment in the para-para storage system with this treatment is 5.52 ± 0.22 %, 4.71 ± 0.1 %, 80.83 ± 0.8 %, and 82.01 ± 0.8 % [24]. The aeration treatment with forced air flow for storing seed potato tubers in the para-para system has a real effect on the amount of heat released into the environment, or the para-para system for storing seed potatoes with the addition of an aeration system with forced air flow is effective in controlling temperature and air humidity around the tuber. The lighting treatment for storing potato tubers using a para-para system does not have a real impact because the total difference in heat that can be dissipated between the treatment with light and the treatment without light is on average 0.156 ± 0.02 kJ/kg.

As previously mentioned, aeration with forced air flow is more likely to remove heat from respiration, so that the heat lost to the environment with forced air flow treatment will be higher than the heat lost to the environment with natural air flow [16, 28; 31, 34]. Therefore, if Figures 9a and 9b are compared, the ANSL treatment is the treatment with the highest amount of heat lost to the environment, so this treatment is the best treatment for storing seed potatoes because the heat resulting from respiration is quickly released into the environment.

4.1.6. Storage air temperature

The storage air temperature is still tolerated when storing potatoes for use as seeds [14]. The aeration system for storing potatoes in para-para is able to control the air temperature to optimal storage limits.

The air temperature around the potato tubers for storage in group G3 for storage treatments with NANSL, NASL, ANSL, and ASL is related to storage time in a second-level polynomial or quadratic pattern with the respective equations: $y = -0.026x^2 + 0.47x + 23.53$, $y = -0.023x^2 + 0.43x + 23.36$, $y = -0.022x^2 + 0.37x + 23.27$, and $y = -0.0197x^2 + 0.33x + 23.17$. The respective equation coefficient values are $-0.02>a>-0.026$, $0.33<b<0.47$, and $23.17<c< 23.53$. The quadratic pattern of the relationship between air temperature and storage time in the para-shaped potato storage room is dominated by the respiration pattern of potato tubers.

In the 0th week to the 8th week, potato tubers generally have not entered the dormancy phase or experienced active respiration, but after the eighth week, the potato tubers enter a mass of dormancy with increasingly weakened respiration. Before the dormancy mass, the air temperature in the storage room for the NANSL, NASL, ANSL, and AS treatments increased by 0.52, 0.45 ± 0.01, 0.31 ± 0.03, and 0.26 ± 0.02°C/week. During dormancy, the air temperature for each treatment decreased by 0.12 ± 0.02, 0.09 ± 0.03, 0.11 ± 0.03, and 0.11 ± 0.02°C/week.

The air temperature in the forced air flow treatment increased by 0.14–1.2°C, while for the natural air flow treatment in the para-para, the air temperature around the potato tubers increased by 0.2–2.3°C. The presence or absence of light entering the para-para room does not have a significant effect on changes in air temperature, but the air flow model has a significant effect on the air temperature around the potato tubers. The average inter-shelf temperature differences for the NANSL, NASL, ANSL, and ASL treatments were 0.34 ± 0.02, 0.35 ± 0.01, 0.22 ± 0.02, and 0.18 ± 0.01°C, respectively.

Figure 10 shows the same trend in the relationship between storage time and air temperature around the potato tubers from the para-para model storage system. However, there were differences in air temperature around the potato tubers between treatments during storage. As previously mentioned, aeration with forced air flow is more likely to remove heat from respiration, so that the air temperature around potato tubers with forced air flow treatment will be lower than the air temperature around the tubers with natural air flow [28, 34]. Therefore, ASL treatment shows the lowest air temperature around the potato tubers, so it is the best treatment for storing seed potatoes because the heat resulting from respiration is quickly released into the environment.

4.2. Mass balance in the storage of potato tubers in the para-para system

4.2.1. Evaporation

Water vapor pressure in potato tubers at a temperature of 25.5°C and 80% water content is 23.76 mmHg, while the water vapor pressure in the air is 25.35°C and 80% humidity is 23.2 mmHg. The aeration treatment had a greater impact than the treatment of providing light in the storage room; the NANSL, NASL, ANSL, and ASL storage treatments had water evaporation rates from the material into the environment of 8.03 ± 0.67, 8.05 ± 0.77, 8.35 ±

0.87, and 8.41 ± 0.94 g/kg tubers/week, respectively.

The mass of air that passes through stored potato tubers affects the availability of oxygen for the respiration process, the magnitude of the difference in water vapor pressure between the tubers and the air (evaporation rate), and the ability of the air to carry water vapor outside the storage space. These three things have a direct impact on the amount of water evaporated from potato tubers during storage, and the evaporation rate for the treatment with aeration was 8.09 ± 0.18 g/kg tubers/week, while for the treatment without aeration, the water evaporation rate was 9.33 ± 0.14 g/kg tubers/week [29, 35]. This weight loss value is lower than the research results of Fenir et al., [24], because the air temperature around the tubers in this experiment was 10°C.

As previously mentioned, aeration with forced air flow is more likely to remove heat from respiration and carry water vapor from evaporation from potato tubers, so that the weight loss of potato tubers with forced air flow treatment will be higher than the weight loss of tubers with air flow [31, 34]. Therefore, NASL is the treatment with the lowest weight loss of potato tubers, so it is the best treatment.

4.2.2. Humidity

Statistically, the storage treatment of potato tubers has no significant effect on the water vapor content in the air, which shows the success of the aeration system in storing potato tubers [29, 35]. Air flow with a flow rate of 3.14 m^3/sec passes through the mass of potato tubers stored in the para-para. Apart from being able to control temperature due to respiration, it is also able to control air humidity. Increasing the level of storage shelves in the para-para has an impact on the accumulation of water vapor on the next shelf; therefore, the lowest shelf (30 cm) has a humidity difference of 0.65% and the highest shelf (180 cm) has a humidity difference of 8.55% [4, 6].

This increase in air humidity is a result of the respiration process, which produces water vapor, and the accumulation of water vapor at higher shelf levels due to differences in vapor pressure at the two levels. The average difference in air humidity between treatments was 0.31%, while the difference in air humidity between shelves was 0.21–0.42%. The movement of water vapor between shelves is due to differences in the ability of the air to hold water vapor [24].

4.3. Quality of seed potato tubers stored in para-para

Seed potato tubers stored in para-para for 4 months with NANSL, NASL, ANSL, and ASL treatments had specific gravity of 0.96±0.07, 95.07±0.07, 0.97±0.03, and 0.98±0.06 g/cc [36, 37]. Evaporation of water from the tubers into the environment as a result of changes in environmental temperature and humidity due to aeration treatment has an impact on changes in the specific gravity of potato tubers due to changes in water content because the volume of potato tubers remains constant while the weight of potato tubers after 4 months of storage decreases, as in the discussion above.

However, statistically, the specific gravity and water content of potato tubers between storage treatments were not significantly different; this is in accordance with research by Purnomo et al. [38, 39]. This is also supported by the uniformity of the hardness parameters of seed potato tubers stored for 4 months, which are relatively stable at 153.4 ± 2.3 kPa, and the level of roundness of the potatoes, which ranges from 80.74 to 81.42%.

Apart from being able to maintain the specific gravity, water content, roundness, and hardness of potato tubers during storage, NANSL, NASL, ANSL, and ASL can also reduce the number of damaged tubers. The number of tubers damaged from treatment with forced air flow is 5.50 ± 0.39 % and 5.5 ± 0.33 %, while for storage treatment with natural air flow, the number of damaged potato tubers was 3.43 ± 0.33 % and 3.29 ± 0.36 %. The number of potato tubers damaged during storage was lower than the research results by Babarinsa and Williams [4]. Aeration treatment was able to reduce the number of damaged tubers by 2.17–2.21%. Aeration or air flow through potato tubers is able to control the storage temperature between 23.5 and 25.8 °C and the air humidity between 71.0 and 82.1%, so that microbes that damage the tubers are not able to develop properly.

The things mentioned above indicate that the metabolic activity of the tubers during storage or dormancy is going well or that the storage system is able to control environmental conditions (temperature, humidity, and light). The storage system for seed potato tubers using the para-para model is able to guarantee that the quality of the potato tubers is maintained in terms of the parameters of specific gravity, water content, and roundness; this is also visible in the rate of tuber weight loss [36]. The rate of weight loss of potato tubers based on tuber group and weight group has a value of 1.71±0.12% to 1.87±0.07%, or less than 3%. The low level of weight loss reflects that the tuber metabolic processes, especially respiration, can be controlled due to successful control of temperature and air humidity around the stored tubers [3, 40, 41, 42].

Figure 12 shows that the storage treatment for seed potato tubers in NANSL and NASL shows that the number of tubers that grow apical buds is more than 80% for 4 months of storage; even for the NANSL storage treatment, the number of tubers that grow apical buds in storage for 4 months is 92±2.7%. Meanwhile, in the treatment of storing potato tubers for 4 months (ANSL and ASL), the number of potato tubers growing apical shoots was 70.2 ± 2.3% and 62.4 ± 3.2% [42].

The light factor entering the storage room inhibits shoot growth by 13.0 ± 0.7%, while the aeration factor inhibits 23.0 ± 1.7%. Aeration during storage of seed potato tubers has an impact on air temperature and humidity, water content, and carbohydrate content in the tubers. The next impact of aeration is on the metabolic processes in potato tubers: respiration, dormancy, and apical shoot growth [41, 44, 45].

Therefore, after 3 months, the number of apical shoots on the stored seed potato tubers was more than 25%, and up to 4 months of storage, the potato tubers that grew apical shoots for the ANSL and ASL treatments were 30% and 38%, respectively. The number of tubers that grow apical buds is closer to the results of research by Babarinsa and Williams [4] using the DLS and TSR methods. The growth rate of apical shoots is influenced by the temperature and humidity of the air around the tuber as well as the light falling on the potato tuber [46]. Storage air temperature approaching ±25ºC and air humidity ±80% can reduce the dormancy period of stored potato tubers; the dormancy mass of potato tubers is generally 84 days or 24 weeks [46, 47].

The growth of apical shoots is more influenced by the dormancy factor of potato tubers during the storage process. Artificial breaking of tuber dormancy through exposure to bromoethane [48] or gibberellic acid [49, 50] causes increased starch breakdown through increased metabolic activity of starch-breaking enzymes.

5. Conclusions

Aeration with an air flow of 3.14 m^3/sec and lighting of 200 lux for storing granola variety seed potato tubers in para-para is able to control the temperature by 2.63 ± 0.2°C and the air humidity by 8.55 ± 0.12%. The total heat lost to the outside for the NANSL, NASL, ANSL, and ASL treatments during storage of potato tubers is 0.89 ± 0.05, 0.73 ± 0.02, 11.43 ± 0.05, and 11.2 ± 0.1 kJ/kg. The seed potato tuber storage system with ANSL treatment is the best treatment and is able to control the storage temperature between 23.25 and 24.84°C, control air humidity at 82.0–84.5%, produce good tubers for seedlings in 4 months of storage at 93.7 ± 2.1%, and reduce the number of damaged tubers to 2.17–2.21%.

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Conflict of interest

There are no conflicts of interest between authors or with third parties in this research or publication.

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