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Convective Cooling of purple-speckled Cocoyam *(Colocasia Esculenta (L.) Schott)*: Influence of Air Velocity, Corm Size and Orientation on Cooling Behaviour

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ABSTRACT

Convective cooling has been successfully applied to provide the ideal storage conditions for various agricultural products. However, the preservation of purple-speckled Cocoyam by cooling is not adequately understood. In this study, forced convection cooling of whole purple-speckled Cocoyam corms under two levels of air velocity (0.5, 0.9 m·s^{-1}), corm size (small, large) and corm orientation to airflow (across, along) was investigated. The time to attain a temperature of 12 ± 0.2 °C at the core of the corms and the energy consumed in the process were investigated and found to be significantly dependent on the cooling settings. The kinetics of the cooling process were adequately modelled by the Two-term model. For both levels of corm size, numerical optimisation results using the desirability function approach found that the air velocity of 0.5 m·s^{-1} and the across orientation to the cooling airstream resulted in optimal cooling time and specific energy consumption. The composite desirability indices attained at the optimal cooling settings were 0.85 for small-sized corms and 0.52 for large-sized corms.

Keywords: *Cooling, Food security, Sensors, Storage, Underutilised species*

INTRODUCTION

Roots and tubers provide an alternative source of food and nutrition to cereals in developing nations and supply more energy per day than cereal crops (Lebot, 2009; Liu, Liu, Zhang, & He, 2014). Previous forecasts of the global demand, supply and trade in food for this century have mainly focused on grains, oilseeds, and livestock (Scott, Rosegrant, & Ringler, 2000). However, with the world population expected to exceed 8.5 Billion by 2030 (United Nations, 2019), the demand for carbohydrates will exceed the production potential of areas set aside for the production of cereals (Lebot, 2009). In this scenario, the importance of root and tuber crops relative to other major crops is predicted to increase (Scott et al., 2000). This is especially the case in the face of climate change whose direct effects in the form of limited food access and utilization and indirect adverse effects on household nutrition and incomes are already being felt (Wheeler & von Braun, 2013).

Purple-speckled Cocoyam, an underutilised crop with high-quality starch and various micronutrients can be upscaled to supplement the major food crops. However, its storability is poor due to a high moisture content of about 60 – 83% (Ndisya et al., 2020; Rashmi et al., 2018). Therefore, the post-harvest losses can be as high as 25 – 45 per cent (FAO, 2012, 2019). Suitable storage conditions are thus required to prevent spoilage in its fresh form which leads to food loss. Traditionally, Cocoyam corms are left buried in the field and only harvested when immediately needed for consumption (Opara, 2003). This has been shown to cause corm rot (Modi, 2007; Wang & Higa, 1983) and to degrade the quality of starch in the corms (Himeda et al., 2012). Convective cooling has been successfully applied to provide the ideal storage conditions for various agricultural products (Davey, 2015; Defraeye et al., 2014; Dincer & Genceli, 1994; Korese, Sturm, Román, & Hensel, 2017). The technique can therefore be applied to design an improved storage solution for purple-speckled Cocoyam.

The design of cooling solutions for fresh products requires an understanding of the evolution temperature, the cooling time and energy consumption during cooling. In this study, the influence of the air velocity, corm size and orientation of corms on the direction of airflow on the cooling time and energy consumption was investigated. The Response Surface Methodology was applied to study the cooling behaviour of whole corms. The optimal settings for reduced cooling time and reduced energy consumption were determined using Derringer’s desirability function approach. This study is a segment of a larger extensive study on the preservation of nutritious traditional African crops to reduce post-harvest losses, boost food security and promote household nutritional diversity.

MATERIALS AND METHODS

Materials

Mature Cocoyam (*Colocasia esculenta (L.) Schott)* corms were harvested in December 2019 and sorted to remove pieces with blemishes. The corms were graded by size (i.e., small, 173.42 ± 30 g and large, 466.98 ± 95 g). The corms were then cleaned with a soft brush and cured in open sunlight for 8 hours to cure harvesting wounds to slow down physiological deterioration in the duration of the experiments.

Experimental design

Forced convection cooling experiments were conducted to study the effect of air velocity, corm size and corm orientation on airflow on the total cooling time. The corms were initially preheated in a climate chamber at 30 ± 2 °C temperature and 90% relative humidity until the body temperature was uniform. The corms were then cooled to a core temperature of 12 ± 0.2 °C. The predictor variables and the level settings are provided in Table 1.

Table 1. Predictor variables and their settings

Predictor	Type	Coded units	Coded levels	
			Coded low	Coded high
Air velocity ($m \cdot s^{-1}$)	Numeric	X_1	0.5	0.9
Corm size	Categoric	X_2	Small	Large
Corm orientation	Categoric	X_3	Across	Along

A full factorial experimental design with 24 runs and 2 replications was created in the Design-Expert software version 11 (Stat-Ease Inc., Minneapolis, United States). Experiments were conducted following a randomised order produced from the software. The Response Surface Methodology (RSM) was applied to explore the between the predictor-response relationships and for conduct optimisation. The experimental data were fitted into the generalised polynomial model whose form is given in Eqn. (1).

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i<j} \beta_{ij} X_i X_j + \sum_{i=1}^{k} \beta_{ii} X_i^2 \quad (1)$$

Where Y = response variable, X_i, X_j = predictor variables, k = total number of variables, β_0 = model intercept, β_i, β_{ii}, β_{ij} = regression coefficients, linear terms, quadratic terms and interaction terms respectively (Box & Wilson, 1951; Montgomery, 2017).

The developed models were statistically assessed using analysis of variance (ANOVA), adjusted coefficient of determination (R^2_{adj}) and lack-of-fit tests.

Experimental apparatus

Figure 1 provides the experimental apparatus utilised in this study. Experiments were conducted using a test apparatus placed inside a VCL 400 climate chamber (Vötsch Industrietechnik GmBH, Reiskirchen-Lindenstruth, Germany) with air temperature set at 10 ± 0.2 °C and relative humidity at 90 ± 2 %. The complete experimental set-up described in Ndisya et al. (2021) was utilised. The set-up consisted of a well-insulated test box equipped with Pt-1000 RTD sensors (Therma Thermofühler GmbH, Lindlar Germany) inserted at the core of the corms and transmitting data to an Agilent Keysight 34970A multi-channel data logger (Keysight Technologies, California, USA). An axial fan with a variable speed controller was utilised to provide the desired air velocities.

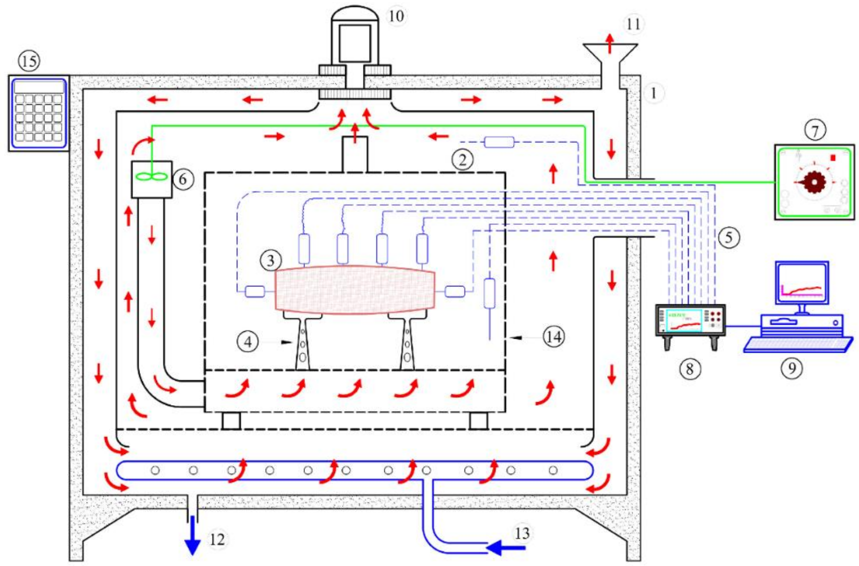

Figure 1: Experimental set-up (1. Vötsch VCL 400 Climate chamber, 2. Pt-1000 sensors, 3. Corm, 4. Corm support, 5. RTD wiring, 6. EBM Papst Axial Suction Fan, 7. PHYWE Automatic Voltage/Speed regulator, 8. Keysight Data logger, 9. Logging computer, 10. Motor and Radial Blower Fan, 11. Vapour exhaust vent, 12. Condensate exhaust vent, 13. Distilled water inlet and humidifier, 14. Insulated test box, 15. Climate chamber control panel) (Ndisya et al., 2021).

Empirical Model fitting

The collected experimental data were fitted into 4 empirical models commonly utilised to model the kinetics of different processes in biological materials. Non-linear regression was conducted to find the optimal model parameters in the MATLAB® software version R2020a (MathWorks, Massachusetts, USA). The models were assessed using SSE, R^2_{Adj} and RMSE. Table 2 provides the forms of the empirical models fitted.

Table 2. Empirical models fitted

No	Model	Form of Model	
1	Two-term model	$T_t = A \cdot exp(B \cdot t) + C \cdot exp(D \cdot t)$	(2)
2	Weibull model	$T_t = T_e + (T_o - T_e) \cdot \left[-\left(\frac{t}{B}\right)^A \right]$	(3)
3	Exponential model	$T_t = A \cdot exp(-B \cdot t) + C)$	(4)
4	Vega-Gálvez model	$T_t = A \cdot exp\left[\frac{-B}{(1+t)^C}\right]$	(5)

Energy consumption estimation

The energy consumed to cool the corms was estimated using the method proposed by Koyuncu, Pinar & Lule (2007) using Eqn. (6).

$$\frac{E_s = A \cdot \vartheta \cdot \rho_a \cdot c_a \cdot \Delta T \cdot t}{M} \quad (6)$$

Where E_s = specific energy consumed (kJ·kg^{-1}), A = surface area of corm (m^2), ϑ = air velocity (m·s^{-1}), ρ_a = density of cooling air at 10 °C and 1 atm pressure (kg·m^{-3}), c_a =

specific heat capacity of cooling air at 10 °C and 1 atm pressure ($kJ \cdot kg^{-1} \cdot K^{-1}$), ΔT = temperature difference between start and end of cooling (K), t = total cooling time (s), M = mass of corm (kg).

Parameter Optimisation

Parameter optimisation was undertaken using the Desirability function approach in Design-Expert software using the method proposed by Derringer & Suich (1980). The method involves evaluating objective criteria then computing desirability indices for each response. The desirability indices are then combined into a composite desirability index by computing their geometric mean.

RESULTS AND DISCUSSIONS

Cooling kinetics

Figure 2 shows the changes in the core temperature of the corms as a function of time at the different settings during forced convection cooling. The cooling behaviour depicted by the curves shows an exponential reduction of core temperature at a high rate in the initial stages of cooling and a diminished as the core temperature converges towards the temperature of the cooling air. Similar findings have been reported for oranges and tomatoes (Kumar et al., 2008), grapes (Dincer, 1995) and sweet potatoes (Korese et al., 2017).

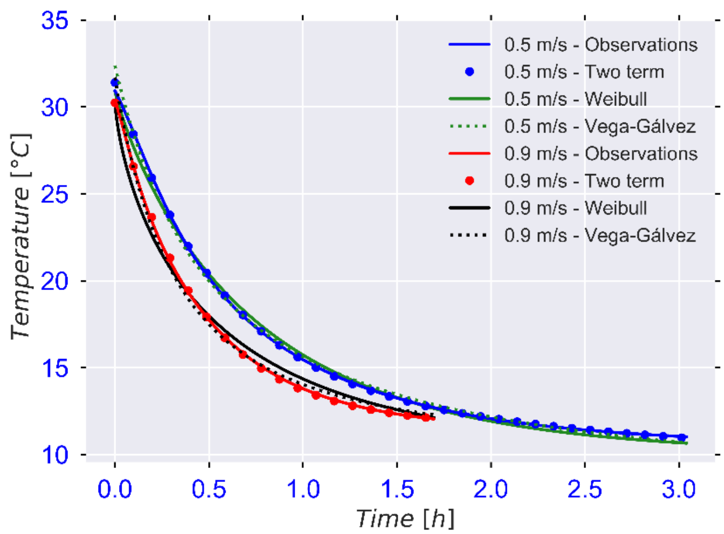

Figure 2: Cooling kinetics and fitted model

Model fitting found the Two-term model to return the highest values of the R^2_{Adj} and lowest values of SSE and RMSE in the range of the empirical models considered. The model therefore adequately modelled the cooling kinetics of purple-speckled Cocoyam under the specified experimental conditions. Table 3 provides the statistical results and model parameters obtained for the Two-term model.

Table 3. Statistical results and Two-term model parameters

ϑ (m·s^{-1})	CS	CO	SSE	R^2_{Adj}	RMSE	A	B	C	D
0.50	small	along	1.279	1.000	0.037	22.04	-1.248	10.86	-0.004
	large	along	76.355	0.998	0.224	23.91	-0.611	6.01	0.110
	small	across	5.018	1.000	0.068	18.36	-1.766	13.05	-0.060
	large	across	4.941	1.000	0.063	29.28	-0.383	2.35	0.233
0.90	small	along	2.848	1.000	0.047	18.61	-1.624	12.17	-0.015
	large	along	16.164	1.000	0.115	21.33	-0.973	10.11	0.028
	small	across	7.367	1.000	0.078	18.07	-2.304	12.17	-0.022
	large	across	54.578	0.998	0.213	22.68	-0.933	8.81	0.068

Where ϑ = air velocity, CS = corm size, CO = orientation to airflow, SSE = Error Sum of Squares, R^2_{Adj} = adjusted coefficient of determination, RMSE = Root Mean Squared Error, A, B, C, D = model parameters.

Cooling time and Energy consumption

The time taken to cool the corms to the target core temperature was significantly influenced by the velocity of cooling air ($p < 0.05$) and the corm size ($p < 0.0001$) but not the orientation of the corms to the direction of airflow. The temperature at the core of the corms reduced with an increase in the air velocity. As shown in Figure 3, smaller sized corms depicted a faster decrease in core temperature than larger sized corms. This is consistent with the findings on sweet potatoes during forced convection cooling (Korese et al., 2017). However, airflow properties have more impact on heat transfer than body properties such as shape, dimensions and position in the airstream (Becker & Fricke, 2004; Ghisalberti & Kondjoyan, 1999). Nevertheless, in a mixed batch of agricultural products in storage, the larger (greater mass) items take longer to cool than the smaller items (Davey, 2015). This is because, smaller sized items have higher and larger sized items have lower values of the surface heat transfer coefficient (Jain & Pathare, 2007).

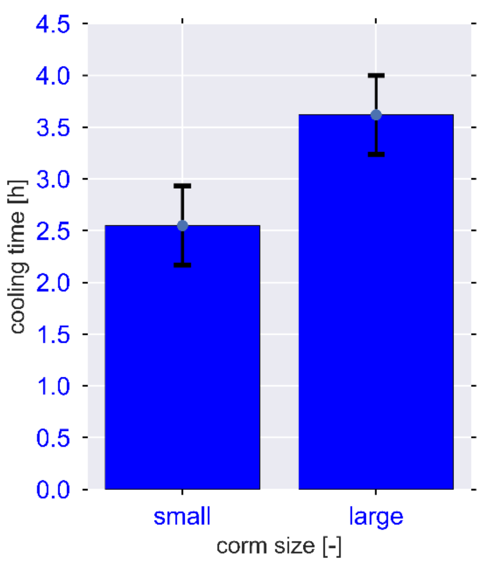

Figure 3: cooling time

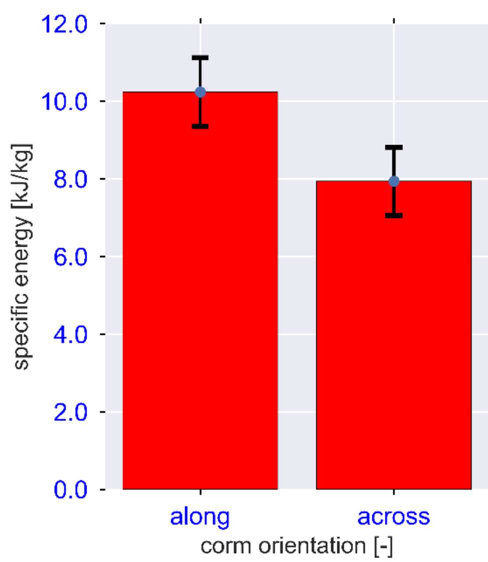

Figure 4: specific energy consumption

The specific energy consumed was found to be significantly influenced by the velocity of cooling air ($p < 0.0001$) and the corm size ($p < 0.05$) and the orientation of the corms to the direction of airflow ($p < 0.0001$). An increase in the air velocity caused a corresponding increase in the specific energy consumption. As shown in Figure 4, smaller sized corms oriented across the cooling airstream required less energy to cool than larger sized corms oriented along the cooling airstream. In cooling applications, besides the energy required to precool the cooling air, a significant amount of the energy is consumed by the ventilation system to deliver the cooling air and to remove the exhaust air after cooling. This energy is a function of the power demand for producing airflow (i.e., fan power) and the amount of time required to sustain the airflow (i.e., total cooling time) (Defraeye et al., 2014). Moreover, the aerodynamic resistance of the product as a result of the shape and size also influences the fan power (Defraeye et al., 2014).

Numerical optimisation

Table 4 provides the cooling settings derived from the most desirable numerical optimisation result. The most optimal solution reveals cooling corms at the air velocity of 0.5 $m \cdot s^{-1}$ while oriented across the cooling airstream could result in an optimal cooling time and specific energy consumption. However, the numerical solution selected placed more importance on the specific energy consumption than the cooling time for large-sized corms. This occurred even after setting the relative importance of the cooling time to specific energy consumption to be higher in the optimisation algorithm. This led to a lower composite desirability index for large corms.

Table 4. Selected numerical solution

Parameter	Optimisation target	Selected setting	Desirability index
Factors			
Air velocity ($m \cdot s^{-1}$)	keep in range	0.5	1.0
Corm size	keep in range	small, large	1.0
Orientation to airflow	keep in range	across	1.0
Responses			
Cooling time (min) – small corms	minimise	147	0.72
Cooling time (min) – large corms	minimise	217	0.28
Specific energy consumption (kJ/kg) – small corms	minimise	7.45	0.85
Specific energy consumption (kJ/kg) – large corms	minimise	8.43	0.96
Composite desirability index – small corms	*maximise*	-	*0.85*
Composite desirability index – large corms	*maximise*	-	*0.52*

CONCLUSION

Purple-speckled Cocoyam is rich in micronutrients and high-quality starch but is highly perishable in its fresh form. Convective cooling can provide suitable storage conditions to enhance its shelf-life after harvest which could improve its addition and marketability. This study provides the cooling kinetics of whole Cocoyam corms and presents the influence of the velocity of cooling air, corm size and corm orientation to the direction and airflow on the total time needed for cooling and the energy consumption. In the air corm size range under consideration, optimal cooling results can be obtained by using the lower setting of the air velocity and orienting the corms across the direction of airflow. These results provide an initial understanding of heat transfer during the cooling of individual purple-speckled Cocoyam corms. Future studies will focus on transferring the insights gained to design a cooling solution for the storage of bulk Cocoyam corms to enhance applicability in an actual on-farm storage setting.

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REFERENCES

Becker, B. R., & Fricke, B. A. (2004). Heat transfer coefficients for forced-air cooling and freezing of selected foods. *International Journal of Refrigeration*, *27*(5), 540–551. https://doi.org/10.1016/j.ijrefrig.2004.02.006

Box, W. E. ., & Wilson, K. . (1951). On the Experimental Attainment of Optimum Conditions. *Journal of the Royal Statistical Society*, *13*, 1–45.

Davey, K. R. (2015). Development and illustration of a computationally convenient App for simulation of transient cooling of fish in ice slurry at sea. *LWT - Food Science and Technology*, *60*(1), 308–314. https://doi.org/10.1016/j.lwt.2014.08.022

Defraeye, T., Lambrecht, R., Delele, M. A., Tsige, A. A., Opara, U. L., Cronjé, P., … Nicolai, B. (2014). Forced-convective cooling of citrus fruit: Cooling conditions and energy consumption in relation to package design. *Journal of Food Engineering*, *121*, 118–127. https://doi.org/10.1016/j.jfoodeng.2013.08.021

Derringer, G., & Suich, R. (1980). Simultaneous Optimization of Several Response Variables. *Journal of Quality Technology*, *12*(4), 214–219. https://doi.org/10.1080/00224065.1980.11980968

Dincer, I. (1995). Air flow precooling of individual grapes. *Journal of Food Engineering*, *26*(2), 243–249. https://doi.org/10.1016/0260-8774(94)00049-F

Dincer, I., & Genceli, O. F. (1994). Cooling process and heat transfer parameters of cylindrical products cooled both in water and in air. *International Journal of Heat and Mass Transfer*, *37*(4), 625–633. https://doi.org/10.1016/0017-9310(94)90134-1

FAO. (2012). Save Food: Global Initiative on Food Loss and Waste. /

FAO. (2019). *The State of Food and Agriculture 2019: Moving forward on food loss and waste reduction*. Rome, Italy.

Ghisalberti, L., & Kondjoyan, A. (1999). Convective heat transfer coefficients between air flow and a short cylinder. Effect of air velocity and turbulence. Effect of body shape, dimensions and position in the flow. *Journal of Food Engineering*, *42*(1), 33–44. https://doi.org/10.1016/S0260-8774(99)00100-4

Himeda, M., Yanou, N. N., Nguimbou, R. M., Gaiani, C., Scher, J., Facho, J. B., & Mbofung, C. M. F. (2012). Physicochemical, rheological and thermal properties of taro (Colocassia esculenta) starch harvested at different maturity stages. *International Journal of Biosciences*, *2*(3), 14–27.

Jain, D., & Pathare, P. (2007). Modelling of the Internal Cooling of Fish during Ice Storage. *International Journal of Food Engineering*, *3*(4). https://doi.org/10.2202/1556-3758.1131

Korese, J. K., Sturm, B., Román, F., & Hensel, O. (2017). Simulation of transient heat transfer during cooling and heating of whole sweet potato (Ipomoea batatas (L.) Lam.) roots under forced-air conditions. *Applied Thermal Engineering*, *111*(L), 1171–1178. https://doi.org/10.1016/j.applthermaleng.2016.09.137

Koyuncu, T., Pinar, Y., & Lule, F. (2007). Convective drying characteristics of azarole red (Crataegus monogyna Jacq.) and yellow (Crataegus aronia Bosc.) fruits. *Journal of Food Engineering*, *78*(4), 1471–1475. https://doi.org/10.1016/j.jfoodeng.2005.09.036

Kumar, R., Kumar, A., & Murthy, U. N. (2008). Heat transfer during forced air precooling of perishable food products. *Biosystems Engineering*, *99*(2), 228–233. https://doi.org/10.1016/j.biosystemseng.2007.10.012

Lebot, V. (2009). *Tropical Root and Tuber Crops: Cassava, Sweet Potato, Yams and Aroids*. CABI.

Liu, Q., Liu, J., Zhang, P., & He, S. (2014). Root and Tuber Crops. In *Encyclopedia of Agriculture and Food Systems* (pp. 46–61). Elsevier. https://doi.org/10.1016/B978-0-444-52512-3.00151-0

Modi, A. T. (2007). Effect of indigenous storage method on performance of taro [Colocasia esculenta (L.) Schott] under field conditions in a warm subtropical area. *South African Journal of Plant and Soil*, *24*(4), 214–219. https://doi.org/10.1080/02571862.2007.10634812

Montgomery, D. . (2017). *Design and Analysis of Experiments* (9th ed.). Wiley.

Ndisya, J., Mbuge, D., Kulig, B., Gitau, A., Hensel, O., & Sturm, B. (2020). Hot air drying of purple-speckled Cocoyam (Colocasia esculenta (L.) Schott) slices: Optimisation of drying conditions for improved product quality and energy savings. *Thermal Science and Engineering Progress*, *18*, 100557. https://doi.org/10.1016/j.tsep.2020.100557

Ndisya, J., Mbuge, D., Roman, F., Gitau, A., Sturm, B., & Hensel, O. (2021). Simulation of unsteady state heat transfer during forced convection cooling of whole Cocoyam (Colocasia Esculenta (L) Schott) corms. *[Unpublished Manuscript]*.

Opara, L. (2003). *Edible Aroids: Post-Harvest Operation*. Palmerston North.

Rashmi, D., Raghu, N., Gopenath, T., Pradeep, P., Pugazhandhi, B Murugesan, K., Ashok, G., … Kanthesh, M. (2018). Taro (Colocasia esculenta): An overview. *Journal of Medicinal Plants Studies*, *6*(4), 156–161.

Scott, G. J., Rosegrant, M. W., & Ringler, C. (2000). Global projections for root and tuber crops to the year 2020. *Food Policy*, *25*(5), 561–597. https://doi.org/10.1016/S0306-9192(99)00087-1

United Nations. (2019). World Population Prospects 2019: Highlights.

Wang, J.-K., & Higa, S. (1983). *Taro, a review of colocasia esculenta and its potentials*. Honolulu, Hawaii: University of Hawaii Press. Retrieved from https://scholarspace.manoa.hawaii.edu/bitstream/10125/23024/%234_Wang.pdf
Wheeler, T., & von Braun, J. (2013). Climate Change Impacts on Global Food Security. *Science*, *341*(6145), 508–513. https://doi.org/10.1126/science.1239402