Improving the quality of dried *Theobroma cacao* beans using a solar assisted desiccant-based dryer

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Abstract

Theobroma cacao beans are an economically significant commodity for the Fiji Islands. The cocoa beans are harvested in the wild and then fermented and sun-dried under tropical weather conditions. The high relative humidity (RH) as well as the unpredictable weather conditions extend the sun-drying time and causes quality issues in the final dried product. Maintaining product quality is important as export quality cocoa beans are sold at premium prices to chocolate manufacturers internationally. The problems in sun-dying can be solved by reducing the RH of drying air stream. This is possible with desiccant wheel technology (DWT). The solid desiccant material in DWT desorbs moisture from air and reduces humidity. The desiccant material can be regeneration between 60 and 100 °C for the next cycle. This temperature conditions can be achieved by using a solar dryer. This study tested the drying conditions below 20% RH on small batches (6 kg) of fermented Fijian cocoa beans at 45 °C and 55 °C. Impact of these conditions on the drying kinetics and bioactive quality was tested. Experimental data was used to validate a mechanistic drying model. The model was developed using partial differential equations (PDEs) with an implicit scheme for a targeted drying time of 72 hours. Finite difference method (FDM) was used to solve PDEs. The model output was comparable to experimental data from drying runs in Fiji. Reducing the RH at 45 °C showed a better retention of key bioactive compounds, such as polyphenols, caffeine, and theobromine when compared to other treatments. These findings are presented in detail in this thesis and suggests that DWT can provide consistent drying conditions in a tropical environment. The drying model is a useful tool for predicting the drying conditions for cocoa beans based on multiple input variables. The model can be used to advise cocoa farmers on the estimated processing time for cocoa beans to meet the demands of the export market.

Acknowledgements

My interest in solar drying was inspired by the positive impact this simple technology had on the livelihoods of people, especially women in rural Fijian communities. Community training experience facilitated by the Foundation for Rural and Integrated Enterprises (FRIENDs) enabled me to use the skills I developed from my MSc. programme from the University of the South Pacific (USP). This experience empowered me to further my education in Food Technology. I am thankful to have been awarded an MFAT scholarship by the New Zealand government and to have been accepted into the Massey University PhD in food technology programme. Studying for a PhD enabled me to work outside of my comfort zone and push my boundaries. The staff and graduate students were helpful, and I always learnt new things from them. My study experience introduced me to innovative ideas and beautiful cultures from around the world.

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My PhD journey was made possible with a lot of love and support from my family and friends. I would like to dedicate this thesis to them, to my great grandparents, my maternal grandparents late Mr. Armugam Pillay and Mrs. Rukhmani Pillay, formerly from Labasa but now in Auckland and to my ancestors who came from the beautiful country of India to the beautiful Fiji Islands under the indenture system as Girmityas.

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List of Nomenclature

Variable	Description	Unit
A_a	Area of unshading aperture	m^2
A	Area	m^2
A_{ri}	Inner cross-sectional area of tube	m^2
A_s	Surface area of the parabola	m^2
A_t	Area of tray	m^2
A_w or a_w	Water activity	
Bi	Biots number	
C	Moisture content	kg/m^3
Cp	Specific heat capacity	kJ/kg K
CR	Concentration ratio	
D	Diffusivity	m^2/s
d_b	Diameter of whole bean	m
d_e	Effective diffusivity	m^2/s
di	Dryer inlet	
Dr_0	Theoretical diameter of the receiver tube	mm
dro	Real outside diameter of the receiver	mm
Dgc	Diameter of glass cover	mm
dQl	Energy loss inside glass cover	$W/m^2/K$
dt	Drying time	h
e	Roughness	
F	Focal length	m
f	Fanning factor	
F'	Collector efficiency factor	
F''	Collector flow factor	
FR	Gain factor	
Gapt	Tray gap	m
h_{gco}	Convective heat transfer coefficient	$W/ m^2 K (W m^2 K^1)$
h_{fi}	Convective heat transfer coefficient	$W/ m^2 K (W m^2 K^1)$
H	Humidity	kg/kg dry air
hp	Height of parabola	m
h	Height of tray	m
H_{Latent}	Latent Heat of vaporisation	kJ/kg
h_m	Mass transfer coefficient	m/s
h / h_c	Heat transfer coefficient	$W/ m^2 K (W m^2 K^1)$
lt	Solar insolation	kW/m^2
K	Ratio of real diameter to theoretical one	mm
L	Length	m
L_{tray}	Length tray	m
Le	Lewis Number	
M_a	Moisture content of air	kg/mol
m_a	Mass of drying air	kg
M_b	Percentage in mass of dried cotyledon to dried bean weight	%
mc	Moisture content	%
m_{dt}	Weight of dried bean	kg
M_{ic}	Average water content in whole bean	%
M_t	Wet whole bean	kg

M_w	Quantity of water removed	kg
N_{tray}	Number of trays	
NL	Number of zones	
NLL	Number of layers divided along radius of the bean	m
nt	Total time steps	
ntt	Number of time steps for simulation of water diffusion	
Nu	Nusselt number	
Nu ai	Nusselt number for internal flow	
Nu_{gco}	Nusselt number for wind outside glass cover	
P	Load of beans on tray	kg
P_{atm}	Atmospheric pressure	Pa
P_{pda}	Saturated moisture pressure of drying air	Pa
Pr	Prandtl number	
ρ_a	Density of air	kg/m^3
ρ_t	Density of dried testa	
Q	Total heat required	W
Q_a	Air quantity needed	kg
Q_{lgco}	Energy loss outside the glass cover	
$Q_{l\ gci}$	Energy loss inside the glass cover	
Q_t	Energy required per hour	W
Q_u	Useful energy gain	W
Ra	Rayleigh number for free convection	
R_{ad}	Radius of bean	m
R_b	Ratio of moisture in bean to dry weight	
R_{bn}	Length of each zone in seed	m
Re	Reynolds number	
R	Radius of parabola	m
Rh	Relative humidity	%
rhot	Density of dried testa	kg/m^3
R_o	Moisture diffusion flux around bean surface	g/m^2 s
r_{rt}	differential radius for each shell within bean	m
Sc	Schmidt Number	
Sh	Sherwood number	
Sp	Saturation pressure	Pa
S	Arc length of parabola	m
t	Total drying time	s
t_0	Initial starting point, time	s
T_{ai}	Drying air temperature at inlet	°C
T_a	Temperature of ambient from FPC	°C
T_{area}	Tray area	m^2
T_{at}	Temperature of air in model	°C
T_{bi}	Initial seed temperature	°C
T_{hkt}	Thickness of testa	m
T	Temperature	°C
T_i	Temperature at dryer inlet	°C
T_r	Temperature at PTSC outlet	°C
T_m	Average temperature of air	°C
T_{mgcr}	Mean temperature of air between glass cover and receiver	°C

dT_{out}	Dryer outlet temperature difference, Tout-Tr	°C
U_L	Heat loss coefficient	
U_{wind}	Wind speed	m/s
ν_a	Air viscosity	m^2/s
v_{ra} or $\cup a$	Air velocity	m/s
W	Water	
W_a	Width of aperture	m
Wt.	Weight	kg
W_{tray}	Width of tray	m
x	Distance for each tray zone	m
X	Humidity	kg water/ kg dry air
X	Moisture content	kg water/kg dry matter

Subscripts

Variable	Description
a or air	Air
ae	Exhaust air
ai or amb	Ambient Air
b or bt	Cocoa bean
c	Cotyledon
g	Glass
gci	Glass cover inside collector
gco	Glass cover outside collector
i	Inlet
p	Plate
r	Parabolic collector receiver
ro	Receiver outer surface
s	Bean surface
Sky	Sky
t0	Testa
out	Receiver outlet
v	Water vapour
w	Water

List of Symbols

Symbols	Details	Unit
θm	Half-angle subtended by the sun	°
φr	Rim angle	°
λ	Latent heat of water	kJ/kg
δ	Thickness	mm
δ_{gc}	Thickness of glass cover	mm
δgr	Distance between glass and tube	mm
λa	Thermal conductivity of air	W/m K
λ_b	Thermal conductivity of insulation material	W/m K
λt	Thermal conductivity of carbon steel (<0.5%C)	W/m K
εt	Emissivity of rolled steel	
ε_{gc}	Emissivity of glass	
λ_{gc}	Thermal conductivity of glass	W/m K
λa_{gco}	Thermal conductivity of air outside glass cover	W/m K
λa_{gci}	Thermal conductivity of air inside glass cover	W/m K
αa_{gci}	Thermal diffusivity of air inside glass cover	W/m K
$\lambda eff\ a_{gci}$	Effective thermal conductivity of air inside glass cover	W/m K
ΔT_a	Increase in air temperature increase in the receiver	°C
ΔT_{ra}	Mean temperature difference between receiver and air	°C
η	Thermal efficiency of PTC	
ΔP	Pressure drop	Pa
Φ	Drying rate	kg/kg dry bean
$\boldsymbol{\sigma}$	Stephan Boltzmann constant	
ε	Emissivity	
λ	Thermal conductivity	W/m K
$\lambda seed$ or $\boldsymbol{k_\beta}$	Thermal conductivity of seed	W/m K
ρ	Density	kg/m^3
u	Air velocity	m/s
Φ	Drying rate	kg water/ kg dry solid/ h

Chapter 1 Introduction

1. Introduction

Theobroma cacao (cocoa) is a significant agricultural crop in the global commodity market. Despite the impact of COVID-19 pandemic, the market size for cocoa beans is estimated to be worth $15,501.1 million by 2027 (Wood, 2021). Fermented and dried cocoa beans are used as the prime raw material in chocolate and chocolate products. These cacao beans are harvested from cocoa trees, native to central and south America. The trees are squat cauliflorous and can produce numerous elongated and large oval pods (15-30 cm) as shown in Figure 1.1.

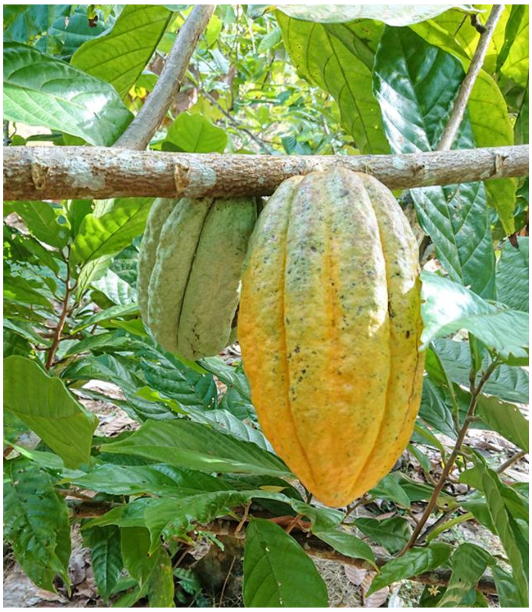


Figure 1.1. Forastero variety of *Theobroma cacao* in Fiji. Forastero cacao pods are oval and change colour from green to yellow upon ripening.

The growth cycle of cocoa trees is characterised by leaf flushing with two harvest seasons in a year. The small white flowers are pollinated by midges of the family *Ceratopogonidae* (Young, 1983). Each cocoa pod can weigh about 400 to 600 grams and has 20 to 60 pulp-covered ellipsoidal beans that are one to six centimeters in length (Koua *et al.*, 2017). Each bean can weigh between one to six grams depending on maturity and cultivar.

Cocoa trees are cultivated in West Africa, Indonesia, Sri Lanka, South India, and the Pacific Islands. Cocoa production in the Ivory Coast in Ghana (West Africa) accounts for more than

50% of the global supply (TradingEconomics, 2019). The tropical climate, volcanic soil, rainfall, and an altitude above 600 m in these countries are ideal for cocoa farming (McGregor and McGregor, 1999). About 1000 to 2500 trees can be cultivated in a hectare (Ha) of land with a maximum fresh cocoa pod yield of three metric tonnes (Mt) per year. An average tree produces a maximum of 60 pods per season with an average of 40 cocoa beans per pod.

There are three main cultivars of cocoa. These are Criollo, Trinitario, and Forastero (Aeschlimann and Beckett, 2000). The Criollo variety is not commercially viable as it is susceptible to diseases, but it is valued for fine flavoured chocolate production. The most commercial variety is the Trinitario cocoa beans, which is a hybrid from Forastero and Criollo. Trinitario and Forastero variety of cacao are often earthy and robust in flavour profile. These varieties are blended to make cocoa liquor, which is used for chocolate production. Another Forastero variety is Amelonado, which is widely cultivated around the world.

In Fiji, the main cacao varieties are Forastero, Amelonado (Forastero hybrid), and Trinitario. These are known to produce exotic flavours for superior quality dark chocolates. Trinitario, Forastero, and Amelonado cacao have a robust earthy flavour composition. Poorly dried varieties of these cocoa beans are often used in bulk grinding markets for chocolate or cocoa products (Xiao- Wei *et al.*, 2017). Bulk grinding markets produce cocoa liquor from dried and roasted *Theobroma cacao* beans to produce chocolate, cocoa butter, and cocoa powder in quantities large enough to limit unit cost.

Currently, a rising global demand for cocoa beans with unique flavour profiles is driving the market towards the Pacific (ICCO, 2018). Small holder farms in the Pacific Island Nations, such as PNG, Vanuatu, Solomon Islands, Samoa, and Fiji are suppliers of Forastero and Trinitario cocoa beans to local and overseas chocolate industries. The demand for cocoa for chocolate production dates to the colonial period. Cocoa plantations in the Fiji Islands were established during the indenture system by the British Empire. Trinitario seedlings were imported from Sri Lanka and planted in the central and northern districts of the Fiji Islands (Figure 1.2). In the central division, cocoa trees were planted in the province of Tailevu, but it was also cultivated on a smaller scale in Rakiraki, which is on the western side of Vitilevu. In the northern division, cocoa has been cultivated in the Macuata province on the island of Vanua Levu as shown in Figure 1.2.

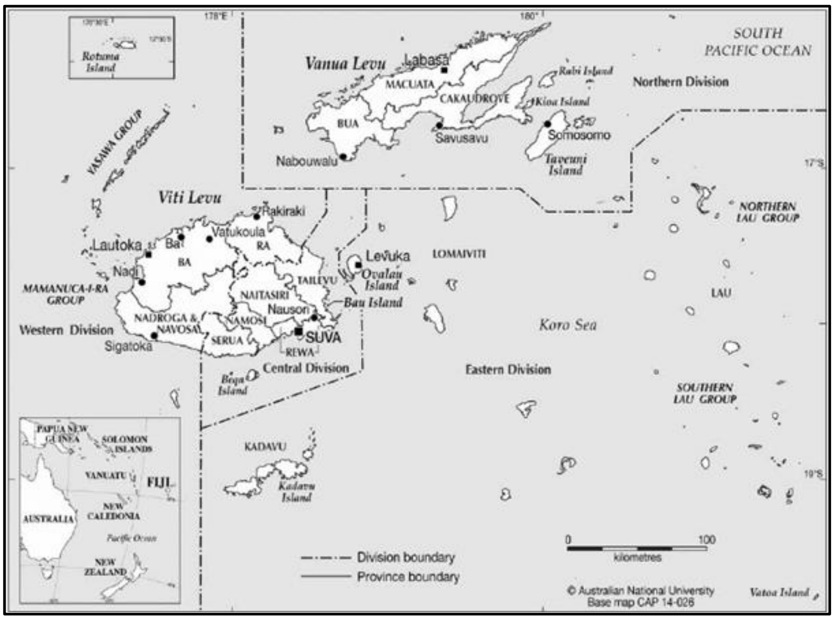


Figure 1.2. A map of the Fiji Islands showing different districts
http://asiapacific.anu.edu.au/mapsonline/base-maps/fiji-base-map

Expansion of the cocoa plantations in Fiji began in the 1930's by the Fiji Department of Agriculture. During this period cocoa nurseries were established in the central area through market research. In 1944, Trinitario cocoa trees were initially cultivated in Fiji, but the high acidity in Fijian Trinitario cocoa beans affected trade. The Trinitario variety was replaced by Amelonado, which was more suited to cultivation because of resistant to *Phytophthora palmivora* fungal infestation and higher yield when compared to other hybrids as mentioned in Table 1.1. By the 1960s, cocoa plantations were centralised in the Tailevu province (McGregor and McGregor, 1999).

A summary of research projects conducted on *Theobroma cacao* cultivation in Fiji reported from 1930 to 1987 are presented in Table 1.1. Production of fresh cocoa pods in Fiji declined drastically after the 1980's (Table 1.1). This decline was caused by several factors, such as tropical cyclones, aging trees, deforestation, lack of investment, and poor management of orchards. Currently, the international demand for premium cocoa beans has revived cocoa farming in the northern, central, and western areas of Fiji. The cocoa industry has also received funding, planting materials, and processing equipment to support postharvest processing. In 2017, the European union (EU) funded several cocoa processing units for Fiji under the Secretariat of the Pacific Community (SPC) to improve export of cocoa (Matanimeke, 2017).

Table 1.1. A summary of *Theobroma cacao* cultivation in Fiji from 1930 to 1987

Year	Description	Reference
1930-1939	Establishment of a cocoa nursery through market research.	Jack, H. W. 1936. Cocoa. Fiji Agricultural Journal, 8 (2), 45-46.
1940-1949	Cocoa trees planted in wet and dry zones in the northern district. Initially 60% of the cocoa plants were of the Criollo variety and 40% were of the Forastero variety. The common pest of the cocoa plants were rats.	French-Mullen, M. D. 1944. Summary of a preliminary survey of existing cacao in the Northern district, Fiji. *Fiji Agri. J.*, 15 (1), 8-13.
1950-1959	The Fiji Ministry for Agriculture provided information on the sources of planting material and recent cultivars of cocoa plants to create interest amongst farmers. In 1952, A review of cocoa production in Fiji by the South Pacific Commission (SPC) revealed that the soil and climate conditions were suitable for small scale cocoa cultivation. Cocoa seedlings were sourced from Western Samoa and a detailed information on the pests and diseases in cocoa was provided by the SPC. By 1954, cocoa plantation was established by the Naduruloulou agriculture research station in Nausori, Fiji. The plant materials were used for propagation and several trails were tested before distributing the plant materials to farmers. Sills, (1957) reported that biological variability in cocoa plants affected the quality of Fijian cocoa beans. Cultivation of clonal varieties was encouraged to limit biological variability and improve dried cocoa bean quality. In 1959, farming conditions in Fiji were identified to be highly suitable for cocoa plantations. The main factors suggested for planting cocoa trees were shade, wind breaks, and rainfall. The early attempts in 1880's to establish cocoa plantations were reported to be successful, but there were quality issues in dried cocoa beans. The research priority identified by the Fiji Department of Agriculture was an investigation of cocoa bean quality. Soil selection is also of importance when cultivation cocoa beans. Soil depth, structure, root development, and soil fertility were identified as critical parameters for planting cocoa trees.	Parham, B. E. V. 1952. Cacao-review and prospects. *Fiji Agri. J.*, 23 (2), 14-24. Urquhart, D. H. 1952. Cocoa Growing in the Fiji Islands. Technical Paper No.36, South Pacific Commission, Noumea, 15 pp. Parham, B. E. V. 1954. Cacao at Naduruloulou, 1953. *Fiji Agri. J.*, 25 (1), 24-26. Sills, V. E. 1957. Chocolate flavour and the quality assessment of Fiji cocoas for 1955/56. *Fiji Agri. J.*, 28 (3/4), 62-67. Harwood, L. W. 1959. Fiji harvests first cocoa crop. South Pacific Commission Quarterly Bulletin, 9 (1), 29-32. Harwood, L. W. 1959. Establishment of a cocoa industry in Fiji. *Fiji Agri. J.*, 29 (2/3), 50-55. Harwood, L. W. 1959. Cocoa planting. *Fiji Agri. J.*, 29 (2/3), 65-75. Harwood, L. W. 1959. Plans for the future. *Fiji Agri. J.*, 29 (2/3), 107-111. Harwood, L. W. & McPaul. J. W. 1959. The soil requirements of cocoa. *Fiji Agri. J.*, 29 (2/3), 62-64.

	Key natural conditions for cocoa production were humidity and temperature. Quality grades of cocoa beans were affected by fermentation and drying conditions. The fermentary in Naduruloulou agriculture station was established with various drying techniques. Fermentation and drying affected the economic value of cocoa beans used for chocolate, cocoa butter, and beverage production.	McPaul, J. W. 1959. Notes on cocoa nutrition. *Fiji Agri. J.*, 29 (2/3), 99-106. Sills, V. E. 1959. The preparation of cocoa. *Fiji Agri. J.*, 29 (2/3), 76-90.
1960-1969	Fermentation issues were reported during processing of fresh cocoa beans.	Sills, V. E. 1960. Cocoa bean studies in Fiji. South Pacific Commission Quarterly Bulletin, 10 (2), 28-31.
1970-1979	Clones were tested by the Fiji Department of Agriculture. Amelonado clone was found to be resistant to *Phytophthora palmivora.* Annual yields were estimated from experimental plots using sample harvest records. Research data from FDA shows that Amelonado variety of cocoa beans planted in-situ were much bigger than seedlings transplanted from the nursery. The first Amelonado cocoa planting in Waimaro yielded up to 3700 kg/ha. Cocoa plants were found to be highly sensitive to small variations in soil conditions. Variations in climate affected the incidence of black pod diseases. High rainfall increases losses of cocoa pods to black pods by 25%.	Department of Agriculture, Fiji. (1971). Report for the Year 1970. Suva, 34 pp. Vernon, A. J. 1971. The estimation of annual yield of experimental plots of cocoa from sample picks. *Fiji Agri. J.*, 33 (2), 41-46. Sundarum, S. 1972. A comparison of direct seedling with transplanting of cocoa. Turrialba, 22 (3), 354-357. Sundarum, S. and Hassan, M. 1973. Further notes on the Waimato cocoa: Part 2 Yield. *Fiji Agri. J.*, 35 (2), 61-66.
1980-1987	Cocoa trees planted with shade trees, such as bananas and coconut trees had an average yield of 1494 kg/ha when compared to shading with cassava and taro (1066 to 1135 kg/ha). Amelonado variety of cocoa trees were found to produce the highest yield (2106 kg/ha) at Wainigata when compared to upper Amazon and Trinitario hybrids in the same site. Amelonado cocoa beans showed acceptable pod value and tolerance towards *P. palmivora.* In 1984, there was an extensive damage to cocoa plantations by two cyclones. Deteriorating political situation in Fiji also contributed to the loss of cocoa beans.	Martin, M. P. L. D., Pratap, R. & Prasad, G. 1984. Residual effects of shade species during establishment on the yield of cocoa. *Fiji Agri. J.*, 46 (1), 17-20. Martin, M. P. L. D. 1987. Cocoa in Fiji. Cocoa Growers' Bulletin, 38:23-27. Martin, M. P. L. D. 1987. Performance of Amelonado and hybrid cocoa in Fiji. *Fiji Agri. J.*, 49 (1), 17-24.

*Sourced from Lim and Fleming. Food and Other Crops in Fiji - an Annotated Bibliography (ACIAR Monographs).

Cocoa production can also be improved by cultivating high yielding clonal varieties that are disease resistant. While clonal varieties have been developed through research, there is little known about genetic variations within the wild varieties planted during the colonial period. These wild varieties of Trinitario and Forastero are mainly harvested by the Fijian villagers for in the highland areas that are difficult to access. The main issues experienced by cocoa producers in Fiji are the lack of appropriate postharvest processing technology and postharvest handling skills. A better control of fermentation and drying is important to preserve the organoleptic and microbial quality of dried cocoa beans for export. There are many drying techniques suggested in scientific literature that improve the drying process. However, a suitable drying technology should be recommended based on ambient conditions around the cocoa plantation and the socio-economic and socio-cultural factors. Improvements in the drying process are critical for retention of key bioactive components that develop flavour and aroma precursors for downstream processing.

1.1. Postharvest processing treatments for *Theobroma cacao* beans

In Fiji, cocoa pods are harvested biannually and on a weekly basis, during the main season (October to December) and mid-season (March to May). Post-harvest processing is critical for cocoa-specific flavour and aroma precursors, mainly for chocolate production (Koua *et al.*, 2017). Various postharvest treatments such as pod storage, microbial fermentation, drying, and roasting (downstream processing) enable development of cocoa-specific flavour, aroma, and dark colour. The initial step during primary processing of cocoa beans is fermentation. Microbial fermentation in Fiji is generally spontaneous and usually lasts for seven days under ambient conditions. However, some Fijian cocoa processors are reducing fermentation to three days to meet the commercial demands. Fermented cocoa beans are sun-dried in the open for 14 days to extend shelf-life. A summary of these processing stages is presented in the flow diagram in Figure 1.3.

Step 1 in Figure 1.3 shows that ripe *Theobroma cacao* pods are harvested and sorted prior to further processing. Pods that have obvious fungal infestation are discarded. Ripeness is recognised as change in pod colour from green to orange, yellow or purple, depending on cultivar. The second step during processing is dehulling, where ripe pods are cracked using the blunt edge of machetes and wooden sticks to remove cacao beans (step 2). Precautions are taken during pod cracking to avoid damage to cocoa beans inside the pods, as this would cause product loss from spoilage.

Extracted cocoa beans (step 2) are packed in boxes, baskets, or heaps for fermentation (step 3). Cocoa bean fermentation consists of a short anaerobic phase (0-24 h) followed by an extended aerobic phase that lasts for another 144 to 168 h. In Fiji, fermentation is a spontaneous process, involving natural microbial flora. Yeast and lactic acid bacteria (LAB) from cocoa farm workers' hands, machetes, fermentation boxes, and cocoa pods facilitate pulp fermentation (Crafack *et al.*, 2014). The microbes metabolise acids and sugars in the pectin-rich pulp into volatile acetic acid, carbon dioxide (CO_2) and water (Schwan and Wheals, 2004; Lima *et al.*, 2011). Free amino acids and reducing sugars are released as flavour and aroma precursors (Zzaman and Yang, 2014).

In West African countries, heap fermentation on the ground with heaps covered by banana leaves is a traditional practice. Basket, box, and tray fermentation are other methods that are widely practiced as well (Hii *et al.*, 2009; Ndukwu *et al.*, 2012; Jespersen *et al.*, 2005). FAO (1970) recommends fermenting cocoa beans in wooden boxes for seven to ten days. This type of fermentation is the standard technique in cocoa farms around Fiji. Some Fijian cocoa processors remove excess pulp around the cocoa beans to expedite fermentation. In the first 24 hours the pulp drips from the bean mass because of compression caused by packing of beans inside the fermentation box. After 24 hours, the bean mass is mixed mainly using hands to incorporate oxygen. This process is called aeration and it is done daily to encourage oxidation of polyphenols and reduce pathogenic mould growth.

During the first three days of fermentation, cocoa bean temperature increases to approximately 50 °C. This spike in temperature is caused by exothermic reactions during acidification by acetic acid and ethanol. Acidification devitalises the cocoa bean embryo and prevents complete germination. High temperature and low pH (3 to 3.5) favour resilient strains of microbes, such as acetic acid bacteria (Efraín *et al.*, 2019). However, *Bacillus* species and mould, such as *Aspergillus* sp. can be present if fermentation extends beyond 10 days (Aradhna and Fleet, 2003). The spores and mycotoxins from these pathogens contaminate the dried cocoa bean and lead to losses.

Length of fermentation and temperature of bean mass have an impact on certain organoleptic quality parameters in cocoa beans. The quality of the fermentation process is monitored by farmers using a visual examination of colour change through a cut test. This test is performed by cutting the beans longitudinally to examine the colour change. A colour change from purple to brown is highly desirable and demonstrates oxidation of polyphenolic compounds to tannins. Cocoa beans contain a wide variety of polyphenolic compounds. The three main groups of polyphenols are proanthocyanins, catechins, and anthocyanins. These compounds are naturally produced in cocoa beans through shikimate and acetate pathways. Biochemical reactions during fermentation reduce the polyphenol content and alter composition in cocoa beans. Fully fermented cocoa beans are brown in colour with a distinct aroma profile, such as a fruity or floral aroma from volatile compounds. Poor fermentation results in dull coloured cocoa beans with a putrid odour (Fowler, 2009). These defects persist during drying and reduces the commercial value of dried cocoa beans (Schwan and Wheals, 2004).

In step 4 of processing, fully fermented cocoa beans are sun dried in deeps beds of 5 mm between seven and 14 days to remove excess moisture and extend shelf life for safe storage (Bonaparte *et al.*, 1998). This additional 14 days of drying after seven days of fermentation hinders the ability of Fijian farmers to supply export quality cocoa beans. Drying is important as it reduces acidity and enables the process of oxidation for the development of cocoa-specific flavour and aroma (Afoakwa, 2014; Chinenye *et al.*, 2010). Sun drying in the open is used worldwide but this technique can cause hygiene issues. The main disadvantage of sun drying in the open is intermittent weather conditions, which delays drying and export of dried cocoa beans. These delays could be avoided by limiting the processing time to one week, where cocoa beans are fermented for four days and dried for three days. This could allow the Fijian farmers to meet their week production targets for export. Introducing a reliable but low-cost dryer could reduce the time required for cocoa beans to dry to a safe moisture content for export.

A low-cost drying technology, which is suitable for tropical conditions are solar dryers. Some key benefits of solar dryers are hygienic drying conditions and protection from rain. Introducing a solar dryer could eliminate the labour required for monitoring and handling the cocoa beans during sun-drying in the open. The main limitation with solar dryers is the high relative humidity (RH) of ambient air stream, which is typical of the tropics. The high RH of air (75%) could limit the drying potential. During sun-drying, homogenous drying conditions are maintained by mechanical methods, such as frequent raking to mix cocoa beans in the drying bed. This technique damages the cocoa bean.

Solar dryers, as well as artificial (electric) dryers can be used to dry cocoa beans safely. These drying technologies can decrease the drying time significantly when compared to 14 days of sun- drying. However, the organoleptic quality of cocoa beans dried in these different dryers are not consistent. In electric dryers, rapid drying under high temperature conditions (>60 °C) results in acidic and brittle beans that break easily during roasting (>90 °C). Solar dryers are a more feasible solution as there is abundance of sunshine in Fiji and the dryer designs are versatile.

The dried cocoa beans are graded onsite to evaluate the dried product quality. This is conducted as step 5 in the processing sequence in Figure 1.3. Dried cocoa beans are graded and sorted for defective beans based on size, bean count per batch, and internal bean colour using a cut test (Kongor *et al.*, 2016; Afoakwa *et al.*, 2011). Sorting eliminates mouldy and fragmented pieces of the bean. Graded and sorted cocoa beans are weighed (step 6) into jute bags for storage under ambient conditions (step 7) and are transported to distribution facilities (step 8). Grading is usually conducted manually by workers in the cocoa farm.

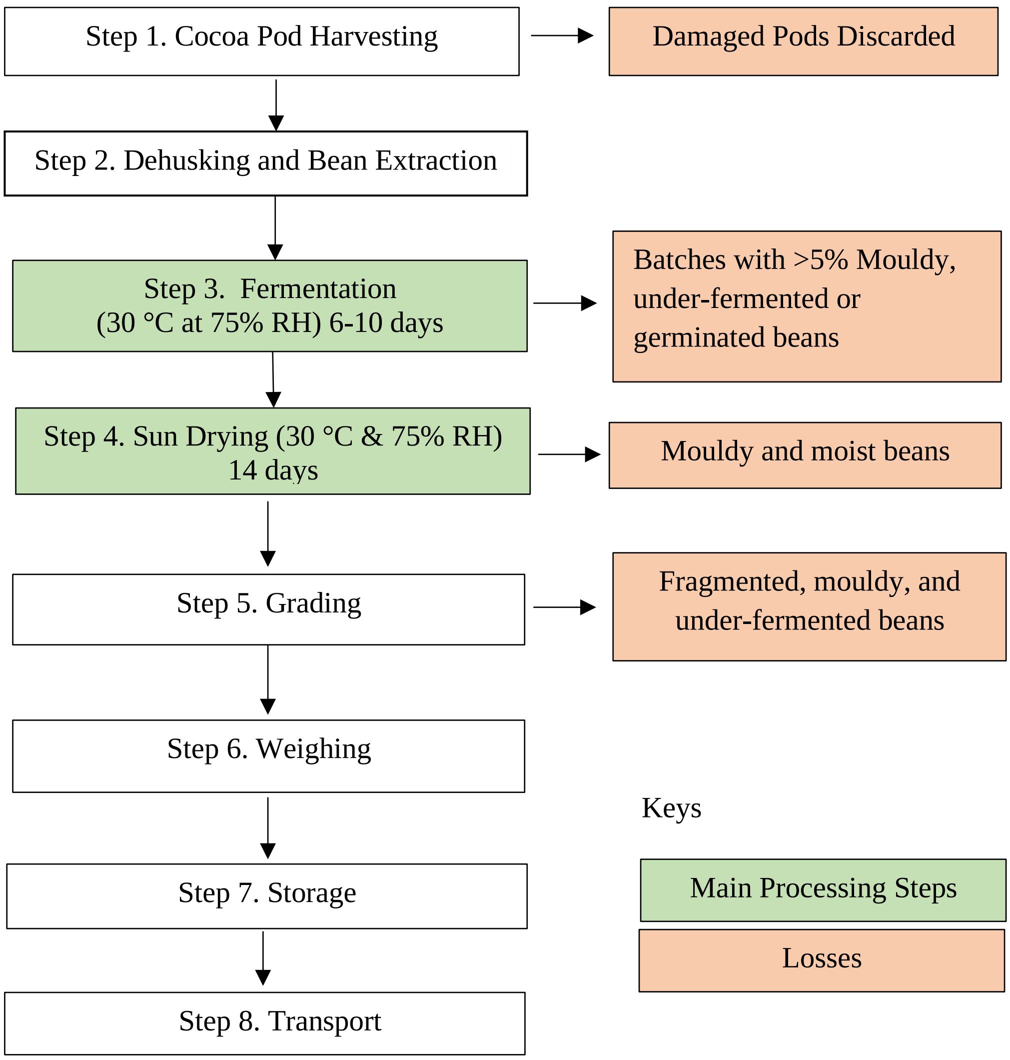


Figure 1.3. Processing stages for cocoa fermentation and drying

Certain quality guidelines define acceptable levels of mouldy and defective cocoa beans in a graded batch. ASEAN standards (ASEAN Stan 34:2014) classifies cocoa beans as extra class, which is of superior quality, class I (good quality) and class II beans, which meets the minimum quality requirements. In superior quality and class I cocoa beans, mould growth should affect <3% of beans per bag. Class II beans should have <4% of mould growth per bag. Contaminants are often classified as waste, which is identified as flat beans, bean and shell fragments, and remnants of placenta and pulp. Premium quality beans have a value of approximately USD 10 per kg whereas poor quality beans with defects maybe valued at USD 2.50 per kg and sold to bulk grinding markets in Asia.

1.2. Quality issues in cocoa processing

Quality issues in dried cocoa beans are often experienced during postharvest handling and processing when standard protocols are not followed (Fowler, 2009). Dry bean weight, dry bean moisture content, mould growth, and a cut test score of >60% in a dried batch are some key quality parameters assessed by cocoa processors in the dried product. Dried batches that are non-compliant for these quality standards are rejected.

Mould growth, germination, and colour change using cut test on fermented and dried *Theobroma cacao* beans are assessed through visual inspection. The subjective nature of visual inspections can be unreliable and inconsistent. Despite these shortfalls, chocolate manufacturers depend on visual examination of bean colour and appearance to determine acceptable quality. The commercial quality aspects of fermented and dried cocoa beans are determined using three main categories:

1. Flavour and aroma profiles from bioactive components, mainly polyphenols, theobromine, and caffeine (methylxanthines).

2. Physical parameters, such as bean size and colour, as well as insect infestations and germinated beans in a batch. Size measurements, such as length, width, and thickness determine bean sphericity and shrinkage after drying. Bean sphericity should be >0.50, which means that the dried cocoa beans are not flat. The cocoa industry sets an acceptable limit for flat beans in a dried batch as <5%. This is because a greater percentage (>5% per batch) of flat dried cocoa beans lower the bean mass after roasting, which causes a reduction in amount of roasted cocoa beans for the manufacture of chocolate or cocoa products.

3. Final dried bean moisture content of 7-8% on a wet weight basis (w.b) for extended storage and transport, as well as to limit mould and mycotoxin contamination.

1.2.1. Quality limitations caused by drying conditions

Relying on spontaneous fermentation generates batch to batch variation in moisture content and other intrinsic variables in the cocoa beans. This contributes to inconsistency in dried product quality. Variations in initial moisture content of wet fermented cocoa beans prior to drying may result in partially dried cocoa beans that are susceptible to mould infestation. Mycotoxic mould growth is the key quality issue during drying. Mould contamination causes commercial loss for cocoa processors and farmers in Fiji. Limited process control and optimisation of processing conditions results in dried beans that do not meet the organoleptic quality standards for international markets. According to ICCO (2008) high-grade cocoa beans should be:

1. Fully fermented and brown in colour.
2. Dried ideally to 7% moisture content on a wet weight basis.
3. Free from smoky and foreign odour.
4. Free from broken beans, shell fragments, and foreign matter.

These quality control problems mainly arise due to lack of process control measures during drying and limited postharvest training available to cocoa farmers. In Fiji, fermentation is a spontaneous process that is dependent on warm ambient conditions (25 to 35 °C and 70 to 90% RH). Fermented cocoa beans are sundried under the same ambient conditions. The limited drying potential and intermittent weather conditions during sun drying have been known to extend the drying time, which deteriorates the organoleptic quality and increases product loss from spoilage (Ong, 1999; Bal *et al.*, 2011). Seasonal variations during cocoa harvest period are another factor that influences fermentation and drying conditions (Indarti *et al.*, 2011).

Drying is mainly influenced by air temperature, relative humidity (RH), and air velocity. These parameters are not controlled under conventional sun-drying conditions. Therefore, uniform drying is encouraged by raking to mix the cocoa beans in the drying bed. This technique also prevents formation of bean clumps that can cause quality issues in a dried batch. For uniform drying removal of moisture trapped within the bean bed is critical. Excess local moisture causes mould growth, which deteriorates product quality and value. Figure 1.4 shows the extent of mould growth in sun dried cocoa beans exposed to rain.

Conversely, frequent raking and handling of cocoa beans disturbs the drying process and causes product breakage and loss. These constant monitoring techniques during sun drying are labour intensive, which contributes to the cost of production. Despite the added cost to the product the quality standards for export are not met. These quality issues can be minimised by a more hygienic approach and better control of drying parameters, such as using solar dryer technology. Drying cocoa beans in a solar dryer can prevent contamination from dust, mould, as well as insect infestation commonly seen in sundried beans (Onwuka and Nwachukwu, 2013). Efficient drying conditions have been extensively reported in solar dryers but the effects of solar drying conditions on key bioactive components that are essential for the formation of flavour precursors in *Theobroma cacao* beans are not widely known.

Figure 1.4. A batch of sun-dried *Theobroma cacao* beans in Fiji showing mould infestation

Temperature and RH conditions during drying affect the retention of bioactive compounds, such as polyphenols (Alean *et al.*, 2016; Kongor *et al.*, 2016). Polyphenols in cocoa beans are beneficial to human health and improve the flavour of chocolate by forming flavour precursors during drying. Flavour profile of chocolate and cocoa products is an important sensory quality for consumers. Afoakwa et al. 2008 identifies fermentation and drying conditions to be important in the development of flavour profile in *Theobroma cacao* beans. Unfermented cocoa beans are bitter and astringent due to high native polyphenol content. Epicatechins impart an undesirable bitterness to unfermented cocoa beans. Methylxanthines, such as caffeine and theobromine also impart a bitter flavour, but the concentrations of these compounds are much lower when compared to the polyphenol content. Unprocessed cocoa beans have a caffeine content of 0.2%, theobromine content between 2 to 4% and total polyphenol content between 12 to 18% of dry whole bean weight. Fermentation and drying allows cocoa processors to reduce the epicatechin content in cocoa beans. This limits undesirable bitterness in the dried product.

Temperature control during drying is critical towards limiting mould growth and flavour development in fermented *Theobroma cacao* beans. Several studies found that quality issues, caused by mould growth and biochemical reactions are limited under the drying temperature of 50 to 60 °C (Kant *et al.,* 2016; Wojdyło *et al.,* 2016). Drying cocoa beans at higher temperature (>60 °C) causes shrinkage and case hardening. These quality problems lower commercial value of the product and increase susceptibility to breakage and product loss during roasting (Urquhart, 1961; Wadsworth, 1955). Rapid drying at >60 °C in artificial dryers deters polyphenol oxidase (PPO) activity, which limits development of flavour precursors (Herman *et al.,* 2018).

Cocoa beans dried at 65 °C showed inactivation of PPO within 24 hours of treatment in a study reported by Quesnel & Singh, (1970). The study also found that drying at 55 °C caused a 95% inactivation of PPO activity. Similarly, high RH has a negative impact on the polyphenol content. Kyi et al. (2005) showed a decline in total polyphenol content in cocoa beans dried between 40 and 60 °C under 50 and 80% RH. These findings indicate that temperature and RH combinations during drying are critical for PPO activity that leads to development of flavour precursors in dried *Theobroma cacao* beans. These mild to moderate drying conditions (30 and 50 °C) can be achieved in solar dryers.

1.2.2. Improving the drying kinetics for *Theobroma cacao* beans with solar dryers

Artificial dryers are more effective in rapidly reducing moisture for safe storage. However, rising fuel prices and energy costs shift the demand towards sustainable technology, which is affordable for Fijian farmers. Currently, many cocoa farmers use biomass or finned heaters for drying cocoa beans during the rainy seasons. Biomass heaters are reported as a cheaper option than diesel or electric dryers but smoke from biomass combustion causes smoke tainting in cocoa beans (Hii *et al.*, 2009). Smoke tainted cocoa beans have an acidic flavour and a smoky odour, which lowers the commercial value of the product and the profit margin for cocoa farmers. Additionally, fuel consumption in biomass heaters increases cost and contributes to pollution. The smoke also contains polyaromatic hydrocarbons (PAHs) that can cause health issues. A more economical approach for drying quality cocoa beans is by using simple solar dryer technology.

In a Pacific nation such as Fiji, solar technology is considered as part of the green economy that contributes towards the United Nations sustainable development goals (SDG) for the environment in the Pacific. The simplicity of this technology minimises the cost for fabrication, which is affordable for farmers and small businesses in rural communities. Solar dryers can also be modified using various techniques for improving and controlling drying conditions (Bonaparte *et al.*, 1998). Design modifications using heat storage has been shown to extend drying time per day and limit microbial growth in the product (Dina *et al.*, 2015). Modifications with materials, such as concrete and water have been shown to improve heat storage. The thermal properties of water (4.1 kJ/kg ˚C) and concrete (1.7 kJ/kg ˚C) makes them effective for heat storage in solar dryers (Kant *et al.*, 2016). Drying requires a high energy input and thermal storage materials can smooth out energy requirements.

Other improvements for improving energy efficiency during drying could be through heat recovery from dryer exhaust air. Heat recovery is recommended by Budin and Mihelić-Bogdanić (2011) and Djaeni et al. (2021) by recycling dryer exhaust air to minimise energy losses during drying. The sensible heat from dryer exhaust has drying potential (Djaeni *et al.*, 2021). Recycling the exhaust air can minimise thermal losses and improve drying conditions. The main limitation with recycling dryer exhaust air for drying is that the high relative humidity impedes drying potential of the air stream and extends the drying time.

Another technique to improve drying conditions with sensible heating is to integrate a desiccant wheel (DW) with the solar dryer system. The DW is a critical component in dehumidifying ambient air for drying fermented cocoa beans. It operates as a heat and mass exchanger for dry air streams at low rotational speed. As shown in Figure 1.5, DW is a cylindrical structure with numerous multilayered porous air flow channels containing desiccant material. These channels are mainly honeycomb in shape, but some have sinusoidal and triangular shapes. DW often has three angular sections for dehumidification (process air), humidification (regeneration air) and purge section (Yadav and Yadav, 2014). In the purge section, exhaust air is dehumidifiedfor regeneration. Dehumidification and regeneration section are two main components of desiccant wheel. In the regeneration section, the moist solid desiccant material is regenerated periodically by regenerating air, which desorbs the moisture from the desiccant. Process air stream through the dehumidification section is used for drying wet product.

Integrating desiccant technology for drying operations reduces energy costs and improves dried product quality (Misha *et al.*, 2012; De Antonellis *et al.*, 2012). Desiccant material in DW is mainly silica gel for adsorbing moisture from the humid air. The wheel has separate air streams for process air (drying) and adsorbent regeneration (dehumidifying and heating) often arranged in a counter current manner as shown in Figure 1.5 (De Antonellis *et al.*, 2016). Rotation of the desiccant wheel generates a vapour pressure gradient between the drying air stream and desiccant material, which facilitates adsorption, desorption, and latent heat transfer (Kang and Lee, 2017). While the high cost of adsorbent-based desiccant systems raises production costs, it has potential for producing quality products with high profitable margins.

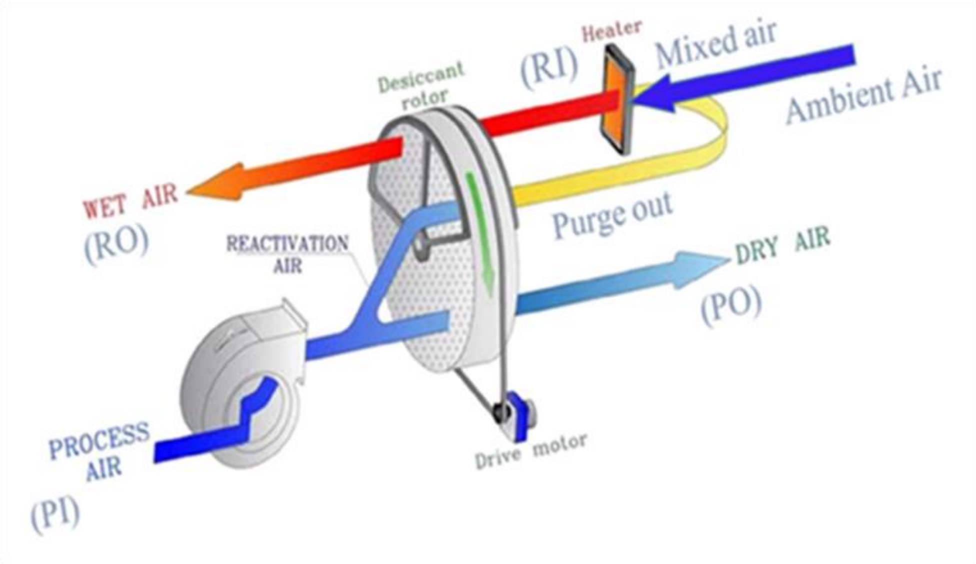


Figure 1.5. Air flow inside a desiccant wheel system. The illustration of a DW with a purge angle is presented by Mandegari et al. (2017). In this diagram, RO is regeneration air out, PI is process air, PO is process air out and RI is regeneration air in.

In a solar dryer integrated with a rotary desiccant wheel, the dryer design can be modified to recycle the desiccant exhaust for drying. This can be done by installing a component where the regeneration exhaust air can be mixed with fresh dehumidified air. Regeneration exhaust has thermal potential and recycling this exhaust air can improve the drying time (Djaeni *et al.*, 2021.

Temperature and low RH combinations on the drying kinetics of fermented *Theobroma cacao* need to be elucidated further. Development of a mathematical model using experimental findings could also predict the drying kinetics that affect cocoa bean quality. The commonly used models to predict the drying time for cocoa beans are semi-theoretical models, such as

Page and logarithmic model (Darvishi *et al.*, 2013; Alean *et al.*, 2016). The drying time for sun-dried cocoa beans is predicted using the Page model, while the logarithmic model is used for cocoa beans dried under hot air-drying conditions above 30 °C (Teh *et al.*, 2016). Semi-theoretical model equations are widely used for fitting the drying curve but are limited in explaining the drying behaviour or predicting the drying kinetics of fermented cocoa beans based on varying drying parameters. A mechanistic drying model can predict and describe the drying behaviour of fermented cocoa beans much more accurately than semi-theoretical models. The development of a mechanistic drying model for fermented cocoa beans dried with desiccant wheel integrated to a solar dryer in Fiji was considered in this study. This type of drying concept is the first for cocoa beans from the Fiji Islands.

1.3. Project background and significance

In the Fiji Islands, sun drying in the open is commonly practiced for drying fermented *Theobroma cacao* beans. Sun drying may be cost effective in terms of energy consumption, but it is time and labour intensive. There is limited control over quality parameters of dried product intended for export. Conversely, artificial dryers are expensive for small holder farms. Rapid drying at hot temperature conditions (>60 °C) impair dried bean quality by causing retention of acids, development of off-flavours, and damage to bean physiology. These drastic impacts on cocoa bean quality can be limited by drying under mild to moderate drying conditions (30 and 60 °C). These conditions are achievable in solar dryers, but the technology needs to be optimised for efficiently drying of wet fermented cocoa beans without quality issues.

Quality problems during sun drying arise from a high ambient RH of 75 and 90% between 28 and 35 °C. These ambient air conditions have limited drying potential, which extends the drying time for cocoa beans to 14 days. This slow drying under high RH increases mould contamination in cocoa beans. Product infestation with mould causes loss of revenue and increases risks of mycotoxin contamination. Preventative measures to limit mould growth, such as raking the cocoa beans at hourly intervals and removing mouldy beans as a quality control measure may not be consistent between farmers in Fiji.

Despite the quality issues in sun dried Fijian *Theobroma cacao* beans, there is a growing market demand for high quality dried specialty cocoa beans from Fiji. Organically grown cocoa beans of single origin with exotic flavour profiles are usually sourced for dark chocolate production. Therefore, the preservation of these exotic and robust flavour profiles imparted by the high polyphenol content is critical for product quality of Fijian cocoa beans. Solar dryer technology appears to be a cost effective and reliable solution for hygienically drying cocoa beans while preserving these key organoleptic qualities.

Design modifications to solar dryers can enable more control over the main drying conditions. The problem of high RH can be minimised in solar dryers by attaching a desiccant wheel (DW). This technology limits the RH at low dry bulb temperature, which can reduce the drying time. Further understanding of low RH at moderate temperature (30-60 °C) conditions on the drying kinetics of cocoa beans is necessary to predict and describe drying time and behaviour in a solar assisted desiccant-based dryer. This can be further elucidated using mathematical models.

Simple semi-empirical mathematical models have been used extensively to predict drying in various food items. However, these models are limited because few input parameters are considered and the internal diffusion of moisture from various layers of the particle is not fully described. The key problem with semi-empirical models is the limitation in predicting drying behaviour under varying drying conditions. A mechanistic model can quantitatively predict the drying kinetics despite variations in drying parameters. Mechanistic models have not been developed for fermented cocoa beans dried under Fijian weather conditions.

Conducting large scale drying experiments using a solar dryer with desiccant wheel on 100 kg of wet fermented Fijian cocoa beans would be expensive and time consuming. Controlling quality problems in large batches of product is challenging as well. Mathematical models are a more efficient and low-cost option to predict the drying kinetics and product quality. Model development can be supported using small scale drying experiments as a cost-effective approach.

The best combination of drying temperature and low RH for optimal drying time and retention of key bioactive compounds is not known. The drying experiments developed in this PhD provides further insight on the bioactive quality in dried cocoa beans and improvement in the drying time. A solar dryer with DW technology has the potential to decrease processing time as the equipment could be available for drying two batches of wet fermented cocoa beans in a week. This allows the cocoa processors and farmers to dry high quality beans for export in less than 14 days.

This study proposes to test the various drying conditions from a conceptual solar dryer with a desiccant wheel on the key quality parameters of Fijian *Theobroma cacao* beans and to develop a mechanistic drying model for predicting drying kinetics under variable drying conditions. The study was supported through the New Zealand scholarship by Ministry of Foreign Affairs and Trade (MFAT), New Zealand. The outcomes from this research would be highly valuable to the scientific community and to the livelihoods of cocoa farmers in Fiji, as well as the Pacific.

1.4. Research hypothesis

The research hypothesis of this study is that a solar dryer with a desiccant wheel will improve the drying kinetics and organoleptic quality of dried Fijian *Theobroma cacao* beans compared to sun drying.

This PhD study will address this hypothesis with the following research questions:

1. What are the temperature and relative humidity conditions for efficiently drying fermented Fijian *Theobroma cacao* beans with maximum retention of polyphenolic compounds and methylxanthines?

2. Can a desiccant wheel be used to dry fermented *Theobroma cacao* beans with recycled air under Fiji conditions?

3. Can a mathematical model predict and describe the drying kinetics of Fijian *Theobroma cacao* beans using drying conditions simulating in a solar dryer with desiccant wheel technology?

4. What changes occur in quality composition of fermented *Theobroma cacao* beans when dried under various conditions?

To address these research questions, the following objectives were selected:

1. Propose a farm-scale solar dryer design with desiccant wheel technology for drying fermented Fijian *Theobroma cacao* beans.

2. Develop a mechanistic drying model based on the solar dryer design to predict the drying kinetics of Fijian *Theobroma cacao* beans under controlled drying conditions.

3. Analyse the key bioactive components that develop flavour precursors, such as polyphenolic content, caffeine, and theobromine in dried Fijian cocoa beans dried at low relative humidity conditions.

These objectives will be addressed in this thesis in the chapters presented in the logic flow in Figure 1.6.

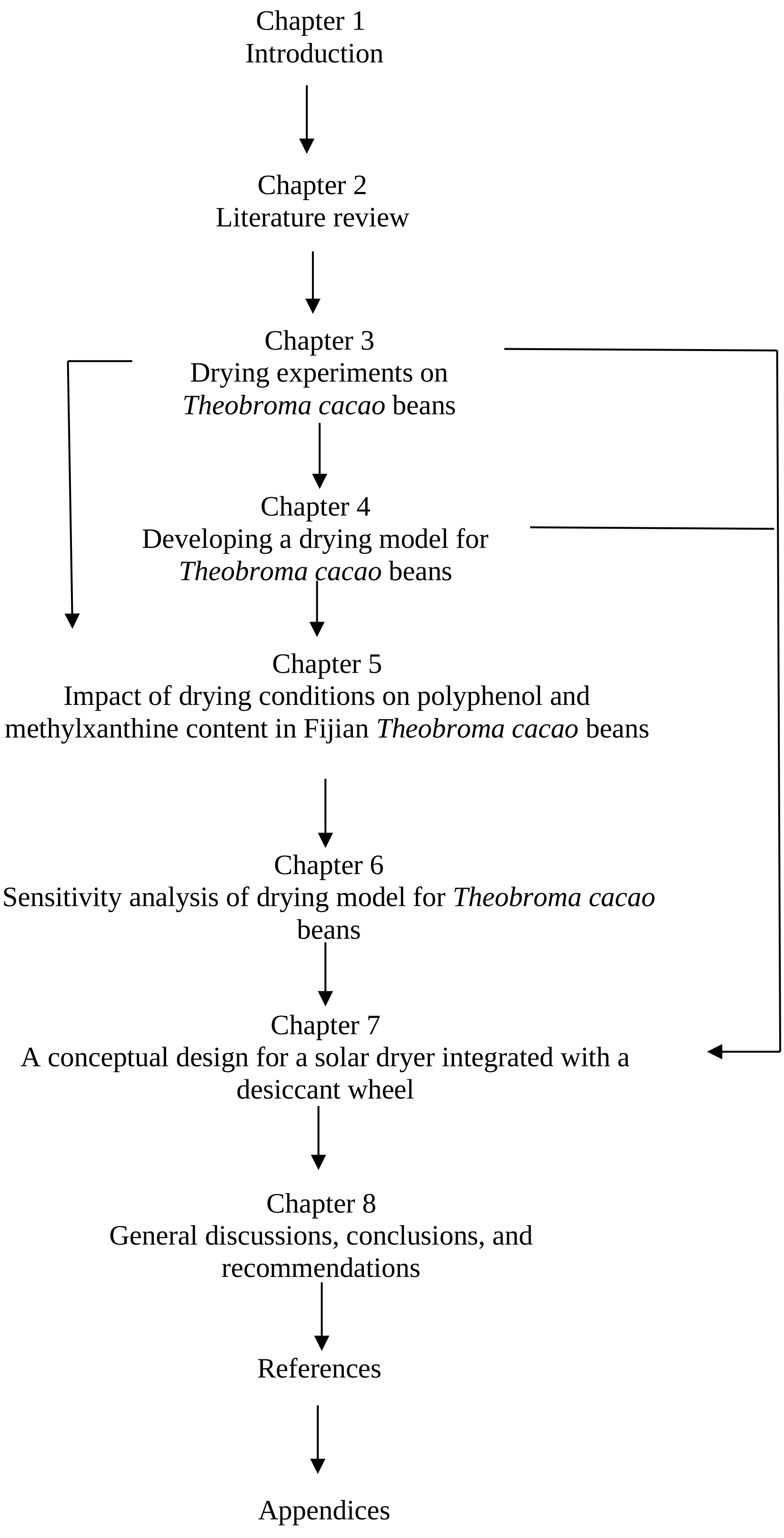


Figure 1.6. Logic flow of thesis chapters

Chapter 2 Literature review

2.1. Introduction

Theobroma cacao was introduced into the Fiji Islands during the colonial period as a new cash crop. The tropical conditions in Fiji are ideal for growing and processing cocoa beans for export. Commercially graded cocoa beans must meet export quality standards for attributes such as moisture content, acidity levels, slatiness, polyphenol content, mold, and mycotoxin (Aroyeun *et al.,* 2009). These quality standards are influenced by the postharvest processing techniques. These primary processing techniques, such as fermentation and sun-drying in the open lower the natural bitterness of cocoa beans caused by purine alkaloids (caffeine and theobromine) and polyphenolic compounds (Stark and Hofmann, 2005; Camu *et al.,* 2007). Postharvest processing also develops essential organoleptic precursors for roasting. These cocoa-specific flavour and aroma precursors are essential in the production of quality chocolates and confectionaries.

The first step of postharvest processing is fermentation. Traditional fermentation techniques depend on spontaneous and highly complex microbial interactions for development of flavour precursors. Fermenting fresh cocoa beans for at least six days 'devitalises' the beans to prevent sprouting, breaks down cellular membranes that impede drying, and causes complex biochemical reactions in the cotyledons. These endogenous enzymatic reactions develop the desirable aroma and flavour precursors in the cocoa bean that are critical for downstream processing (roasting). The key flavour compounds formed during roasting are pyrazines, esters, aldehydes, ketones, alcohols, and carboxylic acids. These precursors are also initially developed during fermentation and drying.

Consistent development of flavour precursors has been reported by studies on small scale batches of cocoa beans under controlled fermentation conditions (Lefeber *et al.,* 2012). Some studies report that naturally fermented cocoa beans have lower theobromine levels when compared to cocoa beans fermented using starter cultures (Afoakwa *et al.,* 2008, Aprotosoaie *et al.,* 2016). Factors such as cocoa cultivar, fermentation techniques, and duration influence flavour development (Kongor *et al.,* 2016). In Fiji, box fermentation is widely practiced on Fijian cocoa farms and processing sites on large quantities of cocoa beans (30-100 kg per box). While natural box fermentation is successful under tropical conditions in Fiji, these same conditions impede the sun-drying process.

The reason for disruptions during drying is the high ambient relative humidity (RH) and intermittent weather conditions. This extends sun-drying to 14 days. Limited control over sun-drying parameters and the extended drying time causes various quality problems, such as microbial spoilage from excess moisture. Problems in sun-drying can easily deteriorate the quality of a well fermented batch of cocoa beans and extend the processing time (Dzelagha, Ngwa, and Bup, 2020). While fermentation time can be reduced to four days, the variable conditions during sun-drying causes processing conditions to be unreliable. Therefore, cocoa farmers are unable to meet the weekly demand for dried cocoa beans for export. A possible solution to the problems with sun-drying in the open is to introduce a simple, low-cost drying technology.

There are several technologies that can improve drying, such as a heat pump dryer (HPD) and desiccant wheel technology (DWT). However, HPD has lower drying efficiency when recycling exhaust air, higher energy as well as capital costs (Minea, 2011). DWT with solid desiccant material can be a cost-effective alternative to HPD when operated with solar energy. Simple solar dryers are also considered as a sustainable alternative to sun-drying and electric dryers. Solar dryer design can be modified by attaching a solar collector to increase ambient air temperature and fans to accelerate air flow during drying. Various solar dryer designs used for drying general agricultural products have been tested on *Theobroma cacao* beans in published literature. The new design features in solar dryers show an increase in air flow and temperature range but the relative humidity of the drying air stream remains high. Since DWT is a cost-effective technique for drying, integrating a desiccant wheel (DW) to the solar dryer system could solve the problem of high RH during drying. Lowering the RH can reduce the drying time but the impact of dehumidified drying condition on the drying kinetics and bioactive quality of Fijian cocoa beans needs to be tested further.

2.2. Fermentation process

Natural fermentation is spontaneous and consists of a short anaerobic phase (24-48 hours) followed by an aerobic cycle (48 to 168 hours). The anaerobic conditions are established by freshly extracted cocoa beans adhering to each other by the sticky and mucilaginous pulp. The packing and adhering of cocoa beans restrict air flow within the fermentation box. The lack of air circulation creates an anaerobic environment, which favours the growth of yeast species (*Saccharomyces*, *Candida*, and *Pichia* sp.), and heterofermentative *Lactobacillus plantarum*.

Enzymes secreted by yeasts and LAB depolymerise pectin and hydrolyse sucrose into ethanol (EtOH) and CO_2 (De Vuyst and Weckx, 2016).

The high moisture content in fresh cocoa beans (75% wet weight basis) and pulp sugar supports the growth of yeast. Microbial growth occurs in the pulp while endogenous enzymes cause biochemical changes that affect the nutrient composition in the bean. Table 2.1 shows the standard nutritional components in raw and unfermented *Theobroma cacao* beans based on fresh weight as reported by Biehl et al. (1982). Pulp sugar and pectin content in cocoa beans are influenced by fruit maturity, cultivar, and geographical locations. Environmental conditions, such as soil type, altitude, and climatic factors vary between geographical locations. These variations cause a difference in the moisture content and organic acids in cocoa beans from around the world (Pettipher, 1986).

Table 2.1. Key nutritional components in unfermented *Theobroma cacao* bean

Component	Content
Water	32 to 39%
Fat	30 to 32%
Free fatty acids	1%
Proteins (albumin and vicilin-class globulin)	8 to 15%
Cellulose	2 to 3%
Sugars	10-15 %
Starch	4 to 6%
Sucrose	2 to 3%
Acids (malic and oxalic acids)	1%
Citric acid	2.1 to 2.4 %
Acetic acid	0.04%
Lactic acid	0.03%
Polyphenols	4 to 6%
Theobromine	1 to 3%
Caffeine	0.1-0.2%

*(Biehl et al., 1982a)
*Results are reported in fresh dried cocoa beans

Fermentation of pulp sugar produces aromatic compounds, such as alcohols, aldehydes, esters, and volatile organic acids, which are aroma and flavour precursors. Alcohol and esters released by yeast impart a floral and fruity aroma. Various LAB species also ferment glucose, fructose, and citric acid into volatile organic acids and aromatic compounds. Some species of LAB, such as *L. fermentum* from the fermentation mass remain viable for up to three days of sun drying (Hamdouche *et al.*, 2015). The mild drying conditions allows further development of flavour and aroma precursors. Acetic acid bacteria (AAB) oxidise EtOH to volatile acetic acid, acetoin, water, and CO_2 (De Vuyst and Weckx, 2016; Sandhya *et al.*, 2016). A summary of the metabolites produced by various microbes at different stages of fermentation is given in detail in Table 2.2.

Table 2.2. Microbial metabolites produced during fermentation of *Theobroma cacao* beans

Duration	Microbes	Species	Conditions	Metabolites	Authors
24-48 hours	Yeasts	*Hanseniaspora sp.* *Saccharomyces cerevisae* *Pichia sp.*	Anaerobic	Ethanol Citric acid	Camu et al. (2008)
24-72 hours	Lactic Acid Bacteria (LAB)	*Tatumella sp.* *Lactobacillus sp.* *Leuconostoc Pseudo-mesenteroides* *Fructobacillus sp.*	Anaerobic	Citric acid Lactic acid Acetic acid Mannitol Carbon dioxide Acetic acid	Lefeber et al. (2012) Camu et al. (2008) Hamdouche et al. (2015) Camu et al. (2007)
48-112 hours	Acetic Acid Bacteria (AAB)	*Acetobacter ghanensis* *Acetobacter senegalensis* *Acetobacter pasteurianus* *Acetobacter syzgii* *Acetobacter tropicalis*	Aerobic	Acetoin Acetic acid Carbon dioxide Water	Crafack et al. (2014), De Vuyst and Weckx, (2016), Camu et al. (2007), Schwan and Wheals, (2004b), Nielsen et al. (2007)

Acidification by acetic acid from AAB also affects enzymatic reactions, mainly polyphenol oxidases (PPO). Polyphenol oxidation to tannins and quinones imparts a desirable dark colour to the cocoa bean. Conversely, excess acetic acid can also bind to functional groups in polyphenols and impede oxidation. This could have a detrimental effect on development of organoleptic precursors in cocoa beans as the polyphenols would not be available for biochemical reactions during downstream processing. Acidification and a rise in bean temperature are also critical points for the termination of incipient germination and control of microbial growth. Accumulation of acetic acid in the testa devitalises the embryo and this causes break down of cell walls inside the cotyledon. Information on the structural changes in the cocoa bean tissue structure is limited in literature, apart from generic statements that fermentation causes cocoa beans to become mesoporous because of morphological changes to the cell structure (Alean *et al.*, 2019; Brito *et al.*, 2000).

During microbial fermentation, cocoa-specific aroma precursors are produced when vicilin-type (7S) globulin is metabolised into hydrophilic oligopeptides, and hydrophobic free amino acids by carboxypeptidase (Kongor *et al.*, 2016; Voigt *et al.*, 1994). Several studies show that proteolytic activity peaks during acidification (De Witt, 1957; Seiki, 1973; Forsyth *et al.*, 1958). Other flavour precursors develop from hydrolysis of sucrose by invertase, anthocyanin, and terpene cleavage by glycosidase and polyphenol oxidase (PPO) (De Vuyst and Weckx, 2016; Schwan and Wheals, 2004).

2.2.1. Polyphenol degradation

Theobroma cacao beans are rich in polyphenols (12-18% of dry whole bean weight), which are found in the folded parenchyma cells. In fresh cocoa beans, 10% of storage parenchyma is polyphenolic cells, which are concentrated near the vascular bundles (Elwers *et al.*, 2010). The main groups of polyphenols in cocoa beans are catechins, flavonols, glycosides, anthocyanins, and procyanidins. Fermentation and drying conditions can drastically reduce polyphenols, caffeine, and theobromine in cocoa beans (Table 2.3). Therefore, understanding a favourable drying time, as well as RH and temperature combination for preserving most of the polyphenols is critical for dried cocoa bean quality.

A summary on the impact of biochemical reactions during fermentation on the polyphenolic compounds in *Theobroma cacao* beans is provided in Figure 2.1. A major component of these polyphenolic compounds is flavonoids (Afoakwa *et al.*, 2012). Variations in the heterocyclic structure results in other flavonoid classes, such as flavanols (catechins), isoflavones, flavonols, flavones, flavanones, flavanonols, and anthocyanidins. Alkaloids such as methylxanthines are also found in polyphenolic cells (Kadow *et al.*, 2015; Afoakwa *et al.*, 2012). Membrane disintegration during acidification stage of fermentation disrupts the polyphenolic cells and releases the polyphenols and alkaloids into the bean tissue. These compounds are oxidised by PPO. Anthocyanins are oxidised into less bitter and darker coloured anthocyanidins and quinones, while methylxanthine content remains stable (Biehl *et al.*, 1985).

A decline in caffeine and theobromine occurs in the bean during processing. This is caused by diffusion of alkaloids into the testa (Peláez *et al.*, 2016). While low levels of these compounds may reduce bitterness in cocoa beans, a certain portion of compounds need to be retained to generate desirable sensory properties in the finished chocolate. The desirable polyphenol content in dark chocolate is between 1.7 and 8.4 mg/g of chocolate (Urbanska *et al.*, 2019). This concentration also depends on product formulation and the content of non-fat cocoa solids.

Table 2.3. Change in theobromine and caffeine content in *Theobroma cacao* beans during fermentation and drying

Key Bioactive components	Theobromine	Caffeine	Reference
Unfermented	27-37 mg/g dry bean	6 mg/g dry bean	Menguy et al., (2009)
Fermented	21 mg/g dry bean	4 mg/g dry bean	
Dried	14 mg/g dry bean	1-2 mg/g dry bean	Septianti et al., (2020)

*Content in cocoa beans that have been spontaneously fermented and sun dried

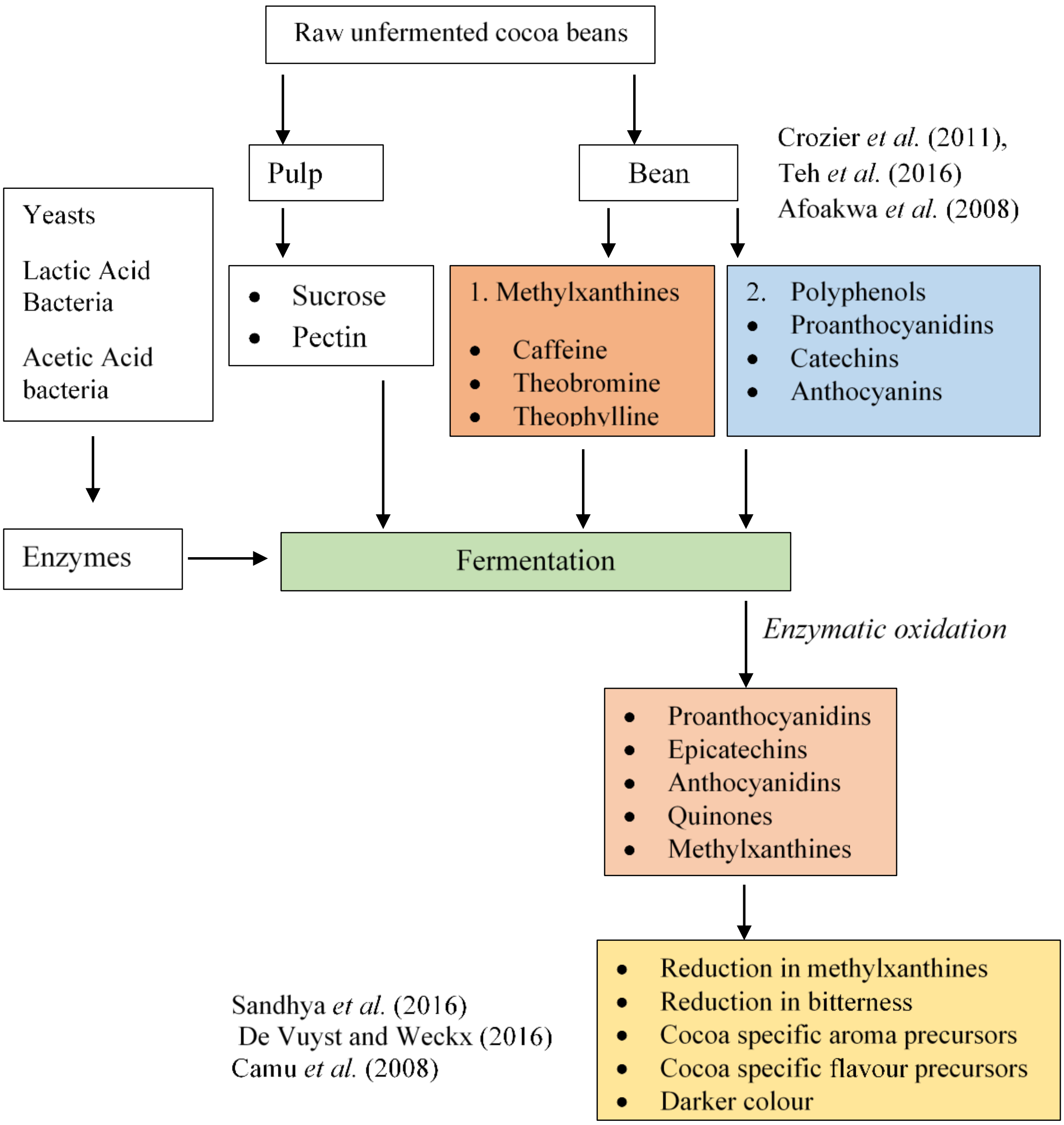


Figure 2.1. Impact of fermentation on the polyphenolic compounds and methylxanthines in *Theobroma cacao* beans.

The quality parameters of cocoa beans, mainly acidity, polyphenols, alkaloids, and fatty acid profiles, are influenced by processing conditions. Acid accumulation is a major quality problem in fermented cocoa beans that are dried in electric dryers above a temperature of 60 °C (Jinap *et al.*, 1994). The problem of acidic flavour retention in cocoa beans is resolved by an alkalisation or 'Dutch processing' technique after roasting. This method is applied by washing dried beans with potassium carbonate solution. Dutch processed cocoa beans can reach an alkaline pH (6-8) and this has an adverse effect on the polyphenol content (Hurst *et al.*, 2011).

Alkalisation could be avoided if the acetic acid in cocoa beans is vapourised during drying. Thus, the control of drying conditions is critical for quality cocoa bean quality for export. The drying conditions should ensure a maximum retention of polyphenols and methylxanthines, as well as volatilisation of acetic acids, and removal of excess moisture. The drying conditions should also ensure product safety from mycotoxic mould that could arise during drying.

2.3. Quality problems in *Theobroma cacao* beans during drying

Drying conditions are critical for the stability of thermo-sensitive polyphenolic compounds (Hii *et al.*, 2012). The extended hours of sun drying oxidises polyphenols, while faster hot air drying (e.g., above 60 ˚C) vitiates flavour development (Teh *et al.*, 2016). The main quality problems in hot air drying at high temperatures are acid retention and case hardening, while sun drying causes product loss from mould growth. A better understanding of quality issues during drying would be useful in identifying the appropriate drying conditions required for superior export quality dried cocoa beans within a shorter drying time.

Drying parameters, such as temperature and RH variations, have a considerable effect on the polyphenol content, physical, and organoleptic quality in dried cocoa beans (Hii *et al.*, 2009). Several studies have recommended moderating drying conditions to minimise acidity and bitterness in cocoa beans (Hamdouche *et al.*, 2015; Hii *et al.*, 2009). Bitter and acidic beans retain volatile compounds, such as acetic, propionic, butyric, isobutric, and isovaleric acid and alkaloids (Jinap, 1994; McDonald *et al.*, 1981). Moderating drying conditions also influences enzymatic oxidation of volatile compounds for cocoa-specific flavour and aroma precursors.

Residual levels of volatiles and alkaloids are acceptable in dried cocoa beans as these compounds impart a desirable bitterness to the dried beans (Hii *et al.*, 2011). Controlling the moisture evaporation rate during drying ensures that these volatile acetic acids are vapourised and acidity decreases in cocoa beans (Chinenye *et al.*, 2010). Drying can reduce volatile acids but it cannot eliminate the less volatile lactic acids. If the drying temperature is increased to more than 60 °C then this causes acid retention in dried beans, which further deteriorates dried bean quality.

The drying temperature also has a strong effect on the polyphenol content in cocoa beans. When the drying temperature is below 60 °C, there is enzymatic oxidation of polyphenols. Enzymatic oxidation of polyphenolic compounds reduces the undesirable bitterness by epicatechins and releases flavour precursors. Drying at a temperature above 60 °C causes thermal degradation of polyphenolic compounds. A few studies have reported the effect of various drying temperatures on polyphenol degradation. Findings by Abhay et al. (2016) and Miletić et al. (2013) show that polyphenol degradation increases when the drying temperature is above 70 °C and under a longer drying time. Various drying techniques tested by Menon et al. (2017) demonstrated thermal degradation of polyphenols occurs when the temperature increases above 65 °C.

While increasing the drying temperature can rapidly reduce free moisture, the high temperature gradient can cause mechanical defects in cocoa beans (Banboye *et al.*, 2020). Uneven moisture gradients in the bean layers and between the testa and cocoa bean during drying could cause case hardening (Hii *et al.*, 2013). The testa in cocoa bean is hygroscopic and has a different cellular structure (Henderson and Pixton, 1980). Rapid loss of moisture at high drying temperature conditions causes contraction of cells in the testa. These contracted cells form a crust that impedes diffusion of internal moisture. Case hardening is more evident at a drying temperature of more than 60 °C.

Rapid drying (above 65 °C) can also cause shrinkage (Hii *et al.*, 2006; McDonald *et al.*, 1981). This is another quality problem in cocoa beans dried rapidly in electrical dryers. Rapid moisture removal creates a pressure imbalance, which causes constriction of the bean structure (Koua*et al.*, 2017). Gulati and Datta (2015) explain that uneven moisture causes stress in the bean tissue, which leads to shrinkage and cracking, as the cell walls contract into spaces previously occupied by fluids. Temperature has a substantial impact on case hardening and shrinkage (Udomkun *et al.*, 2016). Hot air drying of cocoa beans caused significant shrinkage than solar-dried conditions (Páramo *et al.*, 2010). Shrinkage is a problem in cocoa beans as it causes slow moisture diffusion from the product interior, which extends the drying time. Regulating the drying conditions can minimise these mechanical defects by controlling moisture gradients within the cocoa bean (Alean *et al.*, 2016; Gulati and Datta, 2015).

While rapid drying presents mechanical problems in cocoa beans, decreasing the drying temperature to less than 60 °C could increase the risk of mould growth. This causes food safety concerns for contamination with mycotoxins in the dried product. Mycotoxin contamination can easily occur during sun-drying because of hot and humid climate conditions (EFSA, 2007). The occurrence of mycotoxins, such as aflatoxins (AFs) and ochratoxin (OTA) has been widely reported in dried cocoa beans (Copetti *et al.*, 2012; Adebayo, 2016). Mycotoxins are sporadically distributed in cocoa beans, (Raters and Matissek, 2005). Incidence of *Aspergillus* sp. and *Penicillium* sp. in one product can contaminate an entire batch with mycotoxins. The high risk of product contamination by mycotoxins can be limited by controlling the drying conditions.

Mild temperature (30 to 50 °C) drying conditions are desirable for better colour, aroma and flavour development (Miletić *et al.*, 2013; Hii *et al.*, 2009) but the longer drying time and high RH increases the likelihood of mould contamination in the product (Fowler, 2009; Jain and Tiwari, 2015). The best approach to identify the temperature and RH combinations to limit mould growth during drying is to use moisture sorption isotherms for cocoa beans. These isotherms can identify the targeted water activity (a_w) required for the safe storage of cocoa beans at equilibrium moisture content (EMC). Mould growth is inhibited when a_w is below 0.65 in the cocoa beans but a a_W of 0.70 in multilayers is not available for microbial growth as water molecules form hydrogen bonds between these layers (Park, 2008). The ideal conditions for limiting a_w to below 0.65 can be estimated using sorption isotherms for cocoa beans.

2.3.1 Moisture sorption isotherms for cocoa beans

A desorption isotherm for cocoa beans was reported by Koua, Koffi, and Ghaha, 2016 using a gravimetric method between 30 and 60 °C. The study used a Guggenheim-Anderson-de-Boer (GAB) model to correlate with the experimental data. The type II desorption isotherm was used to describe the cocoa beans to be high in hydrophilic compounds. Talib, Daud, and Ibrahim, (1995) reported a similar finding for cocoa beans and described the cocoa bean as a mesoporous product with multilayers within the bean. Temperature has a strong influence on the a_w. The EMC range of 0.10 and 0.07 kg water/ kg bean was identified to be microbially safe for storage of cocoa beans at 30 °C (Koua, Koffi, and Ghaha, 2016; Akmel *et al.* 2015; Talib, Daud, and Ibrahim, 1995).

Other risks of contamination during drying cocoa beans are from pathogenic bacteria, such as *Bacillus* sp. and *Salmonella*. While these are common pathogens in dried cocoa beans, the main concern is contamination with ochratoxin A (OTA) from *Aspergillus* species, which causes human health issues. There are no set guidelines for the limits of OTA in dried cocoa beans in the Fiji Islands. The optimum temperature conditions that have been identified for production of aflatoxins from mycotoxic mould is between 25 and 35 °C (Asis et al., 2002). Aflatoxin contamination can be avoided by drying the cocoa beans above 35 °C but not beyond 60 °C, as this could cause quality issues (Jinap et al., 1994). Drying treatment at 60 °C can rapidly reduce the moisture content of cocoa beans from 60% (w.b) to below 7% (w.b) but a_w is the critical control point for OTA. The isothermal conditions for limiting a_w to safe conditions can be achieved by lowering the RH to below 65% during drying between 40 to 60 °C (Koua, Koffi, and Ghaha, 2016). The low RH conditions could be effectively maintained by introducing a desiccant wheel integrated into a solar dryer design.

In tropical countries, drying and storage conditions for cocoa beans are at ambient temperature and RH. The beans are stored in jute bags. Temperature and RH fluctuations of ambient air, as well as localised re-wetting in cocoa beans during storage in jute bags and transport in shipping containers causes variations in a_w of cocoa beans. This leads to product instability caused by mould activity and enzymatic reactions in the bean. Oxidation of lipids can also cause off-flavours, which is detrimental to dried cocoa bean quality. Enzymatic reactions stabilises when a_w is between 0.45 and 0.20 at any given temperature.

Moisture sorption isotherm under ambient temperature was tested on unfermented cocoa powder by Sandoval and Barreiro (2002). The study used saturated salt solutions to equilibrate Venezuelan cocoa beans over mild temperature conditions (25 and 35 °C). The results of the study were fitted with Brunauer–Emmett–Teller (BET) model but the time required to reach a safe moisture content of 7.34 g water/100 g dry solid (a_w = 0.70) was not reported. Other studies conducted on moisture desorption for cocoa beans at a temperature below 30 °C used a type II sigmoidal isotherm, which represents a food matrix high in fat and starch. Koua et al. (2016) used Guggenheim Anderson de Boer (GAB) model to describe a sigmoidal type II desorption isotherm for cocoa beans between 30 to 60 °C. GAB models were able to accurately describe moisture isotherms up to a_w of 0.90 in this study. Similar temperature conditions were tested on West African cocoa beans from the Ivory coast by Akmel et al. (2015). The study also presented a type II sigmoidal sorption isotherm fitted with BET equation. These studies on moisture sorption isotherms describe the cocoa bean to be high in fat and starch content, which allows a better description of the food matrix for the drying kinetics.

In addition to GAB and BET models, modified Hasley, Henderson, and Chung equations are also used to describe moisture sorption isotherms in foods high in fat. Talib et al. (1995) used these new modified equations and reported a sigmoidal desorption isotherm on cocoa beans between 20-70 °C and at 30-90% RH. Model parameters were fitted to a fifth order polynomial with temperature variations but was not comparable to mid-temperature range (40-60 °C). Evaporation of volatile compounds and biochemical reactions may have caused fluctuations in a_w under these temperatures. The findings from this study concluded that moisture in dried cocoa beans were adsorbed in multilayers.

The type II sigmoidal sorption isotherm presented in these studies suggests presence of hydrophobic compounds, such as fat and starch in fermented cocoa beans. Hydrophobic components and sugar content show a strong influence on moisture desorption in cocoa beans. Composition of hydrophilic and hydrophobic components in the cocoa bean matrix changes with postharvest processing. Chemical constituents, such as starch and lipids influence water-holding properties. Starchy seeds are hygroscopic while seeds with high lipid content are non-hygroscopic. The equilibrium relative humidity (ERH) for seeds with high fat content is lower when compared to starchy seeds, as these seeds have more bound water when compared to seeds high in fat. Generally, cocoa beans have a lipid content between 40 to 55% per weight of cocoa bean (Afoakwa *et al.,* 2013; Torres-Moreno *et al.,* 2015).

Some studies suggest the GAB model to be the most suitable to describe moisture desorption in cocoa beans. Horta de Oliveira et al. (2011) modelled the moisture desorption isotherms of cocoa beans using the GAB model between 25 and 55 °C at 30 and 80% relative humidity (RH). Figure 2.2 shows a sigmoidal desorption curve, which is characteristic for a food material with hydrophobic compounds. The findings of the study suggested that fungal growth in cocoa beans can be minimised between a_w 0.30 and 0.70 in the multi-layer region of the bean. This implies that cocoa beans dried to an equilibrium moisture content (EMC) between 5 and 14% on a dry basis (d.b) reduces the risks from fungal growth. When EMC is converted to a wet weight basis (w.b) then these findings imply that a moisture content of 5 and 12% (w.b) is acceptable. The study also found that the RH of the drying system can be at 70% when the drying temperature is at 55 °C but when the temperature is at 30 °C then the RH should be below 60% (Figure 2.2).

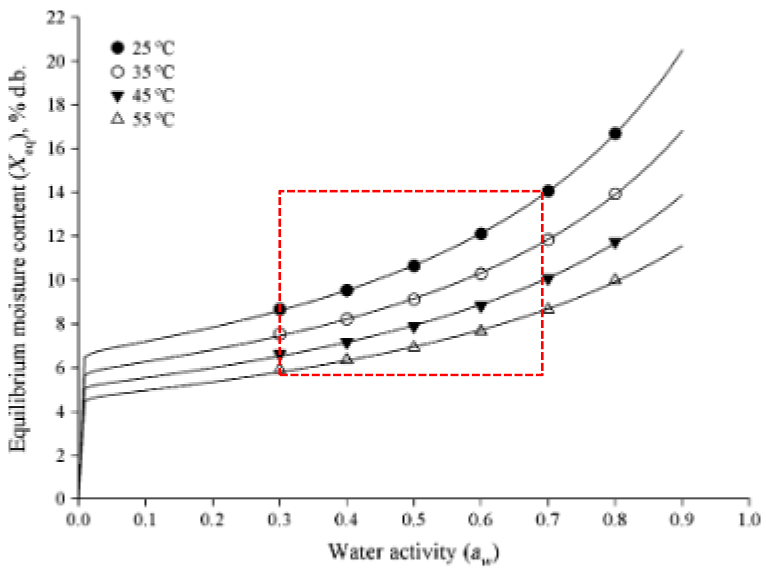


Figure 2.2. Moisture desorption isotherm for fermented cocoa beans. The isotherm is fitted with a GAB model at constant temperature conditions by Horta de Oliveira et al., 2011.

2.4. Solar dryer technology

Many studies describe various models of solar dryers as a cost-effective tool to dry a wide variety of crops. Solar dryers can operate effectively under Fijian climate conditions because of an abundance of solar insolation. On average, the solar insolation on a horizontal surface in Fiji is estimated to be around 5.4 kWh/m^2/day from historical data reported by Prasad et al. (2017). Seasonal variation affects the intensity of solar insolation during cocoa harvest season, where mid harvest season (May to July) has an average of 4 kWh/m^2/day and main season harvest (October to December) has 6 kWh/m^2/day (Johnston, 2004; Prasad *et al.*, 2017). Average solar insolation on a horizontal surface in Fiji over a period of ten years is presented in Figure 2.3. The data was obtained from Prasad et al. (2017). The high solar insolation (6 kWh/m^2/day) during main harvest is ideal for operating the solar collector system.

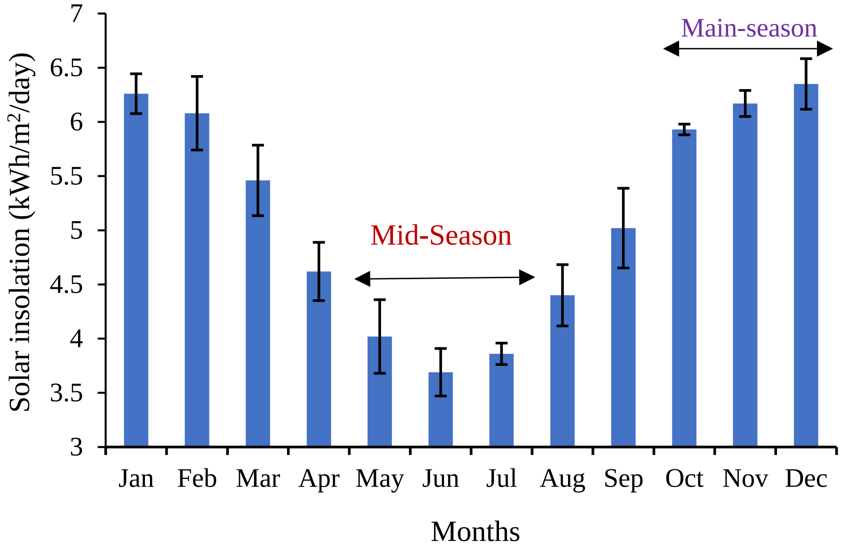


Figure 2.3. Average solar insolation on a horizontal surface in Suva, Fiji. The data presented is over a ten-year period (Prasad et al. 2017).

The basic solar dryer designs have three main components as shown in Figure 2.4; an enclosed drying chamber (1) with a drying shelf, an air flow system (2), and a solar collector (3) (Al-Juamily et al., 2007). Drying chamber size influences the drying efficiency. Heat transfer inside the drying chamber occurs through convection, conduction, and radiation. As the size of the drying chamber expands the temperature and humidity gradients along drying trays increases. Air flow through the drying chamber needs to be controlled to prevent condensation of moisture on the product.

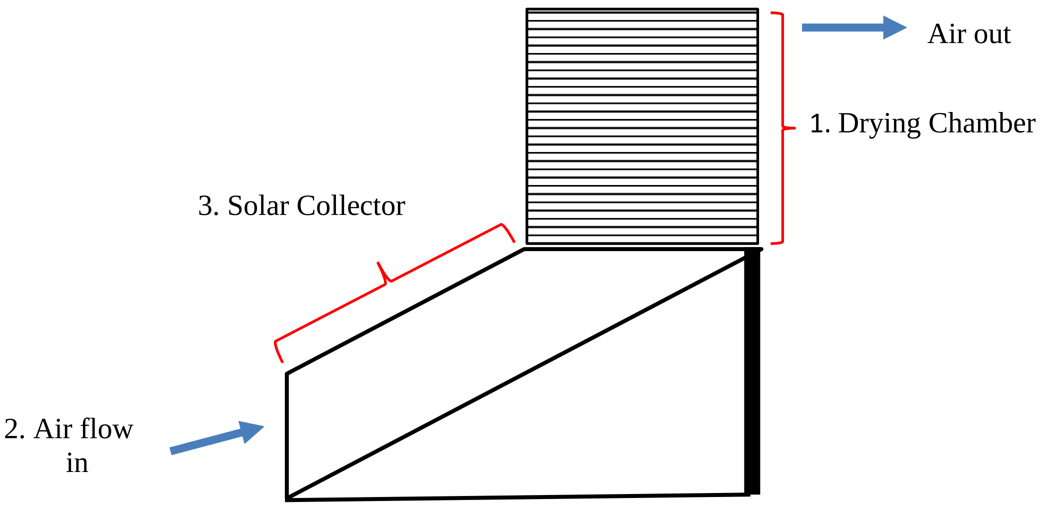


Figure 2.4. A schematic illustration of the components of a solar dryer.

There are various techniques of increasing air flow in the drying chamber to improve drying. Air flow in the solar dryers can be through natural (passive) or forced convection (active) using a fan or blower. In passive dryers, buoyancy-induced air pressure causes natural convection (Sharma *et al.*, 1986). Installing a chimney in passive solar dryers can improve air flow. A solar chimney of 12.3 m in height and 1 meter in diameter was fabricated from wood and fiber glass by Ferreira et al. (2008). Installing the solar chimney reduced the drying time for pre-treated coffee grains from 152 h to 72 h, tomato halves from 195 to 130 h, and for whole bananas from 193 to 139 h. The dryer temperature was 27 ± 2 ˚C and RH was 53% ± 4 with a mass flow of air at 1.40 ± 0.08 kg/s. The drying capacity for the solar chimney dryer was 440 kg in one drying cycle, where the product is dried on a single platform covered with plastic.

In dryers with forced convection, the drying rate increases (Mohanraj and Chandrasekar, 2009). Recent studies by Wang et al. (2018) and Rabha et al. (2017) found that forced convection was more effective in reducing moisture, retaining organoleptic quality, and improving drying rates when compared to natural convection during drying. Wang et al. (2018) improved dryer performance to industry standards by applying forced convection to the design. The thermal efficiency of this type of solar dryer was between 31 to 34% at a temperature of 52 °C. The study did not mention the actual air velocity but in another study on chilli peppers, an air velocity of 1.7 m/s at 57 °C showed a rapid drying rate (Rabha *et al.*, 2017). In addition to increasing the drying rate, forced convection can also be used to conserve energy by recycling exhaust air for drying by Janjai et al. (2009). The main problem in exhaust air is the high RH, which can be lowered through re-heating. Solar collectors can be used to re-heat the exhaust air. Other improvements made to the solar dryers could be to attach fans that are operated using a solar photovoltaic (PV) panel (Sakonidou *et al.*, 2008; Ferreira *et al.*, 2008). The combination of solar PV panel and collectors provides more control over drying.

2.4.1. Solar collectors

Solar collectors are mainly designed for heating fluids. Solar collectors can be non-concentrating (stationary) or concentrating. Concentrating collectors, such as parabolic trough collectors (PTC), can increase the temperature of ambient air to 80-105 °C (Kalogirou, 2004; Suman *et al.*, 2015). Drying time can be reduced by combining stationary (flat plate collector) and concentrating collectors (Ringeisen *et al.*, 2014; Stiling *et al.*, 2012; Ullah and Kang, 2017). However, direct drying under this high temperature range can have detrimental effects on the quality of thermally sensitive products, such as *Theobroma cacao* beans.

Many simple solar dryers have flat plate collectors (FPC) integrated in the design (Kalogirou, (2004) and Suman et al. (2015)). FPCs are a simple and cost-effective solar heating system that can heat any fluid up to 50-80 ˚C (Khola *et al.*, 2017). The main components of FPC are an insulating material, a glass cover, and a black absorber plate (Ekechukwu and Norton, 1997). The absorber is a flat metal sheet that allows efficient heat transfer to air by absorbing solar radiation. Metals with a high thermal conductivity (copper) are commonly used as absorbers but thermally conductive polymers can be a cheaper option. Heat transfer within the FPC can be increased by various modifications. Some suggestions to modify the flat plate collectors are given in Table 2.4. Since thermal losses by convection are greater in the absorber plate, structural modifications can be made to minimise these losses (Duffie and Beckman, 1974, Bracamonte and Baritto, 2013). Other factors, such as collector size, location, air velocity, air humidity, and temperature also influence the efficiency of FPC.

Table 2.4. A summary of modifications to a flat plate collector to improve heat transfer

Modifications to flat plate absorber plate	References
Integration of fins or corrugation	Pandey and Chaurasiya (2017)
Glass cover	Lingayat et al. (2017)
Double glazing	Lingayat et al. (2017)

2.5. Solar dryer designs

Solar dryers are designed to be either passive or active depending on air flow (Kumar *et al.*, 2016). Modifications to the dryer design can improve drying conditions and dried product quality. These designs operate based on direct and indirect solar radiation (Leon *et al.*, 2002). The design features of a direct solar dryer consist of an insulated drying chamber with a transparent polycarbonate or glass cover (Gatea, 2011; Chua and Chou, 2003). Drying occurs through convection and direct solar radiation. Solar radiation heats the drying air that is circulated either by natural or forced convection (Kumar *et al.*, 2016). Hot dry air and direct solar radiation increases surface temperature of the product to facilitate drying (Sharma *et al.*, 2009). Cabinet and greenhouse dryers are some commonly used direct dryers for a wide variety of agricultural commodities (Figure 2.5). The operating temperature for cabinet solar dryer is between 20 and 30 ˚C higher than ambient conditions (Minka, 1986).

Cabinet dryer designs are simple and economical. Design modifications, such as perforations for air vents to improve ventilation and replacing glass cover with a clear polyethylene cover are possible. Cabinet dryers can operate effectively under passive mode, which is an advantage for areas without electricity (Chua and Chou, 2003; Tiwari and Ghosal, 2005). While direct dryers are efficient and economical, the direct solar radiation can be detrimental to polyphenols. The direct effects of solar radiation on thermally sensitive products can be minimised by using an indirect solar dryer.

Figure 2.5. Simple solar dryers. A. Greenhouse type dryer and B. Cabinet dryer used for drying fresh fruits in the Fiji Islands (Raju, 2012). The greenhouse type dryer (A) is painted matt black and has a transparent polythene cover while the cabinet dryer (B) has a 3 mm glass cover.

Indirect dryers, as shown in Figure 2.6, mainly operate by convective heat transfer. Kumar et al. (2016) describes indirect dryers as having a separate collector and a drying chamber. The collector absorbs solar radiation and heats the circulating drying air (Sami *et al.*, 2011). This type of dryer has a versatile design but design modifications to improve air temperature and air flow decreases the drying efficiency (Hossain *et al.*, 2008). Some studies have reported increased drying rates for various products after design modifications with a conical collector and sensible heat storage (Toğrul and Pehlivan, 2002; Ferreira *et al.*, 2008; Vivek *et al.* 2015; Mohanraj and Chandrasekar, 2009; Vijayan *et al.*, 2016; Azimi *et al*., 2012). Re-circulating exhaust air through the drying chamber also enhanced dryer efficiency (Komilov *et al.*, 2009).

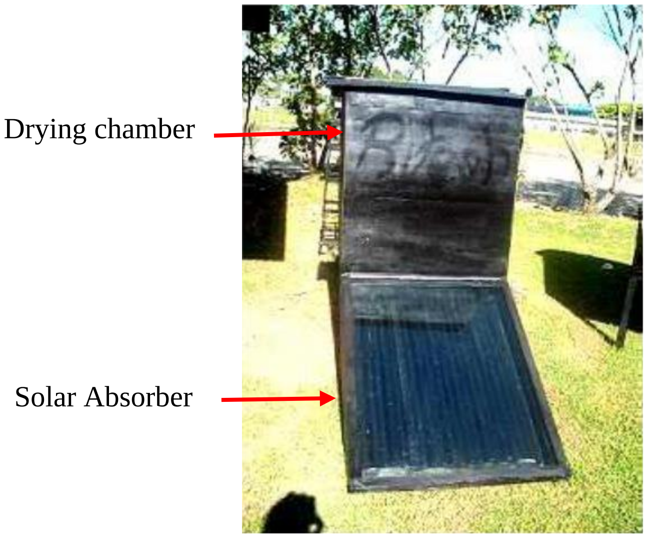


Figure 2.6. Indirect solar dryer. This type of design is used for drying fresh fruits in the Fiji Islands (Raju, 2012). The solar absorber has a 3 mm glass cover and a corrugated iron base, which is painted matt black.

An indirect dryer is suitable for drying thermally sensitive cocoa beans. When considering this design, it is important to understand the extent of variability in the drying rates for all cocoa beans in a batch. Variability in the drying conditions inside indirect dryers have been reported by several studies. Uneven heat distribution within the drying chamber of a simple indirect dryer was experienced by Janjai et al. (2009) when drying banana slices. Banana slices on the bottom tray, which was closer to incoming hot air, dried faster when compared to slices on upper trays near the air outlet. Overheating was also another problem in indirect dryers and this increased. Irregularities in air velocity between trays closer to air inlet (1.10 m/s) and trays nearer to the air outlet (0.28 m/s) caused variability in the drying rate of products at constant temperature. Misha et al. (2015) recommends controlling air velocity, humidity, and temperature conditions in the indirect dryer as these variables significantly influence the drying process.

Another suggestion in literature is to conserve heat, as drying can be an energy intensive process. Re-circulating of exhaust air has been used to conserve heat energy in some dryers. However, the high humidity could delay drying and vitiate product quality from mould growth (Abasi *et al.*, 2016). In some cases, recirculating exhaust air conserved energy by 29 to 31% for copra and cocoa in Trinidad after six hours of continuously venting humid air (McDoom *et al.*, 1999). However, the study did not report the effects of this drying condition on dried product quality. High RH in exhaust air can have drastic effects on the polyphenol content in cocoa beans. Kyi et al. (2005) found that drying cocoa beans between 40 to 60 °C at 50 to 80% RH deteriorated the polyphenol content. This suggests that the RH of air should be below 50% to minimise oxidation of polyphenols. Integrating a solid desiccant into the dryer design can dehumidify the air and lower the RH for drying.

Dehumidification of drying air can improve the drying regime and dried product quality (Madhiyanon *et al.*, 2007). In Malaysia, dehumidification of the air stream at 55 °C improved the organoleptic quality of dried Malaysian cocoa beans in a dryer with a heat pump (Hii *et al.*, 2011). The study found that the step-up drying technique using a heat pump demonstrated better Malaysian cocoa bean flavour profiles, which was comparable to Ghanaian cocoa beans. Similar findings were reported by Giacometti et al. (2015). The step-up drying technique involves a gradual increase in air temperature during the drying process. The integration of a heat pump in the dryer dehumidified the ambient air and reduced the drying time. While this technology is effective for dehumidification, it can be costly for cocoa farmers in villages with unreliable supply of electricity. A more feasible option is the application of a rotary desiccant wheel with solid desiccant material operated using solar energy.

2.6. Desiccant technology

Recent studies suggest integrating a desiccant wheel (DW) to the solar dryer to improve drying conditions. The solid desiccant material can improve the drying kinetics by lowering the RH of air. The commonly used solid desiccant material in DW is silica gel, which is deposited within a honey-comb structure of the DW. Solid desiccants desorb moisture from ambient air for drying (process air). Moist desiccant can be regenerated by a desorption process using hot air between 60 and 100 °C. Regenerated silica gel can be reused for dehumidification for the next drying cycle. A low-cost technique to increase ambient air temperature for desiccant regeneration is to use a solar collector train. This consists of a flat plate collector attached to a parabolic trough collector. A schematic design of this solar collector system is presented in Figure 2.7. Ambient air is heated between 60 and 100 °C using solar collectors (1). The regenerated section of DW (2) is used for dehumidification of ambient air. Moisture from the air is desorbed by silica gel in DW and the air temperature increases slightly through sensible heating. The dehumidified air (process air) is used for drying cocoa beans in the drying chamber (3). The regeneration exhaust air from DW (2) has thermal energy that can be re-cycled through the solar dryer system, either for re-heating air for desiccant regeneration (1) or for warming the wet cocoa beans for drying (3).

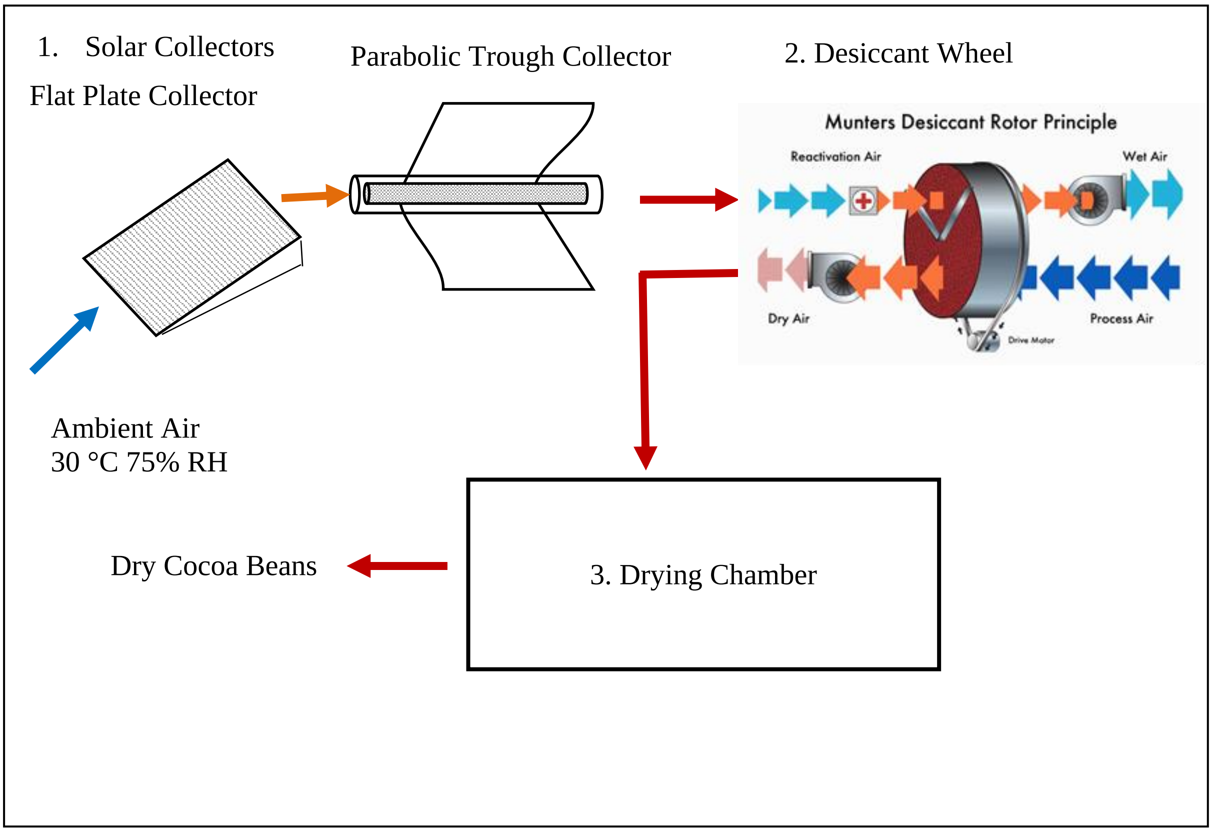


Figure 2.7. A schematic illustration showing air flow through a solar dryer with desiccant wheel

Desiccant technology has been used effectively as an energy efficient and a cost-effective option for dehumidifying air for drying (Thoruwa *et al.*, 2000; VijayaVenkataRaman *et al.*, 2012; Madhiyanon *et al.*, 2007). Several studies have recommended integrating a desiccant system with a solar dryer to control drying conditions, especially for thermally sensitive products (Misha *et al.*, 2012; Misha *et al.*, 2015; De Antonellis *et al.*, 2012). This equipment is not popular with small scale farmers due to the high cost. Low-cost adsorbents, such as silica gels, bentonite, calcium chloride, and kaolinite-calcium chloride have been recommended by Murthy (2009) and Thoruwa et al. (2000) to make this technology affordable for farmers and cocoa processors. Another option is the application of molecular sieves for drying. Dina et al. (2015) demonstrated the impact of integrating desiccants with thermal storage into a solar dryer for drying Indonesian cocoa beans. The desiccant thermal storage materials used were molecular sieves 13 x ($Na86[(AlO_2)86.(SiO_2)106].264H_2O$) and calcium chloride ($CaCl_2$) The drying curves presented in Figure 2.8 demonstrate that continuous drying with desiccants improved the drying time for Indonesian cocoa beans when compared to sun drying. The solar dryers operated without desiccants during the day and were dried with the thermal storage material during the night for extended drying.

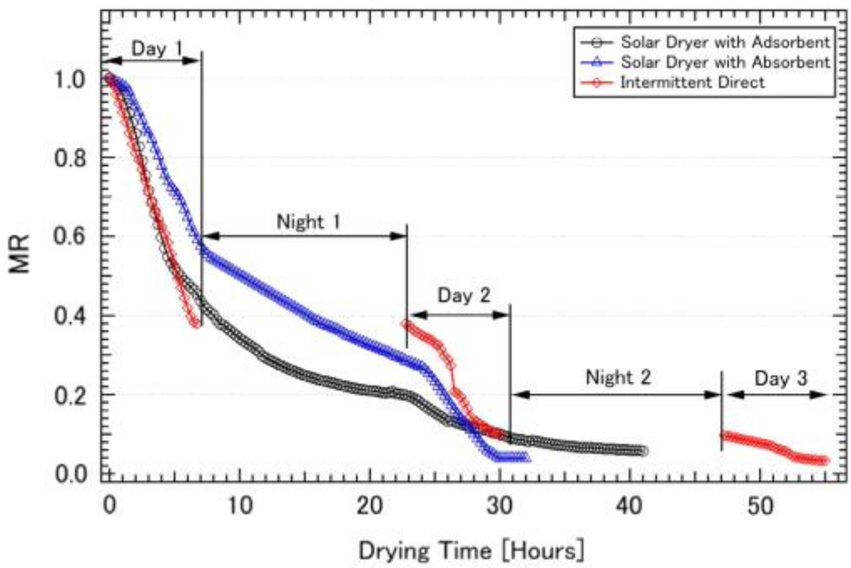


Figure 2.8. Drying curve for Indonesian *Theobroma cacao* beans from a study by Dina et al. (2015). Indonesian cocoa beans were dried under three different conditions. Intermittent direct drying, presented in red shows sun drying, while solar drying with dehumidification is represented by black and blue data points.

Several studies also suggest designing molecular sieves from renewable biomass, such as coconut coir, activated carbon, zeolites, molecular organic frameworks (MOFs), and polymers as an alternative to silica gel (Rawangkul *et al.,* 2010; Asim *et al.,* 2015; Wang *et al.,* 2013; Sharma *et al.,* 2016; Khedari *et al.,* 2003). Information on efficiency of desiccants derived from natural sources is limited in published literature. Therefore, silica gel was considered as the most cost-effective solid desiccant by various studies for efficiently dehumidifying process air.

Operational factors, such as air velocity, regeneration temperature and wheel rotation speed, are critical for optimal performance of DW and limiting energy consumption (De Antonellis *et al.*, 2016). In addition to these operational factors, air channel depth, adsorption isotherms, specific heat, and thermal conductivity are fundamental for heat and mass transfer models for the DW (De Antonellis *et al.*, 2015; Mandegari *et al.*, 2017). The heat transfer area is influenced by the thickness of DW, and this also affects dehumidification and DW performance (Kang and Lee, 2017).

The performance of the DW, as well as temperature and RH variations can be predicted and described using well developed mathematical models. The drying behaviour and variations in drying parameters are described by semi-theoretical models but these models cannot accurately predict the drying time and drying kinetics on the quality outcomes in cocoa beans. Studies in literature identify mechanistic models as a more suitable tool for describing the drying behaviour of cocoa beans. Currently there has not been any study that has developed a mechanistic model by integrating the desiccant wheel operating conditions under the Fijian climate on cocoa beans. This study is the first to report a drying model designed to predict the drying kinetics of Fijian cocoa beans under ambient conditions in Fiji. This model could be useful to predict the drying conditions to achieve export quality cocoa beans despite batch-to-batch variations and poor weather conditions.

2.7. Mathematical models for solar drying

Mathematical models can be used to identify the best operating conditions and to estimate the drying time for sun or solar-dried products (Adrover and Brasiello, 2020). In solar dryers, the heat and mass transfer occur simultaneously. Therefore, drying models need to solve the governing heat and mass transfer equations simultaneously. There are many semi-theoretical equations developed to predict the drying time and moisture content in cocoa beans. Some of these models also predict moisture loss during the overnight resting period (tempering) (Nwakuba, Ejesu, and Okafor, 2017; Hii, Law, and Cloke, 2009). Semi-theoretical models, such as the Newton, Page, as well as Henderson and Pabis model, and two term models are unable to describe the physical meaning of the drying process. These models do not consider bean geometry in the drying equation.

Drying models in literature mainly use spherical geometry for cocoa beans. Some studies also use an ellipsoidal geometry to model the drying kinetics for cocoa beans (Adrover and Brasiello, 2020; Komolafe *et al.,* 2021; Hii *et al.,* 2013; Páramo *et al.,* 2010). Heat and mass transfer during drying can be solved by model equations using ordinary differential equations (ODEs) or partial differential equations (PDEs). ODEs consider a single variable in the drying equations and therefore are limited in describing the drying process mechanistically. PDEs consider multiple variables to solve drying equations with spatial and temporal discretization. There are various numerical methods used to solve PDEs, such as the finite element methods (FEM), finite difference method (FDM), and finite volume methods (FVM).

Few studies have reported the use these numerical methods on cocoa beans. Adrover and Brasiello (2020) solved a 3-dimensional (3D) moving boundary numerically using a finite elements method (FEM), while Komolafe et al. (2021) solved the heat and mass transfer numerically for a 3D ellipsoidal cocoa bean using the finite volume method (FVM). A 3D approach is more complex when compared to solving one dimensional model for a spherical geometry. For simplicity, a one-dimensional model was developed in this study. In this case, the numerical method used was FDM to convert PDEs from non-linear to linear equations using matrix algebraic equations. FDMs use derivatives with finite differences to solve differential equations.

The FDM method was used by Hii, Law, and Cloke (2009) to develop a one-dimensional model for variable moisture diffusivity in Malaysian cocoa beans in a hybrid heat pump dryer. The model assumed that the cocoa beans were spherical in shape. Fick's second law was used for moisture diffusion, which was discretized using time intervals and bean radius. Explicit finite difference method with 0.01 h time step was used to solve the model. A grid with 20 subdivisions of the radius was considered.

In drying models, the shape of these cocoa beans can be approximated to be spherical with a sphericity value of 0.57-0.6 (Bart-Plange and Baryeh, 2003; Sandoval *et al.*, 2019). The sphericity of cocoa beans is measured using bean length, width, and thickness (Bart-Plange and Baryeh, 2003). Moisture diffusion and internal temperature distribution within a spherical particle can be solved numerically using FDM with an implicit scheme to discretise the governing heat and mass equations. Several studies demonstrated the use of this technique on spherical food products (Arunsadeep *et al.,* 2018; Arunsadeep and Chandramohan, 2018;

Hussain and Dincer, 2008).

Heat and mass transfer is controlled by the drying temperature. Mass transfer within the multilayers of cocoa beans can estimated by effective diffusivity (D_e). The effect of various temperature condition on the D_e of fermented cocoa beans from literature is provided in Table 2.5. The effective diffusivity of moisture in cocoa beans increases with an increase in the drying temperature. Thickness of the drying bed and cocoa bean is also another factor that would affect effective diffusivity.

Table 2.5 Influence of temperature on effective diffusivity of *Theobroma cacao* beans

Temperature (°C)	Drying Technique	Effective Diffusivity D_e (m^2/s)	Air velocity m/s	References
30	Sun drying	3.70×10^{-11}	0.76-1.21	Clement et al. (2009)
55	Heated batch dryer	3.62×10^{-10}	2.51	Ndukwu, Ogunlowo, & Olukunle, (2010)
70		8.98×10^{-10}		
81		9.98×10^{-10}		

Drying models for *Theobroma cacao* beans dried under low RH conditions at moderate temperature are limited in published literature. While various thin layer mathematical models for a variety of agricultural products have been reported widely in scientific literature, these models are limited to non-isothermal conditions. Mechanistic models are complex and can describe drying in several layers of the food particle. Additionally, a wide range of input variables are considered in mechanistic model equations when compared to semi-empirical models. This allows mechanistic models to be useful in improving the scientific understanding of dehydration and for optimising drying conditions for a better process control in the product.

A model for convective drying of Forastero variety of *Theobroma cacao* beans from Amazon was developed by Hermal et al. (2018). Multiple input variables were considered in the model for developing drying equations. These factors were the physical characteristics of the cocoa bean, moisture sorption isotherms, drying conditions, and heat and mass transfer principles.

Drying experiments were conducted in a laboratory scale convective dryer that was designed in the shape of a loop with wood and PVC duct as shown in Figure 2.9. Experimental drying of fermented Amazonian cocoa beans was conducted in this dryer at 30 °C, 40 °C, and 60 °C. The mathematical models were comparable to the drying curves as demonstrated in Figure 2.10.

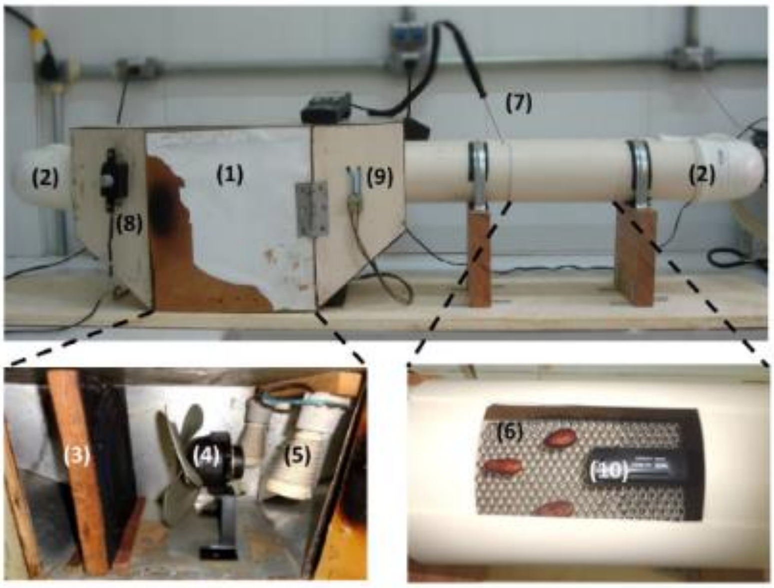


Figure 2.9. Convective dryer designed by Herman et al. (2018). The dryer design shows the 1 – Chamber; 2 – PVC duct; 3 – silica compartment; 4 – fan; 5 – heating elements; 6 – metallic tray; 7 – thermal anemometer; 8 – fan power regulator; 9 – heating elements power regulator; 10 – USB humidity and temperature probe.

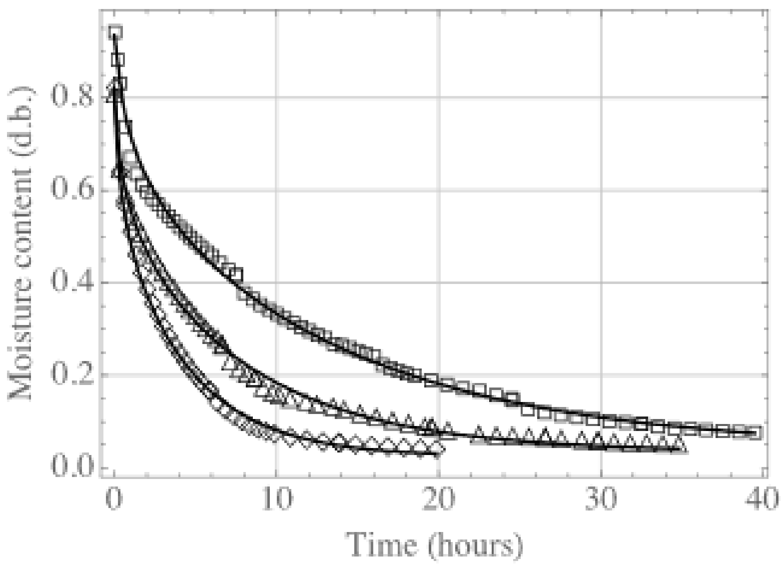


Figure 2.10. Drying curves for *Theobroma cacao* beans adapted from a study by Herman et al. (2018). The graph shows cocoa bean moisture content as a function of drying time (h). The drying curves for 30 °C (squares), 40 °C (triangles), and 60 °C (diamonds) are presented in the graph. The model output for drying regime is represented by solid lines.

2.8 Conclusion

The review of literature suggests that the problem of high RH limiting the drying potential in tropical countries, such as Fiji can be solved by using desiccant technology. There is sufficient evidence published in scientific literature that demonstrates an improvement in the drying kinetics when the RH is decreased. Moisture sorption isotherms for *Theobroma cacao* beans show that the cocoa beans need to be dried to a_w of less than 0.65 for safe storage. A better control of RH in a solar dryer can be established by using a desiccant wheel, which can be easily operated in Fiji using solar energy. The high average solar radiation 5 kWh/m^2/day can be used to operate the rotary DW and to provide the thermal energy using a solar collector system to regenerate the solid desiccant material.

The impact of low RH drying conditions on key bioactive components and moisture content in cocoa beans has not been fully understood. Another gap in scientific literature is the lack of mechanistic models to describe the drying kinetics under low RH conditions. Mechanistic models have been suggested by several studies in literature as a useful tool to predict the drying kinetics for cocoa beans. The conditions in Fiji make it possible to test the concept of integrating a DW into a solar collector system for drying cocoa beans. This study is one of the first to test the drying conditions and to develop a mechanistic drying model with DW conditions for predicting the drying kinetics of Fijian *Theobroma cacao* beans. The model would be useful to advising the cocoa farmers how to control the drying conditions and to predict the drying time required to produce a superior quality of dried cocoa beans for export.

Chapter 3 Drying experiments on *Theobroma cacao beans*

3.1 Introduction

Theobroma cacao beans are commonly sun-dried in the open around the world. The main quality problem in sun-dried cocoa beans is mould growth from slow moisture evaporation. Solar dryers can solve the problem of reliable drying conditions but the relative humidity (RH) in the drying chamber remains high. A possible solution to reduce drying time is to integrate the solar dryer with dehumidification technology for Fijian cocoa farmers in remote locations. The temperature of the drying air stream in the solar dryers increases during the solar cycle. Temperature controls the drying rate and water activity (a_w) of the product during initial stages of drying (Afoakwa *et al.,* 2012). However, temperature and air flow are unable to expedite the drying process during the final stages of drying when the internal resistance to moisture diffusion within the food particle dominates the drying process. Dehumidification of the drying air stream is critical for improving the drying rate during final stages of drying.

Moisture sorption isotherms discussed in chapter 2 also provide further insight into the ideal drying conditions for a shorter drying time and better cocoa bean quality. Cocoa bean drying reaches an equilibrium under a certain relative humidity of drying air in the dryer where the final moisture content of dried beans is the equilibrium moisture content (EMC). The relationship between the RH of drying air and a_w could be described by moisture sorption isotherms. Moisture sorption isotherms for cocoa beans from other countries have been reported at various temperature and RH conditions. These reported isotherms were used as references to determine the possible mild temperature drying conditions (Temperature and RH) in Fiji. The impact of drying temperature on sorption isotherms is negligible when the temperature difference is less than 10 °C (Akmel *et al.,* 2015).

Drying experiments on Fijian cocoa beans were conducted to test the ideal temperature and RH conditions from sorption isotherms on the drying kinetics. Experimental data was used to validate a drying model in chapter 4. Drying experiments were conducted in Fiji using a custom-made dryer for testing the RH and temperature variations on fermented cocoa beans of the Forastero variety.

3.2 Materials and Method

A pilot scale dryer was fabricated at Massey University in New Zealand for drying ten kilograms of wet fermented cocoa beans in Fiji. The customised dryer was designed to test the selected drying conditions on moisture and polyphenol content of cocoa beans. Heat and mass transfer equations were used to determine the design features of the dryer. Forastero variety of cocoa beans were used for the drying experiments. These were sourced and fermented for six days at the Fiji Ministry of Agriculture research station (Kasavu). The moisture content was estimated by measuring weight loss during the uninterrupted drying trials. Dehumidified conditions were maintained using silica gel as the solid desiccant material.

3.2.1 Dryer design

Data on ambient conditions (solar radiation, air temperature, and relative humidity) obtained from the Fiji meteorological office archives were considered for dryer design calculations. A simple indirect solar dryer design retrofitted with desiccant wheel (DW) technology was considered. Iterative conceptual design improvements using calculations were developed using MS Excel Solver®. The current dryer design concept was theoretically designed to handle 100 kg of wet fermented *Theobroma cacao* beans based on equations by Duffie and Beckman (1974). Based on these parameters, the design can be scaled down to facilitate a dryer for 10 kg of wet fermented cocoa beans. While other dimensions, such as height, width, and tray number were scaled down, the length of the customised drying chamber remained at one meter to understand the issues with moisture transfer and condensation along the drying chamber during drying.

The dryer was customised to control temperature, relative humidity (RH), and air flow. Figures 3.1 and 3.2 shows several key components of the bench top dryer. The design concept was adapted from Hossain et al. (2016) and modified by retrofitting with a one-kilowatt (kW) heating element with fins connected electrically to a Proportional Integral Derivative (PID) controller to control temperature. Dryer inlet temperature was monitored with a calibrated K-type thermocouple as a sensor. PID controllers set the process temperature to a desired setpoint and can automatically adjust temperature of the drying system. This is achieved by the PID controller by calculating the response required from the control element, such as a heater. In this study, PID was also used to control air velocity by regulating fan speed. The PID controller was developed by a qualified electrician at Massey University specifically for the heating element and 12V DC fans (120 mm) in the dryer.

Figure 3.1. PID controller used for controlling drying temperature and fan speed. Internal components show a plug pack to supply electricity to operate three 12V DC fans.

The air flow was considered for a drying chamber inlet with a cross-sectional area of 0.22 m^2. Drying chamber inlet was fitted with a perforated aluminium sheet with 1 mm perforations for laminar airflow through a 0.20 m plenum and to the drying shelves. The drying shelves (0.38 m^2) with seven trays (0.36 m^2) were suspended from a spring balance. The drying chamber (1.0 m x 0.38 m x 0.55 m) was constructed using 10 mm marine ply. Other design factors considered for this dryer were adapted from Loesecke (1955).

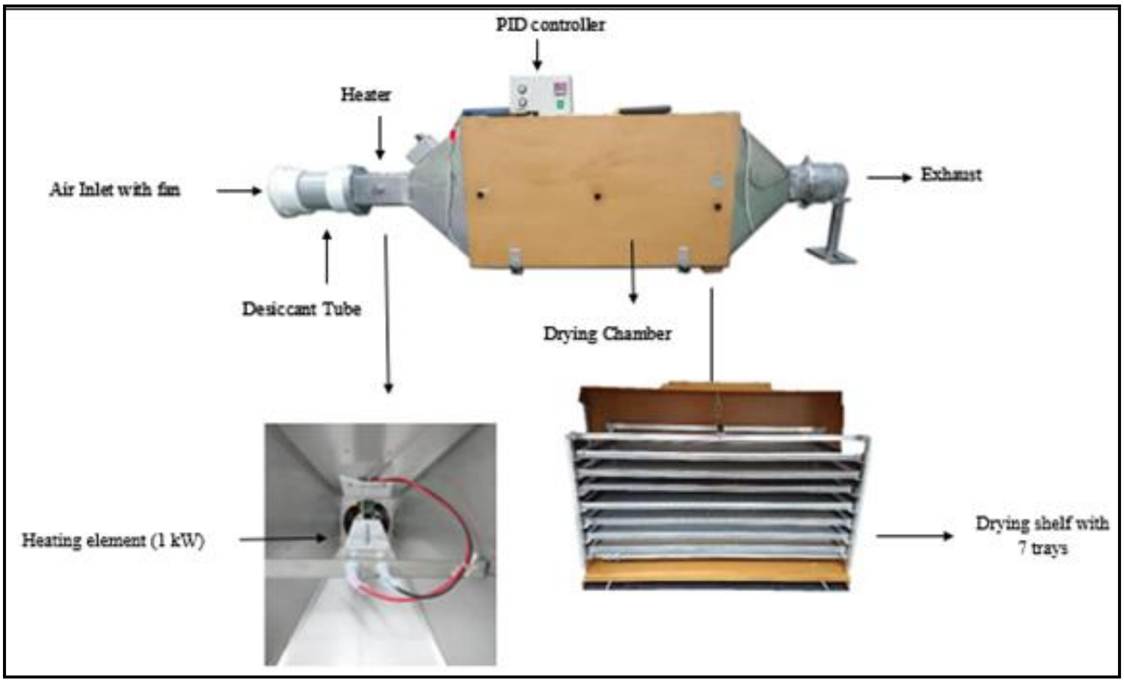


Figure 3.2. Design of a customised dryer for drying experiments on fermented Fijian *Theobroma cacao* beans.

The dryer in Figure 3.2 was equipped with a 12V DC inlet fan to direct air flow over a desiccant tube with 4 kg of silica gel. Dehumidified air was heated to treatment temperature using a 1 kW heating element with fins. Hot dehumidified air was pulled into the drying chamber by another 12V DC fan for drying cocoa beans. Exhaust air was pushed out by a series of two active fans with a stator (stationary fan) in the middle. The stator maintains a steady air flow out of the drying chamber.

During the drying tests, the dryer inlet air temperature was kept constant, but air temperature decreased along the length of the drying chamber. The RH was controlled by the desiccant material. Four kilograms of self- indicating silica gel with a particle size of 2-5 mm from Labco® was used for dehumidification. Quantity of desiccant material and rotation times were used to control RH during drying process to dehumidify air.

A schematic illustration of the dryer design is presented in Figure 3.3. The dryer was designed for 10 kg of fermented wet cocoa beans with a drying chamber (0.55 m x 0.38 m x 1.0 m), a desiccant tube (0.20 m^2) with a length of 0.22 m. The design also included a heating element and 12V DC inlet and outlet fans. Air flow within the drying chamber was estimated to be 0.08 to 0.1 m^3/s. Air flow through the heating element and drying chamber was generated from 12V 380 mA Sirocco® fans (model YX2522, Taiwan).

Fermented cocoa beans of the Forastero variety were sourced from Naduruloulou research station, Ministry of Agriculture in Suva, Fiji. Drying experiments were conducted in the customised bench scale dryer, fabricated at Massey University in New Zealand, and transported by freight to the Institute of Applied Sciences (IAS), USP in Suva, Fiji Islands.

Wet fermented cocoa beans (6 ± 1 kg) were loaded and dried on horizontally stacked drying trays in the dryer. The drying trays (0.4 m x 0.8 m) were made from perforated aluminium sheets and shelf brackets from aluminium angles (25 mm x 25 mm) and frames using aluminium T- track (30 mm x 12.8 mm). The drying shelf was attached to a spring balance (max 32 kg) using an S-hook, which was attached to a heavy-duty stainless eye bolt (6”). The hanging scale extended up to a meter. Details of the materials used for fabrication are provided in Table 3.1.

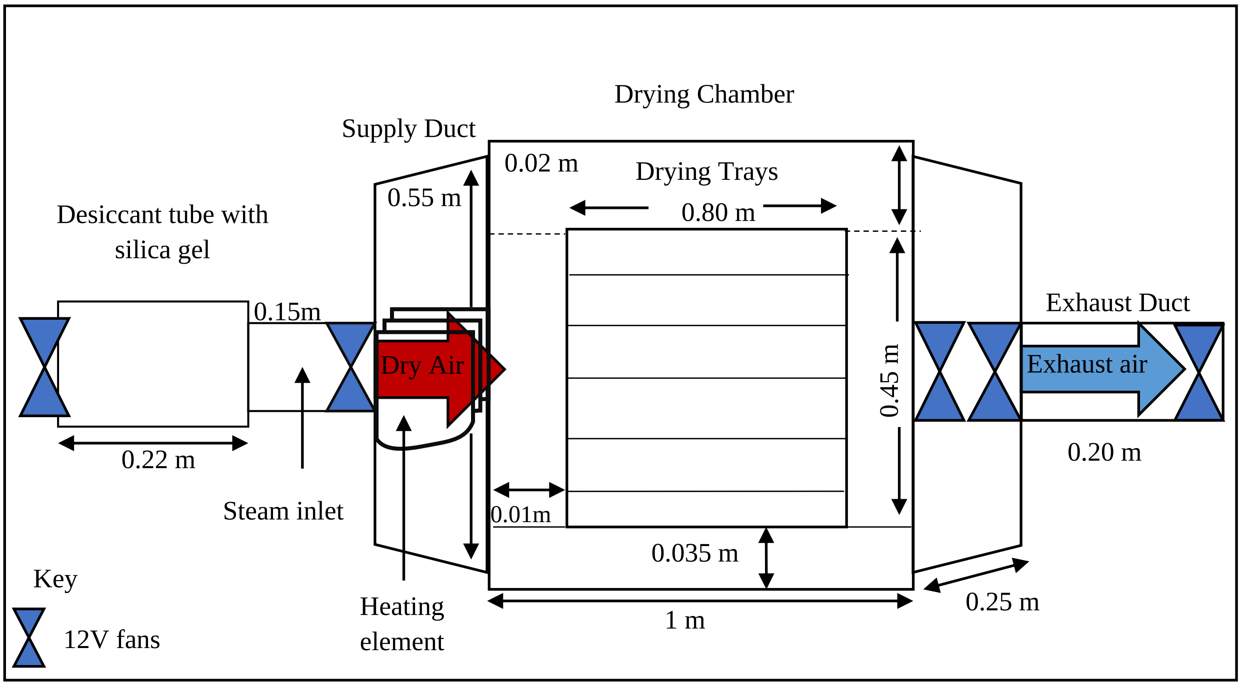


Figure 3.3. A schematic illustration of the experimental drying chamber for drying tests on fermented Fijian *Theobroma cacao* beans.

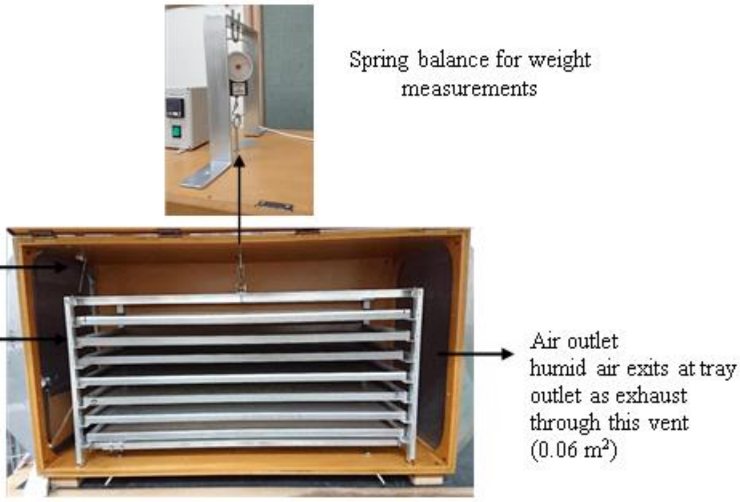


Figure 3.4. Drying chamber of the customised dryer for Fijian *Theobroma cacao* beans showing seven drying trays suspended from a spring balance.

During drying, the inlet air was pushed through the desiccant tube containing four kilograms of silica gel using 12V DC fan to the drying chamber. Each drying tray on the drying shelf had a gap of 0.03m for air flow. Air flow was encouraged through the sides and bottom of drying trays by leaving some space between the drying shelf and dryer wall. The spacing between drying tray and drying chamber walls near dryer inlet and outlet was 0.01 m. When the tray was suspended with no load, the space at the bottom was 0.035 m and spacing at the top was 0.02 m. When wet product was loaded on trays, the drying shelf extended towards the bottom. There was a gap of 0.01 m at the bottom while spacing at the top increased to 0.045 m. The variations in spacing would have occurred throughout the drying run as the metal expanded and contracted due to heating and cooling.

Drying air stream throughout the drying chamber was pushed through the flanges leading to the drying chamber inlet. Humid exhaust air out of the drying chamber was pulled out through the flanges using fan forced convection. The flanges shown in Figures 3.3 and 3.4 are 0.25 m in length and are found on the sides of the dryer. An exhaust pipe made from steel extended out of the exhaust flange from the dryer outlet. This exhaust pipe was fitted with three fans to facilitate flow of humid exhaust air out of the drying chamber. A stator (immobile fan) was inserted in the centre of the exhaust duct to maintain consistent air flow through the drying chamber.

Table 3.1. Design specifications for experimental dryer

Components	Descriptions	Material	Specifications	Manufacturer
Perforated sheet	R-2 mm T-3 mm	Aluminium	Perforated sheets	Massey University
Heating element	Strip heater, flat bracket	Stainless steel	1 kW, 230 V ac Manufacturer part No. RA 4080 1000 Length- 325 mm	Acim Jouanin, France
Drying chamber	1.0 m x 0.4 m x 0.6 m	Marine-grade plywood	Wall thickness 25 mm	Massey University
Desiccant tube				Massey University
Silica gel	2 to 5 mm	Silica	(CAS No. 112926-00-8)	Thermo-Fisher/ Labco
Drying Shelves	0.4 m x 0.8 m			Massey University
Drying Tray	7	Aluminium extrusions		Massey University
Fans	Sirocco fans		3 m/s	Sirocco

3.2.2 Drying experiments on cocoa beans

Drying experiments were conducted on Fijian cocoa beans (var. Forastero). The cocoa beans were fermented for six days in a shallow wooden box (0.30 m depth) under ambient Fijian conditions. A cut test was used as a visual parameter to assess colour change in the cotyledon during fermentation as a quality control measure. The fermented beans were gently washed to remove pulp remnants and excess mucilage. The quick and gentle washing process showed little difference in the moisture content (57 to 60% w.b). Washing is common in Samoa and Ceylon after fermenting robust flavoured Trinitario cocoa beans.

In Fiji, Trinitario and Forastero variety of cocoa beans are also washed after fermentation.

Hall (1914) explains that while washing does not affect the price of dried cocoa beans, it may cause loss in weight or flavour in finer varieties of Criollo beans. Loss of flavour caused by washing was reported in South American Criollo beans but an improvement in astringency of washed and dried Samoan Trinitario beans was noted (Chatt, 1953). Additionally, washing removes excess pulp and debris, which gives a cleaner appearance to dried seed coat.

Six drying runs at 45 °C and six drying runs at 55 °C was tested with RH maintained nominally at below 20%. Drying tests were terminated when the cocoa beans reached a constant weight, which was calculated to be the weight for the product to reach a final moisture content around 7-10% (w.b).

Moisture content in the cocoa during the drying experiments were calculated at hourly intervals based on weight difference over the drying time. The formula used to calculate the moisture content on a dry weight basis was:

$$\text{Moisture content dry basis (kg water/kg dry matter)} = \frac{\text{Wet moisture content (\%)}}{(100 - \text{Wet moisture content (\%)}} \quad (3)$$

The moisture content of the dried samples was determined gravimetrically. The procedure was adapted from AOAC 931.04 for cocoa beans. The dried cocoa bean samples were ground and then weighed (5-10 g) in pre-weighed and pre-dried moisture cans. The samples were dried in an oven set at 105 °C until constant weight. The equation given below was used to determine moisture content on a wet weight basis in fresh and dried cocoa beans.

$$\text{Moisture content (\%)} = \left(\frac{\text{Weight of wet sample (g)} - \text{Weight of dry sample(g)}}{\text{Weight of wet sample (g)}}\right) \times 100 \quad (4)$$

The moisture content on a dry weight basis was considered in the calculation for mass balance in the cocoa beans during drying on the drying tray. The equation is a numerical expression of mass transfer between the bean surface and air based on the bean size and mass transfer coefficient at the drying temperature. Parameters, such as air velocity, temperature, and RH were measured and recorded using pre-calibrated data loggers at various positions (Table 3.2) around the drying chamber.

Table 3.2. Sampling locations in the drying system for air velocity, temperature, and RH

Sampling locations	Air velocity	Temperature	Relative humidity
Dryer inlet	✓	✓	✓
Dryer Exhaust	✓	✓	✓
Drying tray inlet	✓	✓	✓
Drying tray centre	✓	✓	✓
Drying tray outlet	✓	✓	✓
Top tray inlet		✓	✓
Top tray centre		✓	✓
Top tray outlet		✓	✓
Middle tray inlet		✓	✓
Middle tray centre		✓	✓
Middle tray outlet		✓	✓
Bottom tray inlet	✓	✓	✓
Bottom tray centre	✓	✓	✓
Bottom tray outlet	✓	✓	✓

Details and specification of temperature and RH measurement equipment are given in Table 3.3. Temperature and RH data from these loggers were acquired using software TracerDAQ® from Measurement and Computing, USA. The data loggers measured air temperature in the dryer using K and J type thermocouples. Temperature and RH measurements were recorded at every two second interval for each drying run at 45 and 55 °C. Method validation on rehydrated *Theobroma cacao* beans of Trinitario variety from Ghana demonstrated that this experimental approach adapted from various studies by Nimrotham et al. (2017), Catalano et al. (2008), Brewer and Butt (1950) and Suma et al. (2013) was effective for a small-scale drying system with humidity control.

Table 3.3. Specifications for equipment used for measuring air velocity, temperature, and RH of air during drying

Parameter	Description	Equipment Model	Supplier, city	Accuracy and range
Air velocity	Hot wire anemometer	Dwyer 471B-1 hot wire anemometer	Michigan	Accuracy ± 3%
Temperature and RH	Dual temperature and RH logger with K type thermocouple	Center 314	Auckland	Temperature 200 - 1370 °C humidity 0-100%
	32-channel data logger for temperature and RH	Omega OMB-DAQ-2416	UK	Range ± 10 Vdc Accuracy ± 4.0 LSB
	J type thermocouples inserted into data logger	model HH374,	USA	± 0.47 to 1.46
	RH sensors	model HIH-4000-004	Honeywell, USA	± 3.5 %

3.2.3 Statistical analysis of data

Sample sizes for drying runs were small (6 ± 1 kg), therefore statistical analyses were conducted to compare means of different treatment groups based on sample size using ANOVA general linear methods on Minitab. Treatment conditions with the lowest drying time and final dried moisture content were identified based on the differences between means using t-test.

3.3 Results and discussions

The drying treatments for fermented *Theobroma cacao* beans consisted of pre-conditioning at a constant temperature (44 °C) and RH (36-38%). The pre-conditioning step was also considered for preserving the thermally sensitive bioactive components in cocoa beans. Kyi et al. (2005) recommends reducing the drying temperature to less than 60 °C and RH to below 50% for drying cocoa beans. These conditions decreased the deterioration of polyphenols. Pre-conditioning phased was followed by overnight resting under ambient conditions. The overnight resting period is also known as tempering. The process of tempering allows moisture re-distribution within a batch of partially dried cocoa beans. Tempered cocoa beans were dried under low RH at constant air temperature during the second drying cycle. The concept of pre-conditioning was used to recycle heat from the desiccant wheel (DW) regeneration exhaust. In the theoretical design the regeneration exhaust is mixed with ambient air to lower the air temperature. The impact of these drying conditions on the moisture loss in cocoa beans, as well as temperature and RH profile of the drying air stream in the drying chamber is presented in this section.

3.3.1 Drying experiments on cocoa beans

During pre-conditioning, wet fermented cocoa beans were warmed to a temperature of 44 °C between 36 to 38% RH. This pre-treatment step was used to warm wet cocoa beans to the wet bulb temperature of pre-conditioning air stream. The psychrometric properties of the air stream for different drying treatments are presented in Table 3.4. The wet bulb temperature of the pre-conditioning air stream at 44 °C was 30 °C, which is close to ambient air conditions in Fiji. The humidity ratio was also close to the ambient conditions. The reason for pre-processing wet fermented cocoa beans using this pre-conditioning step was to warm the product to inlet conditions and facilitate a rapid transition into the constant rate period.

The drying curves for fermented cocoa beans dried at different temperature treatment are presented in Figure 3.5 (A. 45 °C and B, 55 °C). The steep slope during the initial drying phase shows rapid moisture loss during pre-conditioning. The drying rate curves for all drying treatments are presented in Figure 3.6 for 55 °C and Figure 3.7 for 45 °C. Moisture evaporation is rapid during the initial stages of drying, which is the constant rate drying process. There is rapid reduction in free moisture from the bean surface. At the end of first drying cycle, the moisture content in cocoa beans equilibrated to less than 50%. This is recognised as the critical moisture content in cocoa beans (Ndukwu *et al.,* 2011).

Pre-dried cocoa beans were subjected to overnight resting period (tempering) for up to 12 to 18 hours after the first drying cycle. Overnight cooling conditions may facilitate moisture loss from warm partially dried cocoa beans. This night-time moisture loss has been explained by Hii et al. (2009) as the loss of heat retained in cocoa beans to the cool air stream. This causes a small or negligible amount of moisture loss, which was not recorded by the weighing scale. Limitations in overnight weight data make it difficult to predict the trend in overnight moisture loss.

Tempered cocoa beans were dried under low RH conditions in the second solar cycle. This is demonstrated as Day 2 in the drying curve in Figure 3.5 A for 45 °C and B. for 55 °C. A reduction in the moisture content was evident for all drying treatments. The drying rate curves shown in Figure 3.6 at 55 °C and for Figure 3.7 for 45 °C treatment demonstrated a rapid reduction in moisture during the early stages of pre-conditioning but decreased on day two. This can be described as the falling rate. Drying rate is high during the first hour of Day 2 drying as there is free moisture accumulated on the surface of the cocoa bean from condensation and sweating during overnight resting. The findings are similar to a study published by Liang and Sun (2000).

Some unusual patterns of moisture loss were observed in drying curves for various drying runs at different treatment conditions. The drying rate curves showed that moisture loss was slower for run 4 at 45 °C (Figure 3.7 B) and run 1 at 55 °C treatment (Figure 3.6 A) when compared to other runs within the same drying treatment. The slower drying rate for run 4 at 45 °C can be explained by lower temperature profile of drying air stream, which fluctuated between 42 to 43 °C (Figure 3.8 B). The inlet RH conditions for run 4 at 45 °C treatment fluctuated between 37 and 38% (Figure 3.9 B). This was higher than the inlet RH for drying runs 3 in Figure 3.9 A and drying run 5 in Figure 3.9 C on the second day of drying at 45 °C treatment. The temperature profile for drying run 3 in Figure 3.8 A and for drying 5 in Figure 3.8 C was between 45 to 46 °C. Temperature for drying air stream for these drying runs on Day 2 were higher than the air temperature for drying run 4 at 45 °C treatment.

Moisture loss during Day 2 for drying run 1 at 55 °C treatment was slower in comparison to runs 2 and 6 at 55 °C treatment (Figure 3.5 B). The drying rate curve for run 1 presented in Figure 3.6 A was slower on Day 2 when compared to drying runs 2 in Figure 3.6 B and run 6 in Figure 3.6 C on Day 2 of drying at 55 °C. The slow drying on Day 2 for run 1 may have been caused by a combination of temperature and RH fluctuations. The temperature profile on Day 2 for drying run 1 was between 50 and 56 °C (Figure 3.10 A), which was lower in comparison to drying run 2 (Figure 3.10 B) and 6 (Figure 3.10 C). In addition to the low temperature, the RH of drying run 1 in Figure 3.11 A, fluctuated between 16 and 26%.

Temperature and RH variations during the initial stages of Day 2 drying may have been caused by moisture from tempered cocoa beans and on the drying chamber walls. Excess moisture on cocoa bean surface increases the a_w, which may favour toxigenic mould growth. This problem was experienced during coffee drying by Palacios-Cabrera et al. (2007). The problem of mould infestation was also reported in Malaysian cocoa beans after overnight resting (Hii *et al.*, 2009). Product contamination with mould and mycotoxins can be detrimental to product quality and commercial value. Mycotoxins, such as ochratoxins from *Aspergillus* species is also a concern for human health. The risk of exposure is the greatest for cocoa processors and farm workers. The mycelia of *Aspergillus* species can be viable at a_w of 0.65, which is around 65% RH.

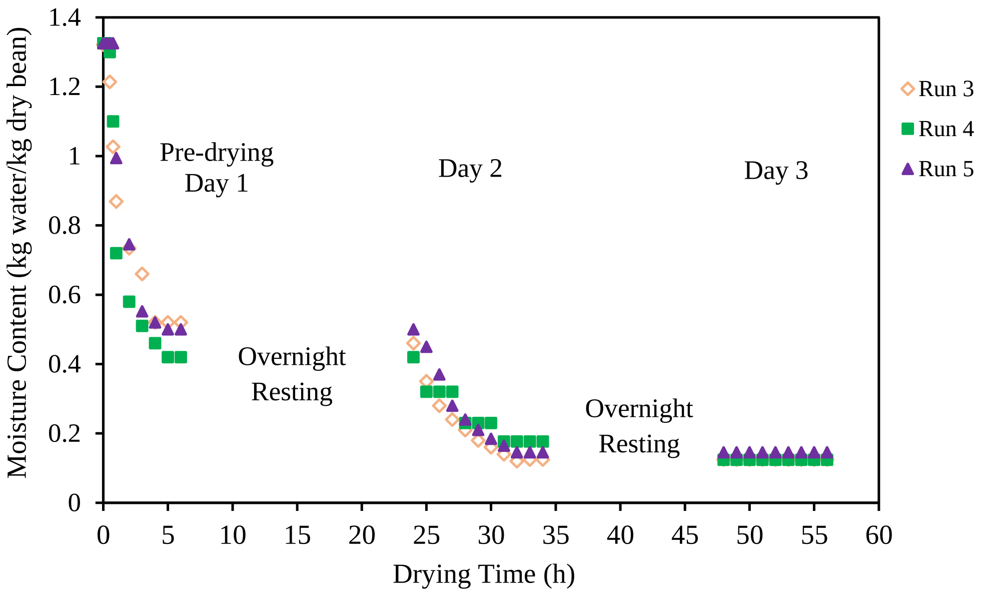
One approach to reduce mould growth is to apply a short pre-conditioning phase for two to three hours. This coincides with the time the regeneration phase of DW. Pre-conditioned cocoa beans can be dried under dehumidified conditions until the critical moisture of 50% w.b is achieved. The moisture sorption isotherm discussed in the Chapter 2, section 2.3.1 mentions that mould growth declines when EMC is below 12% d.b for temperature range of 30 to 55 °C. Another concern during tempering is the lack of solar energy to operate the DW and fans, which can push moist air out of the drying chamber at night. A possible solution could be to open the drying chamber to the clear night sky and allow excess moisture to condense on drying chamber walls rather than on the cocoa beans. This technique may limit mould growth on cocoa beans during drying.

Dehumidifying the air stream was effective for Day 2 and Day 3 of drying at 55 °C treatment. Figure 3.11 shows that RH stabilised by Day 3 of drying, indicating that moisture content declined to 10% w.b. This is evident in the drying curves for Day 3 at 55 °C treatment in Figure 3.5 B. Fluctuations in the RH was observed during Days 2 and 3 for drying runs at 45 °C treatment. Despite these fluctuations, the moisture content in cocoa beans dried at 45 °C declined to less than 10%. As mentioned in chapter 2, the isothermal conditions to limit the a_w for mould growth can be achieved when RH of the drying air stream is less than 65% between 40 to 60 °C (Koua, Koffi, and Ghaha, 2016).

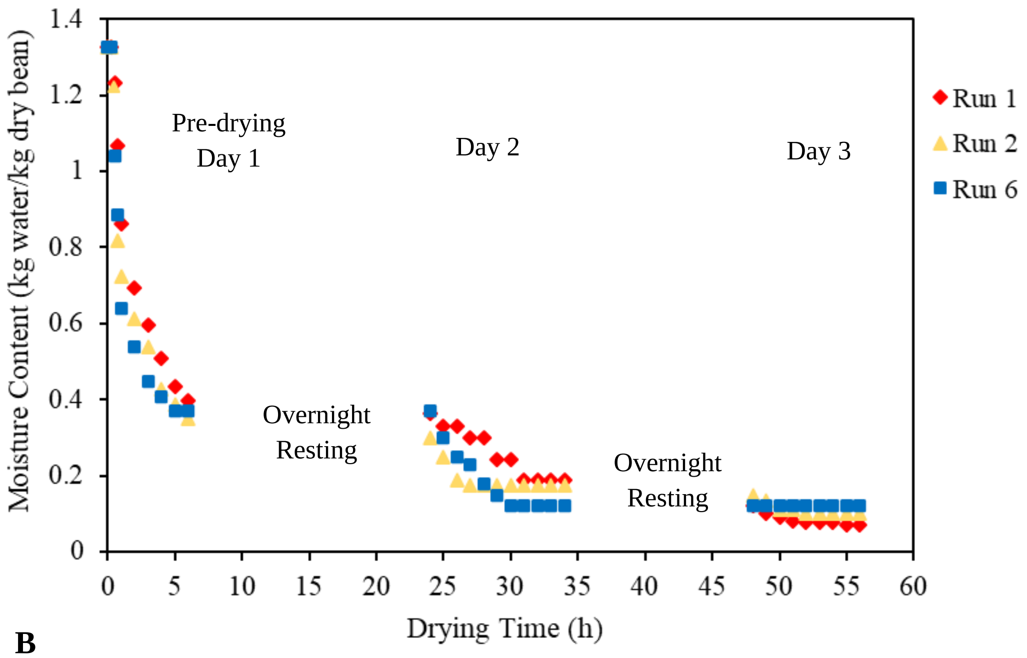
Further drying tests with different air velocities could be conducted to understand the drying behaviour of fermented cocoa beans. This could be time consuming and costly. A more cost-effective approach to predict the drying kinetics is by simulating different drying conditions using a mathematical model. The semi-theoretical equations mentioned in other studies do not fully describe the parameters that influence moisture loss within the multi-layers of the cocoa beans during drying. Development of a mechanistic drying model specifically for cocoa beans is required to describe and predict the generalised drying behaviour under varying ambient Fijian conditions. This will be discussed further in chapter 4.

Table 3.4. Psychrometric conditions of drying air stream

Set Treatment Temperature (°C)	Treatment RH (%)	Wet bulb temperature (°C)	Humidity (g/kg d.a)	Dew point (°C)
44	38	30	21	26
45	10	21	6	6
55	10	26	10	14



A



B

Figure 3.5. Drying curves for cocoa beans treated at A. 45 °C drying treatment and at B. 55 °C treatment

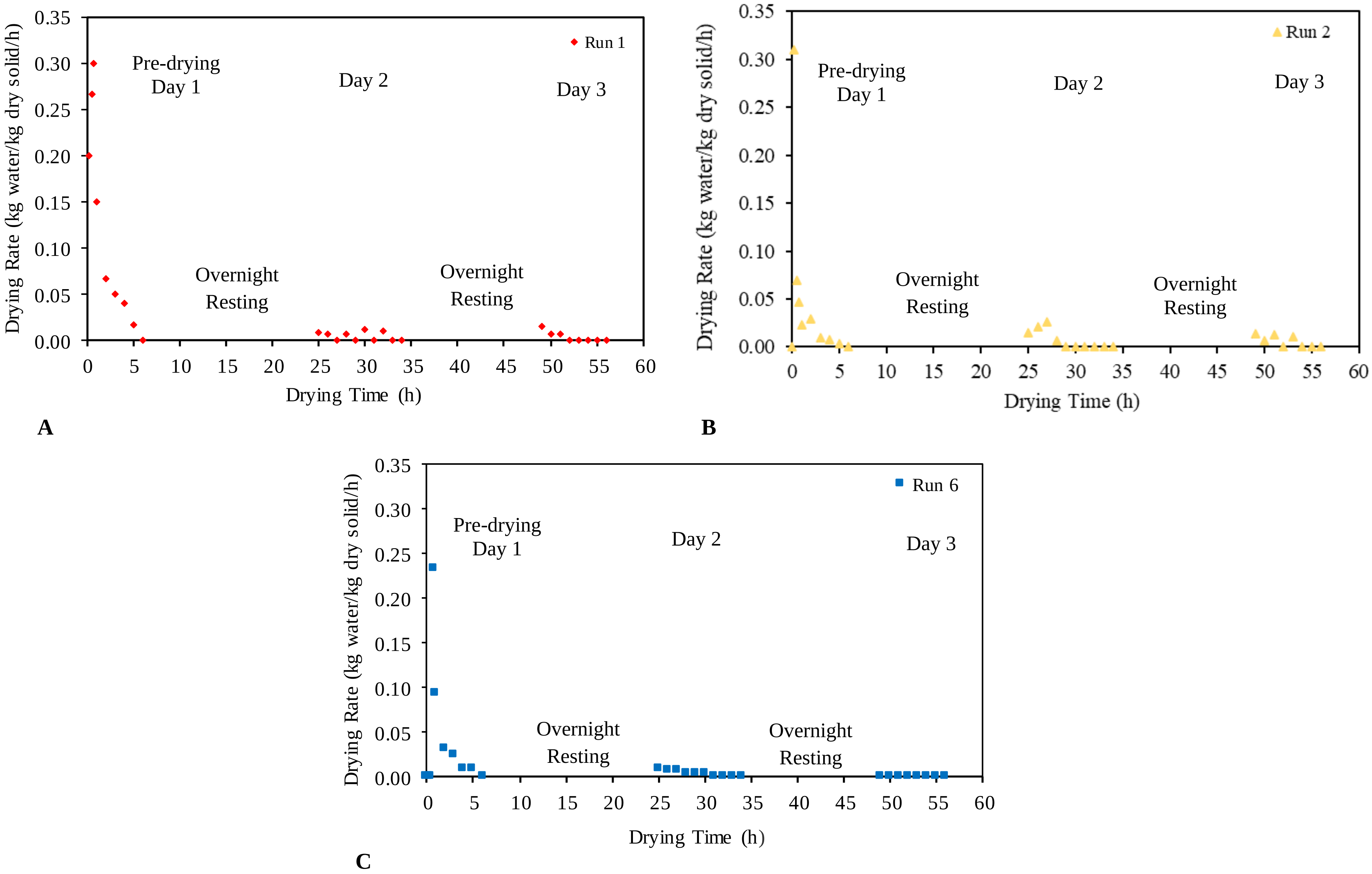


Figure 3.6. Drying rate curves for cocoa beans at 55 °C for drying run 1 (A), drying run 2 (B), and drying run 6 (C)

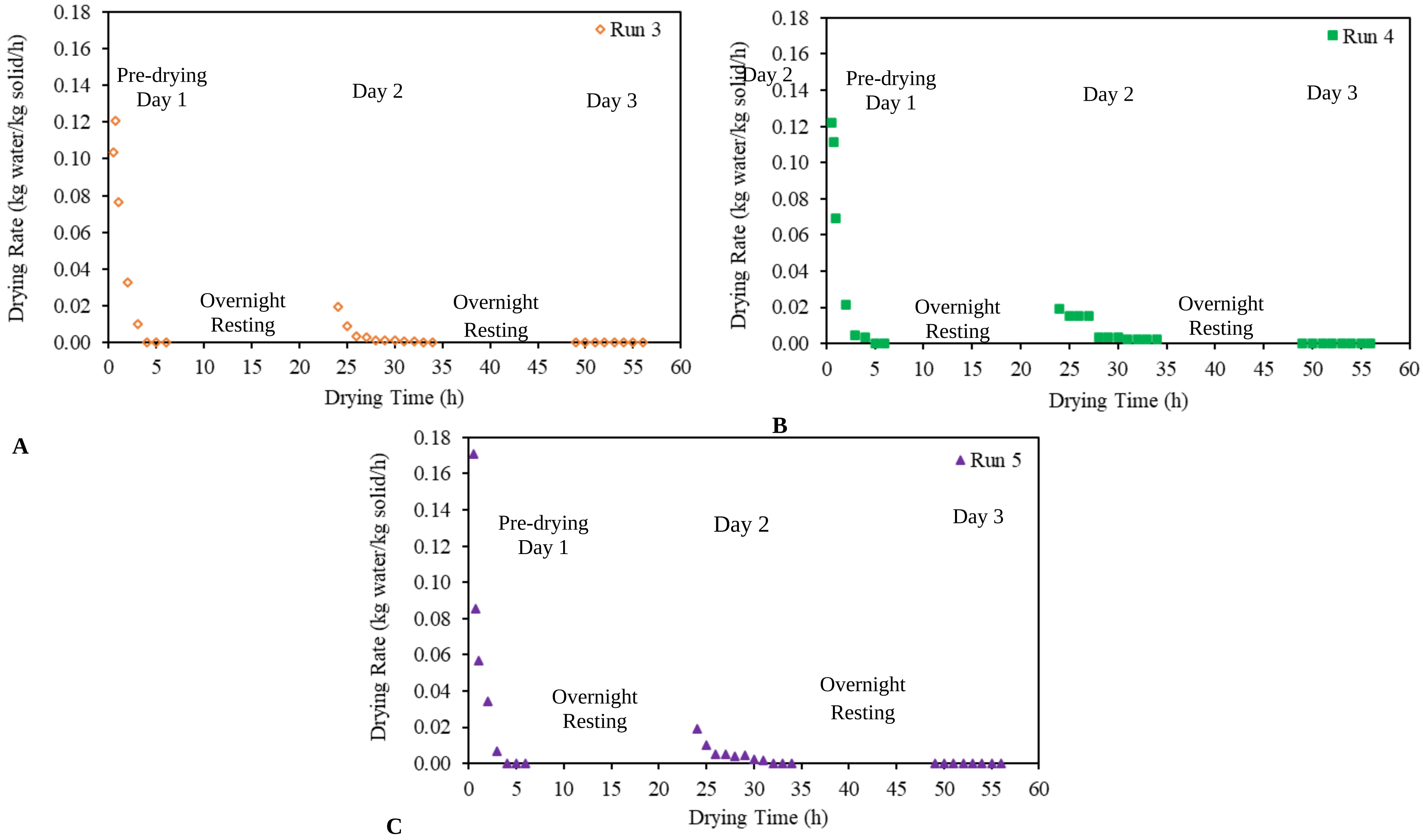
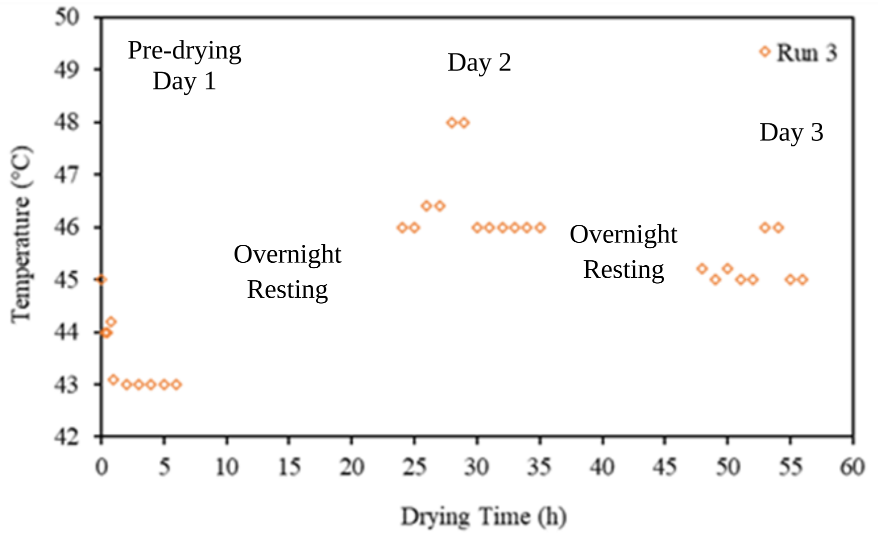
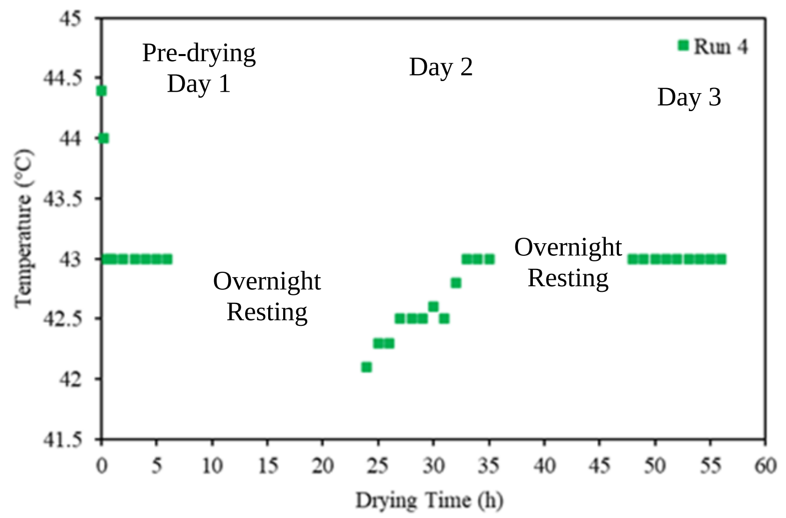


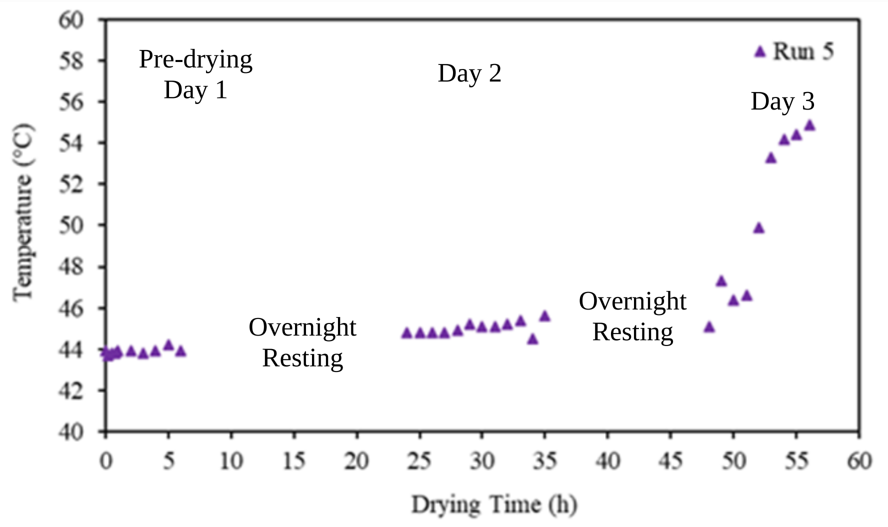
Figure 3.7. Drying rate curves for cocoa beans treated at 45 °C for drying run 3 (A), drying run 4 (B), and drying run 5 (C)



A



B



C

Figure 3.8. Temperature profile of air stream at tray inlet during drying treatment at 45 °C for drying run 3 (A), drying run 4 (B), and drying run 5 (C)

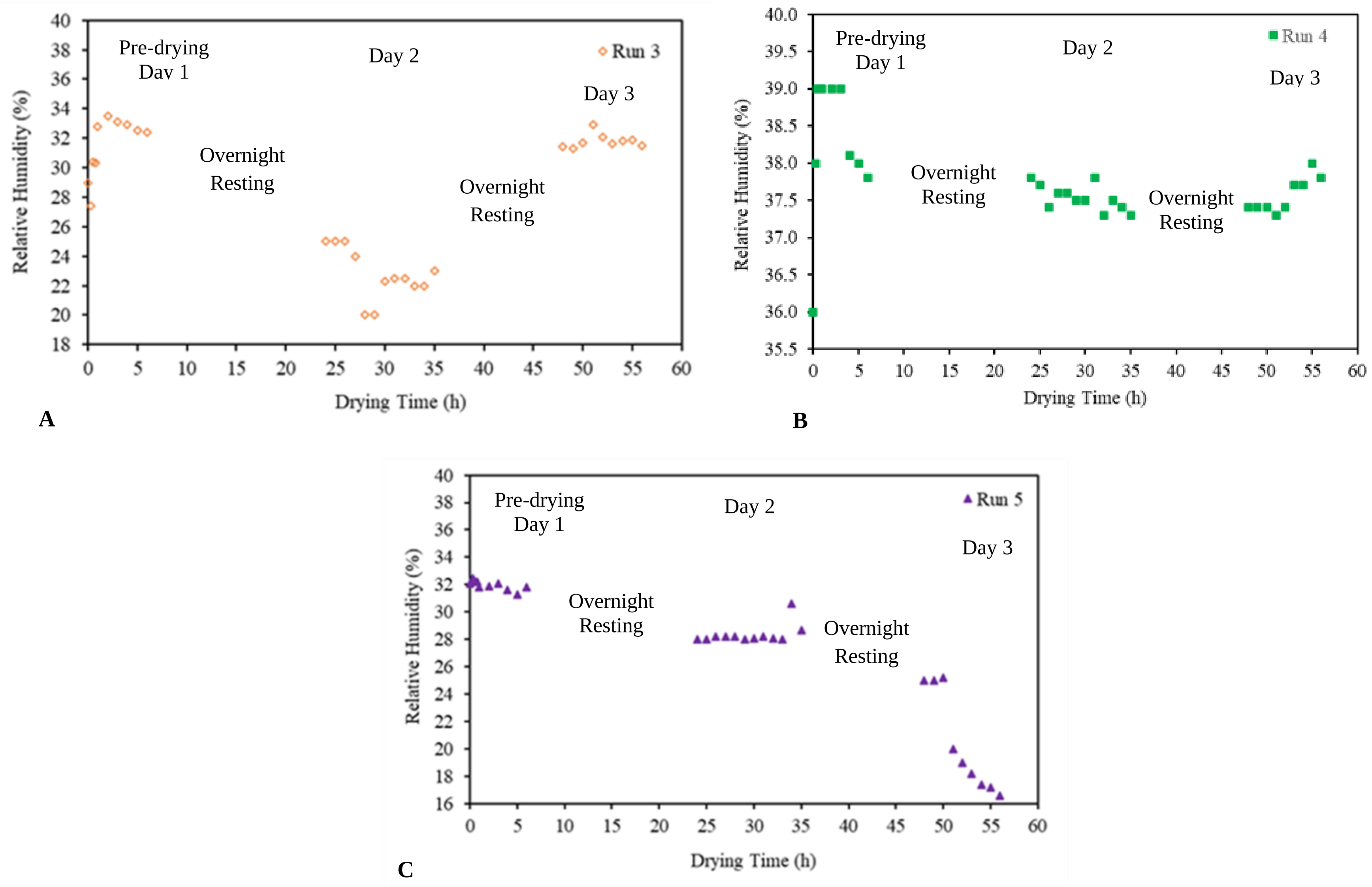


Figure 3.9. Relative humidity profile of air stream at tray inlet during drying treatment at 45 °C for drying run 3 (A), drying run 4 (B), and drying run 5 (C)

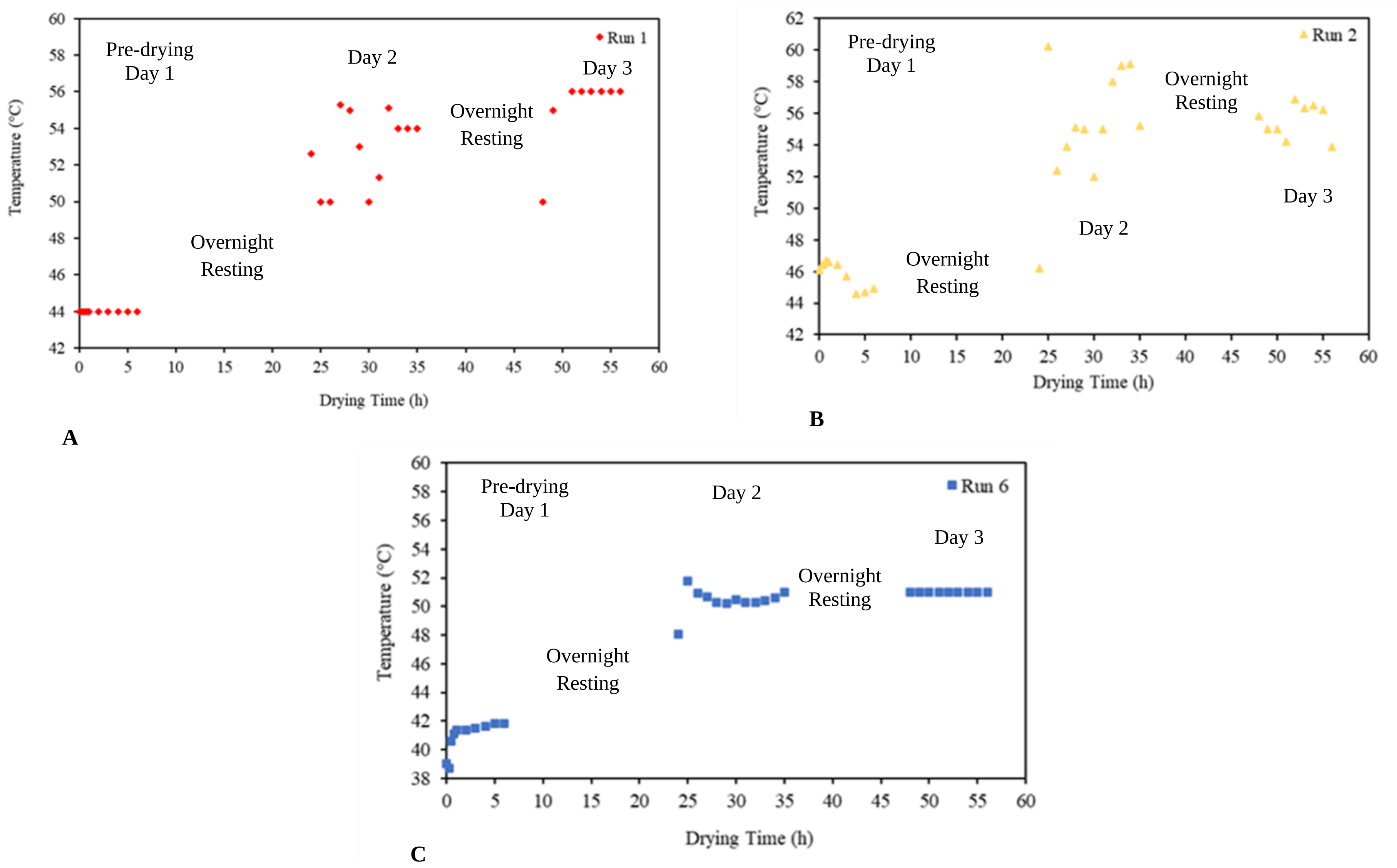


Figure 3.10. Temperature profile of air stream at tray inlet during drying treatment at 55 °C for drying run 1 (A), drying run 2 (B), and drying run 6 (C)

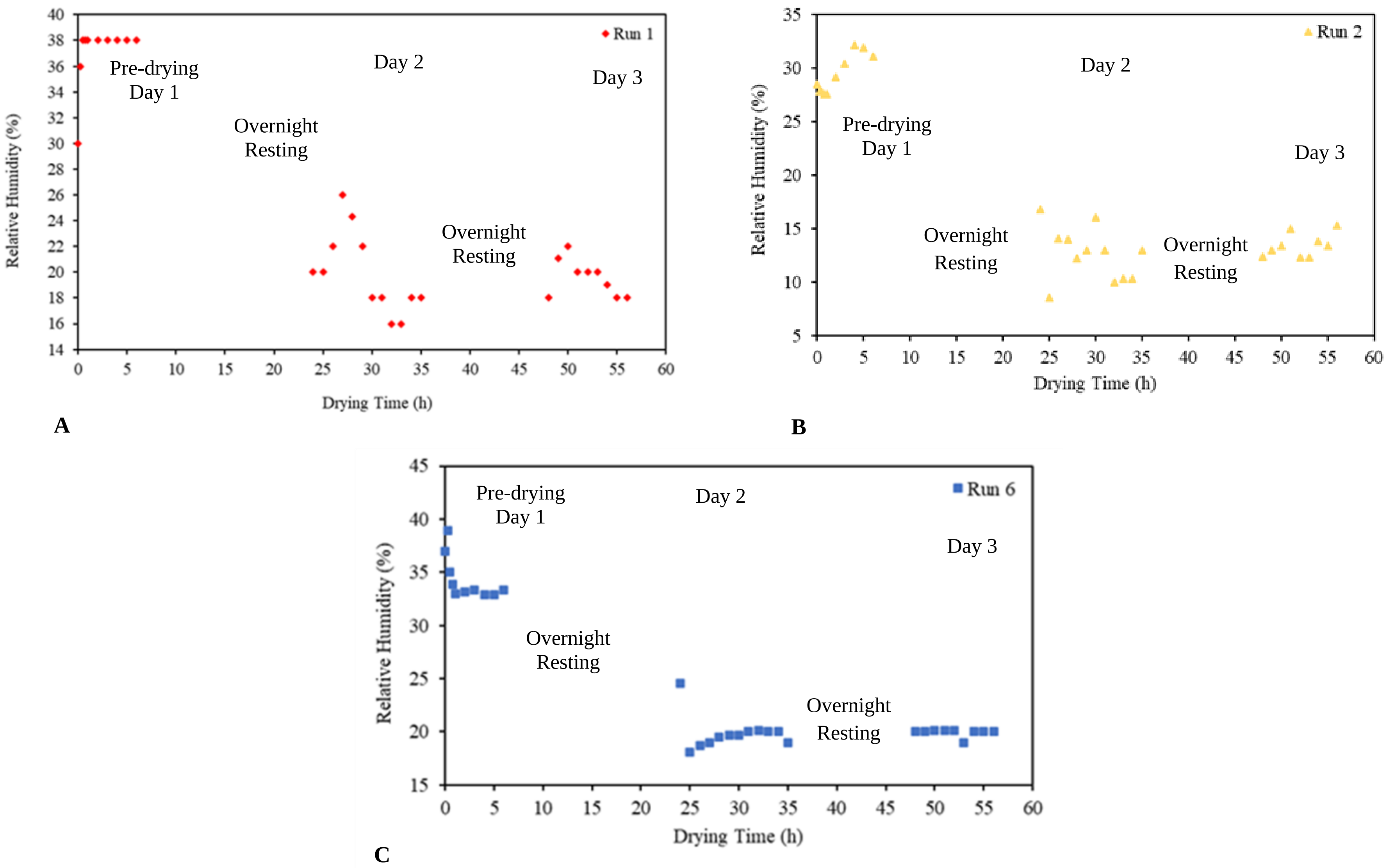


Figure 3.11. Relative humidity profile of air stream at tray inlet during drying treatment at 55 °C for drying run 1 (A), drying run 2 (B), and drying run 6 (C)

3.4 Conclusion

In Fiji, fermented cocoa beans are dried under ambient conditions to a moisture content of 10% within 14 days. The cocoa industry in Fiji meets the demands for export quality cocoa beans within three to four weeks of harvest. The lengthy processing times impair the ability of the cocoa industry to meet industry demands for export quality beans within a short time. The drying experiments demonstrated that the processing time can be reduced to one week when a desiccant wheel (DW) technology is integrated with the solar dryer after four days of fermentation. Drying treatments under low RH at both 45 °C and 55 °C reduced the drying time to three solar cycles (3 days).

In drying experiments, the concept of re-cycling regeneration exhaust air for pre-conditioning cocoa beans was tested successfully. In the drying process, pre-conditioning is a critical stage for pre-treating cocoa beans. This process focuses more on heat transfer from warm air to the wet cocoa beans and prevents drying injury. Recycling exhaust air requires further consideration and an improvement in the drying system design. Pre-conditioning temperature and RH were stable during the six hours. The temperature and low RH conditions were variable and more challenging to control during the second day drying experiments in a benchtop dryer. While this variability is a common issue in most dryers, in drying experiments the fluctuations in RH were caused by replenishing the silica gel every two hours of drying. These fluctuations are expected to be minimum through a DW.

Moisture loss in the drying curves for cocoa beans under all treatment conditions were variable. The variability may have been from batch-to-batch variations in the moisture content of wet cocoa beans, as well as fluctuations in temperature and RH inside the drying chamber. Slow drying was observed for cocoa beans treated at 45 °C in comparison to drying treatments at 55 °C. The temperature and low RH profile of the drying air stream was more stable at 55 °C treatment when compared to treatment at 45 °C. The stable drying air conditions at 55 °C dried the cocoa beans to a moisture content of 10% within three solar cycles, which is much less than 14 days of sun-drying. Drying experiments are extensive and time-consuming. Therefore, a drying model was developed in this study and validated by using the experimental data from this chapter. The input variables from the drying experiments were used to develop a mechanistic model for fermented Fijian cocoa beans, which is discussed in chapter 4.

Chapter 4 Developing a drying model for *Theobroma cacao* beans

4.1 Introduction

Intermittent weather conditions in Fiji slows down the drying process of *Theobroma cacao* beans. Slow drying causes mould growth, which is the main problem in dried cocoa beans. Moisture evaporation during drying is mainly controlled by the gradients in vapour pressure and temperature between wet product and dry air. The temperature gradient also exists between product surface and interior. One of the conventional methods to study drying kinetics is the calculation of loss in mass over the drying time. The loss in mass is measured by recording the change in weight of the food product using a data logger or a weighing scale during drying. The change in mass is used to calculate the average moisture content of the product. Weight measurements are limited in describing moisture distribution and variation within food particle layers and in particles along tray length during drying. This moisture movement within cocoa beans during drying is mainly controlled by internal diffusion (Akpinar, 2006; Doymaz and Pala, 2003). In this regard, deductive mathematical models are necessary to simulate moisture distribution in the product on drying trays.

Empirical or semi-empirical models are usually developed for fitting drying curves obtained from experimental data (Mühlbauer and Müller, 2020). Semi-empirical models simplify Fick's second law of diffusion to fit experimental temperature, RH, product moisture content, and air velocity (Mühlbauer and Müller, 2020). While these simplifications provide an understanding of moisture transport during drying, the data generated simply describe the drying run and is not suitable for predicting drying behaviour under varied drying conditions.

Empirical models share similar characteristics to semi-empirical models. The parameters for empirical models are largely dependent on experimental conditions to fit experimental data. This model is commonly used to describe heat penetration by convection during drying (Mariani *et al.*, 2008). The least square method is used with this model to establish a direct relationship between average moisture content and drying time to fit with experimental data (Mühlbauer and Müller, 2020). The main limitation with empirical and semi-empirical models is that variations in particle temperature and moisture content during drying are not fully described (Chen and Pei, 1989). Temperature variation is a key parameter that influences dried product quality. A robust model should be able to consider these variations to accurately predict the drying time to achieve the targeted moisture content in the product.

Mathematical models used for numerical simulations of drying kinetics are based on drying conditions and key input parameters. Several parameters, such as thermal properties of wet product and dry air, bean geometry, and thickness of bean layers are considered in the model equation. These equations are used in thin layer models to describe moisture transfer between product and air stream. The American Society of Agricultural and Biological Engineers (ASABE) developed a thin layer model, which describes a wet particle as three uniform layers in thickness with particle surface in complete exposure to air stream during drying (ASABE, 2001). In thin layer drying models, particle thickness changes with variations in air temperature, RH, and air velocity (Ertekin and Firat, 2017; Kucuk *et al.*, 2014).

Thin layer models use lumped or distributed heat transfer equations to compute the drying kinetics (Onwude *et al.*, 2016). The distributed approach considers heat and mass transfer from various layers within the bean at time intervals. In the lumped approach, heat transfer in a single particle is expressed as a function of time during drying. Lumped parameters are derived from differential equations with simplified assumptions. The equation used in this model is one dimensional, which considers moisture and temperature distribution to be uniform over drying time. The main disadvantage of models with lumped approach is that they are limited in resolving spatial distribution of moisture and temperature in the product. The advantage of lumping moisture transport mechanism is the low computational costs.

The conceptual solar dryer design considered low RH conditions to improve the drying kinetics of 100 kg (0.1 Mt) of wet fermented cocoa beans for a small holder farm. The mass of wet fermented cocoa beans was estimated from an average mass of 0.1 to 0.3 Mt of fresh cocoa beans from one harvest cycle from small farms in Fijian villages (Fiji Ministry of Agriculture, 2022). The batch-to-batch variations in wet moisture content of fermented cocoa beans would require the drying temperature to be variable during drying. While temperature can be moderated, other drying conditions such as air flow and relative humidity would be difficult to predict. Estimating the optimum drying conditions using large scale drying runs can be costly and time consuming. Therefore, a low-cost approach for effectively predicting the drying time required to reach a safe and ideal moisture content of 7% on a wet weight basis is by using mathematical drying models.

Drying experiments with varying temperature and RH conditions can be used to understand the drying kinetics of cocoa beans. However, these experiments can be costly and time-consuming. Variations in the drying conditions and batch-to-batch moisture content in fermented cocoa beans are the main problems identified during drying experiments. These variations can affect the drying time. Drying equations can be a reliable tool that can be used to estimate the drying conditions required to reduce drying time and product moisture content to safe acceptable levels of 7% w.b.

Developing a drying model for Fijian *Theobroma cacao* beans at different temperatures and RH will allow the development of efficient drying equipment that could operate in tropical conditions. Under simple solar drying conditions, the solar dryer is occupied for a week or longer depending on the intermittent nature of sunshine. The drying time can be reduced by lowering the RH inside the drying chamber in solar dryers. This could allow the batch drying process of cocoa beans and limit long hours of drying in a conventional solar dryer.

4.2 Materials and method

For simplicity, air drying has been modelled by heat and mass transfer between the cocoa beans and drying during the constant rate period and mass transfer within the beans during the falling rate period. A one-dimensional drying model was discretised according to time and spatial domain. The model was solved using finite difference method (FDM) with an upwind forward scheme. The FDM approach considered a one second time step and a grid with 20 divisions for the bean radius and 20 divisions of the drying tray. A double precision approach by a 64-bit process was used to check if the precision remains the same. Input variables from experimental drying runs on wet fermented cocoa beans were used for model parametrisation.

Input variables from experimental drying runs on wet fermented Fijian *Theobroma cacao* beans in chapter 4 were used for model parameter (Tables 4.1 and 4.2). These data were from a biannual cocoa harvest season between October 2018 and May 2019. The model was developed based on the concept of solar assisted drying with desiccant wheel (DW) technology. The design concept involves thermal treatment of ambient air with flat plate and parabolic solar collectors for regeneration of desiccant material.

Table 4.1. Input data used to simulate drying model for fermented *Theobroma cacao* beans

Variables	Description of variables	Value	Unit
M_{dt}	Wet product mass	10	kg
M_{ic}	Initial wet water content	57	%
D_{be}	Bean diameter	20	mm
ρ_t	Density of testa	700	kg/m^3
N_L	Number of zones along tray length	20	
N_{LL}	Number of layers along bean radius	20	
t	Total drying time	295200	s
dt	Time step interval for simulation of air flow along tray	1	s
n_{tt}	Number of time steps for simulation of water diffusion	40	
t_0	Initial time for starting point	0	s
t_{D1}	Day 1 drying time	6	h
t_{D2}	Day 2 drying time	8	h
t_{Night1}	Day 1 overnight	18	h
t_{Night2}	Day 2 overnight	16	h

Table 4.2. Operating conditions during drying simulations

Variable	Description of variable	Value	Unit
T_{ai}	Ambient temperature	30	°C
T_{ai1}	Day 1 drying air temperature at the inlet	44	°C
T_{ai2}	Day 2 drying air temperature at the inlet	45 or 55	°C
T_{bi1}	Initial bean temperature	28	°C
T_{bi2}	Tempered bean temperature (overnight)	25	°C
X_{ai}	Ambient humidity	20	g moisture/ kg dry air
X_{ai1}	Day 1 humidity of air at inlet	20	g moisture/ kg dry air
X_{ai2}	Day 2 humidity of air at inlet	15	g moisture/ kg dry air
u	Velocity of air stream	0.25	m/s

4.2.1 Model parameters and assumptions

Logic flow of model development is illustrated in Figure 4.1. Biphasic nature of drying cocoa beans using pre-conditioning (6 h) and dehumidified air conditions (8 h per day) was considered. Pre-conditioning temperature (44 °C) and RH (36-38%) was estimated from theoretical DW exhaust conditions. The data from drying experiments discussed in chapter 3 was used to validate the mathematical model (Figure 4.1). The model equations did not consider the overnight resting conditions, which lasted for 16 to 18 hours. Moisture loss during overnight resting (tempering) was assumed to be negligible due to a slow drying rate.

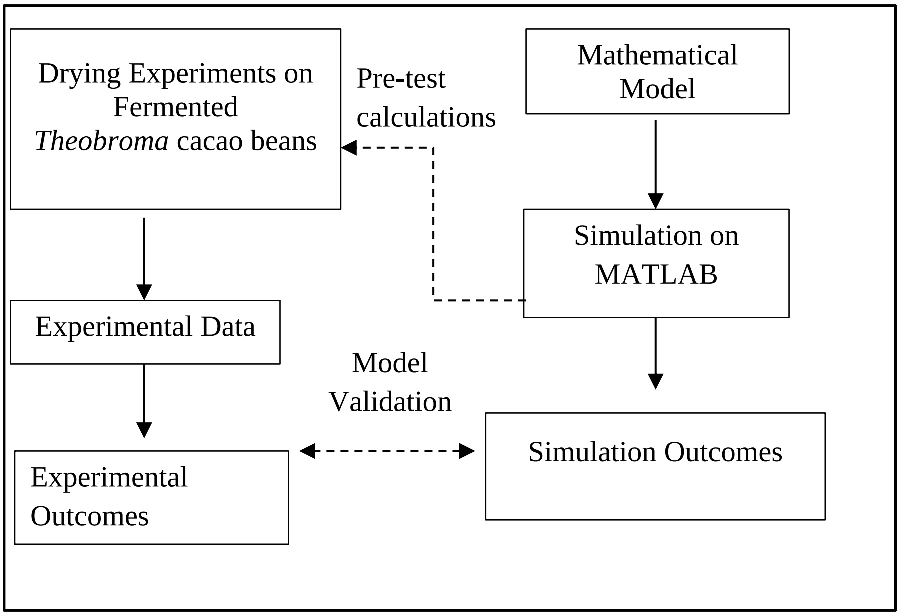


Figure 4.1. Process flow chart showing summary of developing a mathematical model for drying fermented *Theobroma cacao* beans under dehumidified conditions. Weight loss, temperature, and relative humidity data from drying experiments in Fiji were used to validate the model.

Model equations were developed by setting some assumptions that describe the specifications of the drying model. In the model, moisture diffusion on bean surface was assumed to be through convective air flow (mass and heat transfer), while heat conduction within the bean was neglected. Moisture, RH, and temperature distribution along tray zones (n = 20) were simulated within a targeted drying time of 72 h. The following input parameters were considered in the model:

1. Air temperature (45 and 55 °C)
2. Relative humidity (15-20%)
3. Air velocity (0.25 m/s)
4. Initial wet bean moisture content (57% w.b)
5. Mass of fermented bean (10 kg)
6. Size of cocoa bean (20 mm)
7. Effective diffusivity

These model input variables were used to solve the differential equations for bean temperature and moisture content simultaneously with air temperature and humidity at each time step of drying. Liquid diffusion of moisture from the bean to air stream was modelled under mild temperature conditions under unsteady state. Shrinkage during drying was negligible, as this was not evident in cocoa beans during drying under mild temperature conditions.

Moisture diffusion was estimated using Fick's second law of diffusion based on product geometry. The following assumptions were made for developing the drying model:

1. Bean shape is spherical (0.5 to 1) and bean size is uniform.
2. Shrinkage is negligible.
3. Moisture diffusion is isotropic.
4. Effective diffusivity of moisture remains constant in the testa and kernel, during drying.
5. External moisture diffusion is controlled by convection.
6. Moisture evaporation occurs at the surface of testa.
7. Moisture content and water activity of cocoa bean equilibrates during overnight period.
8. Initial temperature distribution in cocoa bean is uniform.
9. Variation in pressure is negligible.
10. Heat transfer occurs on bean surface by convection.
11. The drying process has an initial stage of pre-conditioning the cocoa beans at 44 °C under 36 to 40% RH for 6 h
12. Dehumidified drying process is for 8 h at 55 °C and 45 °C treatment.
13. Overnight tempering period is 12-16 h.

Input variables used in calculations of model equations are provided in Tables 4.1 and 4.2. Initial moisture contentof wet fermented cocoa beans was considered as an average value (57% w.b.) after measuring moisture content gravimetrically. On a dry basis, the initial moisture content (X_{b0}) was calculated using weight of dry solid. The following equation was used for moisture content calculation:

$$X_{b0} \text{ (kg water/kg dry matter)} = M_{ic}/(100-M_{ic}) \tag{1}$$

The dry weight (m_{dt}) or dry matter was calculated by the formula:

$$m_{dt} \text{ (kg)} = M_t \times((100-M_{ic}))/100 \tag{2}$$

Where M_t is the weight of wet cocoa beans and M_{ic} is the moisture content in fermented cocoa beans.

4.2.2 Developing model equations

The governing equations for heat and mass transfer were adapted from several studies in literature mentioned in chapter 2. Mass transfer is the key mechanism that controls moisture transport in cocoa beans. The model was designed to describe temperature and moisture variations in the following levels:

i. Dry air stream and wet cocoa beans along the drying tray and

ii. Within the bean-to-bean surface during drying.

Partial differential equations were simplified for a numerical simulation of the drying process under unsteady state. The model considers key drying parameters, such as air velocity, temperature, and relative humidity over drying time. Additionally, product thermal properties and initial moisture content also affect drying kinetics. These thermophysical properties of product and air were used in the PDEs. Simplification of these PDE's was conducted before a numerical simulation was conducted on MathWorks® software (MatlabR2018a.) New Zealand.

4.2.3 Model equations along the drying tray

The Mass balance of moisture in the beans on the tray was calculated using the following equation:

$$\rho_b V_b \frac{\partial X_b}{\partial t} = -A_b h_m (C_s - C_a) \tag{3}$$

Mass balance of moisture in the drying air along the dryer can be described as:

$$\rho_a A_c \frac{\partial X_a}{\partial t} + \rho_a A_c u \frac{\partial X_a}{\partial x} = W h_m (C_s - C_a) \tag{4}$$

Heat transfer equations were derived for calculating heat transfer between the dry air stream and cocoa beans along each zone of the drying tray. These were described as energy balance equation as below:

Energy balance for the beans:

$$\rho_b V_b \frac{\partial[(c_{pb} + X_b c_{pw}) T_b]}{\partial t} = A_b h_e (T_a - T_b) - A_b h_m (C_s - C_a) H_L \tag{5}$$

Energy balance for the drying air:

$$\rho_a A_c \frac{\partial[(c_{pa} + X_a c_{pm}) T_a]}{\partial t} + \rho_a A_c u \frac{\partial[(c_{pa} + X_a c_{pm}) T_a]}{\partial x} = -W h_e (T_a - T_b) \tag{6}$$

The humidity and temperature of the drying air, and cocoa bean moisture content and temperature variations along 20 zones of the drying tray were modelled over 72 hours of targeted drying time. The illustration in Figure. 4.2 shows the divisions along the trays in the drying shelf in the drying chamber.

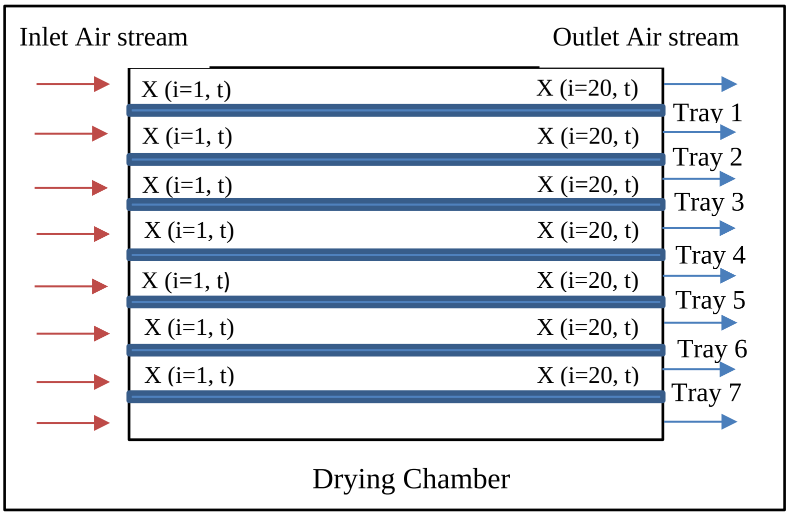


Figure 4.2. Schematic illustration of the number of trays used in the model with zones per tray. Zones in one tray used for drying fermented *Theobroma cacao* beans. Each zone was 0.04 m wide or 0.015 m^2 in area. The load per tray was 2 kg of wet fermented cocoa beans.

4.2.4 Geometrical parameters of the drying trays

In total, seven drying trays (n=7) were considered in the model as shown in Figure 4.2. Variations in temperature and moisture content of cocoa beans were predicted to be similar in each of the 20 zones for seven trays in the dryer. One drying tray represents average temperature and moisture variations on seven trays. Variations from top to bottom tray were not considered in the model. During an interval of 10 seconds, convective heat transfer from dry air stream to bean and moisture diffusion from bean to dry air stream was simulated within 40-time steps along the tray. Temperature and RH conditions of air stream were simultaneously calculated between each zone on the tray. The load of beans (P) on each tray was determined based on dry matter using the following equation:

$$P\left(\frac{kg}{m^2}\right) = \frac{m_{dt}}{A_t} \qquad (7)$$

4.2.5 Coefficients of heat and mass transfer between the air stream and cocoa beans

In the model, heat and mass transfer during drying occurs through convection. Based on the coupled differential equations above, mass transfer coefficient is calculated with the assumption that Lewis number (L*e)* ≈1. Heat and mass transfer coefficient of moisture in air stream was calculated from an equation adapted from Herman-Lara et al. (2005). Heat (h_e) and mass transfer (h_m) coefficients were estimated using dimensionless parameters, such as Nusselt and Sherwood number. Nusselt number was used in heat transfer equations between dry air stream and bean.

Mass transfer is described using Sherwood number, which correlates to product geometry and air flow conditions (Putranto and Chen, 2016). These dimensionless numbers can be constant at low air velocity (0.25 m/s) or can be calculated if air velocity increases with bigger fans for a larger batch of cocoa beans. Air velocity can be described using dimensionless Reynolds number, which was calculated based on relative air velocity between air and the particle. Reynolds number can also be used to calculate heat transfer coefficient of air if mass transfer coefficient is known. The equation for calculating Reynolds number is given below:

$$Re = \frac{ud_e}{\nu_a} \tag{8}$$

If Re ≤2100 then:

Nu = 3.66
Sh = 3.4

If Re is >2100 then:

$$Nu = 0.024 + Re^{0.8}\ Pr^{1/3} \tag{9}$$

4.2.6 Boundary conditions and initial conditions

The model developed in this study considered temperature and RH variations of ambient air stream from desiccant wheel (DW) for drying cocoa beans and regenerating desiccant material. The parameters assumed for regeneration temperature for DW was from 60-120 °C based on the incident solar energy, ambient temperature, and RH variations in Fiji. The drying air is dehumidified by the DW. Figure 4.3 describes adsorption and desorption process in DW. Boundary conditions of the dry air stream for equations (4) and (6) are:

$t>0, x=0, X_a=X_{ai1}$ or X_{ai2}, $T_a=T_{ai1}$ or T_{ai2} (10)

The initial conditions are:

$t=0, X_a=X_{ai}, X_b=X_{b0}, Ta=T_{ai}, T_b=T_{b0}$ (11)

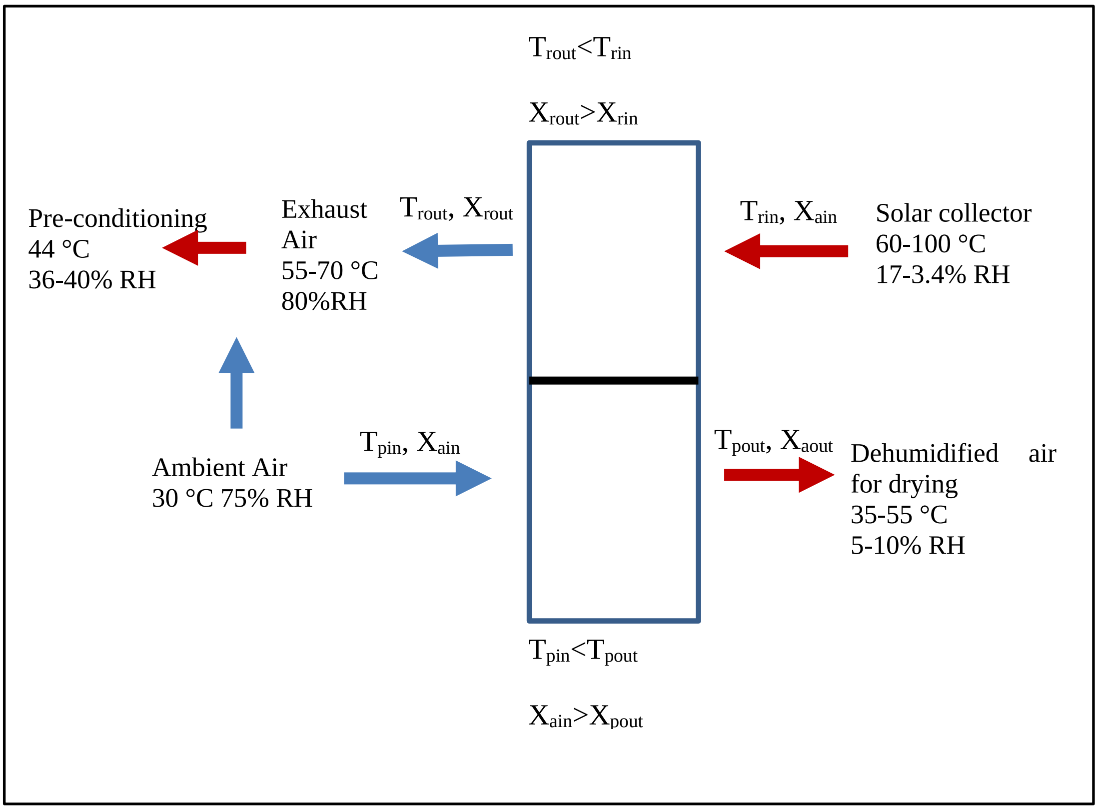


Figure 4.3. Schematic illustration of air flow through a conceptual desiccant wheel design. The design was used in the drying model for predicting drying outcomes on fermented *Theobroma cacao* beans.

4.2.7 Moisture diffusion and heat conduction within cocoa beans

During the drying process, moisture diffuses from bean centre to surface. Moisture evaporation is controlled first by the gradient of water vapour pressure at the bean surface and then the moisture diffusion within the beans. Temperature of cocoa bean is determined by convective heat transfer between dry air stream and bean surface, as well as heat conduction in the bean. Moisture diffusion in each bean was assumed to be through 20 layers as demonstrated in Figure 4.4.

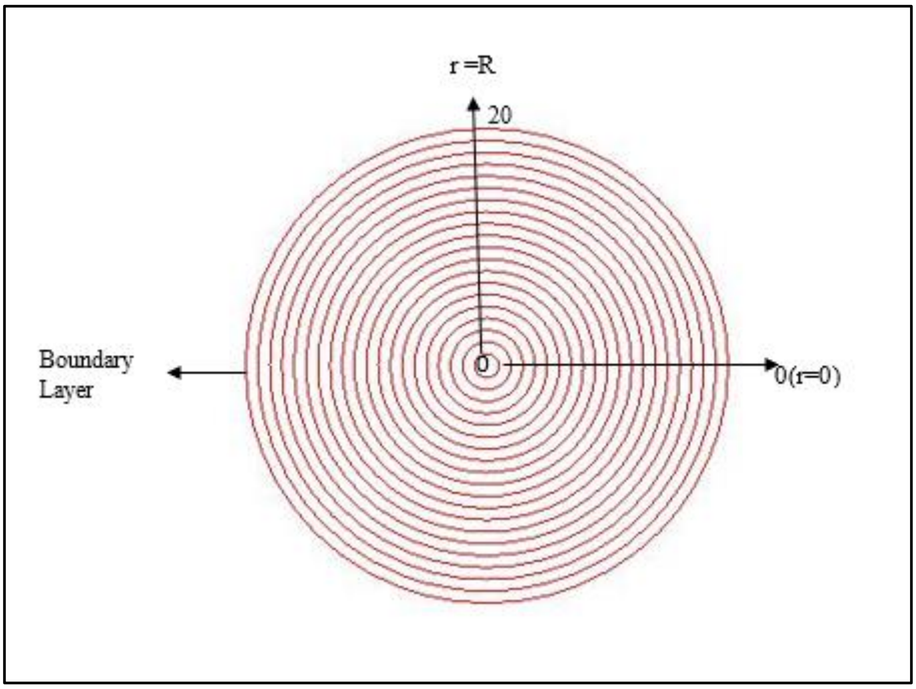


Figure 4.4. Illustration of a particle size for cocoa bean with 20 zones. Zone 0 is the centre with no heat transfer (r=0) and layer 20 is the boundary layer in contact with the air stream for heat and mass transfer.

Mass balance for moisture diffusion within the beans:

$$\frac{\partial X_b}{\partial t} = D\left(\frac{\partial^2 X_b}{\partial r^2} + \frac{2}{r} \times \frac{\partial X_b}{\partial r}\right) \qquad (12)$$

In this equation, the influence of porosity on moisture diffusion is lumped in the parameter of diffusivity (D). Moisture diffusion from bean centre to the surface is controlled by mass transfer in the boundary layer. This can be expressed by the boundary condition as follows:

$$t>0,\ r=R_0,\ -\rho_b D\frac{\partial X_b}{\partial r} = h_m(C_s - C_a) \qquad (13)$$

In the center of the beans,

$$t>0,\ r=0,\ -\rho_b D\frac{\partial X_b}{\partial r} = 0 \qquad (14)$$

Temperature is the driving force for moisture diffusion. Cocoa bean temperature can be calculated using the following equation:

$$\rho C_b \times \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \times \frac{\partial T}{\partial r} \right) \qquad (15)$$

Temperature gradient is established between dry air and wet bean through convective heat transfer. Thus, one of the boundary conditions for the above equation can be expressed as,

$$\lambda_b \frac{\partial T}{\partial r} = h_e \left(T_a - T_b \right) \qquad (16)$$

Convective heat transfer resistance at bean surface can be estimated using Biot number (Hii *et al.*, 2013). When the Biot number is <0.1 then heat transfer within the bean is much faster than heat convection at bean surface. For simplicity, the internal temperature distribution was thus neglected in the model. The model assumes heat and mass transfer is one dimensional, considering bean geometry.

Moisture content influences the thermal properties, such as thermal conductivity in *Theobroma cacao* beans. Thermal conductivity and sorption isotherm were expressed using equation from Ruiz-Lopez et al. (2004). Thermal conductivity is a function of water content, which changes over time as drying proceeds. This water content further determines the water activity (a_w) using sorption isotherms from literature. Garcia-Alamilla et al. (2007) obtained sorption isotherms from experiments on fermented cocoa beans. The sorption isotherm used in the model was expressed as follows:

$$a_w = 1 - e^{-100.16784 X^{1.93938}} \qquad (17)$$

4.3 Results and discussions

Mathematical model that was developed to predict drying kinetics of fermented Fijian cocoa beans operate within a set of input parameters. These input parameters were defined using drying runs for model parameterisation. Variations in the drying parameters can provide an understanding of whether the drying factor or model assumptions are important to the drying kinetics of *Theobroma cacao* beans. The effect of air temperature and RH on drying rate of cocoa beans, moisture content, water activity, and bean temperature profile were expressed numerically.

Heat and mass transfer between; dry air stream and tray, dry air stream and bean surface and heat transfer within bean along drying trays were simulated by the mechanistic model. Model parameterisation by assimilating experimental data demonstrated that the model was able to vary predictions based on variations in drying parameters.

4.3.1 Drying kinetics

Drying data from drying experiments on fermented Fijian cocoa beans was used for parameterising the effective diffusivity of moisture inside the bean. Air temperature at dryer inlet was kept constant during the drying runs. The drying model for cocoa beans predicted bean temperature profile and moisture content relatively well during drying, despite variations in experimental drying conditions. As shown in Figure 4.5. for two different drying treatments, the model predictions are comparable to experimental data at 45 °C drying runs within 95% of model data. Drying data at 55 °C treatment was unique for each run and close to 80% of the model data. The initial stages of drying shows greater deviation from the model when compared to later stages of drying when moisture content declines further. The graph shows a 5% deviation between model output and experimental data. These deviations are common when the mechanisms for the transport of moisture is lumped in model equations (Welsh *et al.*, 2023).

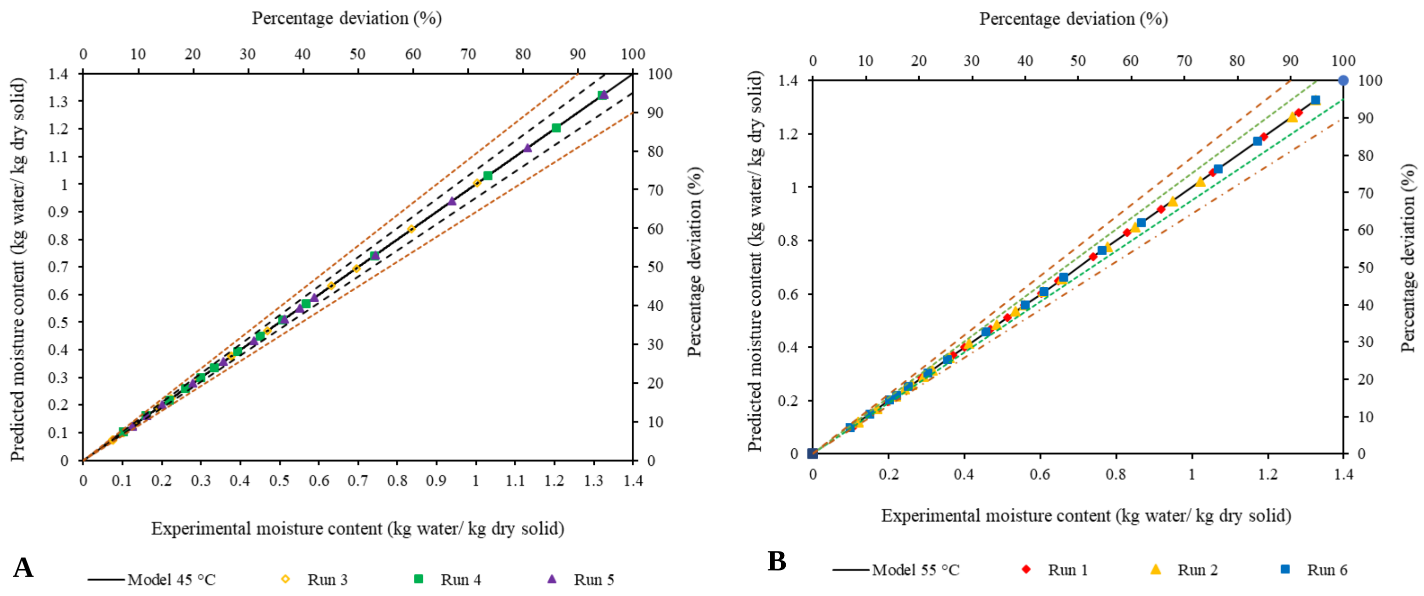


Figure 4.5. Fitted line plots showing predicted moisture content by the drying model versus experimental data on moisture content from drying runs at A. 45 °C and B. 55 °C.

There were deviations in these pre-conditioning treatment conditions between model predictions and experimental data as shown in Figure 4.5 A for 45 °C treatment and B for 55 °C treatment. The model results were closer to the moisture content for drying run 4 in Figure 4.5 A and for drying run 1 for Figure 4.5 B. The main reason for deviations between model output and drying data are variations in the initial moisture content of fermented cocoa beans. Moisture variations in surface layers of fermented Forastero variety of cocoa beans has been reported by Ndukwu et al. (2011). There are several reasons why moisture distribution within a freshly fermented cocoa bean is heterogenous. These could be spontaneous fermentation and biological variability within the cocoa beans. Additionally, poorly washed cocoa beans may have moisture bound to the gelatinous matrix around the bean.

The drying curves for drying runs at 45 °C and 55 °C treatments were compared to the model data (Figure 4.6). The initial moisture content of freshly fermented cocoa beans was assumed to be uniformly distributed in the drying model. This assumption neglects biological variability in the moisture content within a batch of freshly fermented cocoa beans. Moisture variations were evident in early stages of pre-conditioning for drying runs at 45 °C treatment in Figure 4.6 A and for drying runs at 55 °C treatment in Figure 4.6 B. There is no published literature on pre-conditioning process for *Theobroma cacao* beans. The main purpose of pre-conditioning was to minimise drying injury, such as case hardening and shrivelling. The moisture content of pre-conditioned Fijian cocoa beans was close to 30-39% of moisture reported in *Zea maize* seeds by Herter and Burris (1989). While initial moisture content of fresh *Zea maize* is 40 to 50% (w.b), the seeds are biologically and physically different when compared to cocoa beans. Pre-conditioning has been widely reported during drying coffee beans as explained in chapter 2 of this thesis. The pre-dried moisture content of pre-conditioned cocoa beans was closer to pre-dried coffee beans (Coradi *et al.*, 2007; Isquierdo *et al.*, 2012).

Drying curves for the second drying cycle (Day 2) for each drying treatment showed variability. While some of the model data was comparable to the drying runs, these variabilities in moisture content were more evident during the early stages of drying under low RH. Moisture variations may have been caused by fluctuating RH and temperature conditions of the drying treatment after overnight resting. These fluctuations in RH are described in Figure 4.9 for 45 °C treatment and Figure 4.10 for 55 °C treatment. While the effects of tempering on moisture content have not been widely reported for cocoa beans, this treatment has been known to improve coffee bean quality and the drying process (Isquierdo *et al.*, 2012).

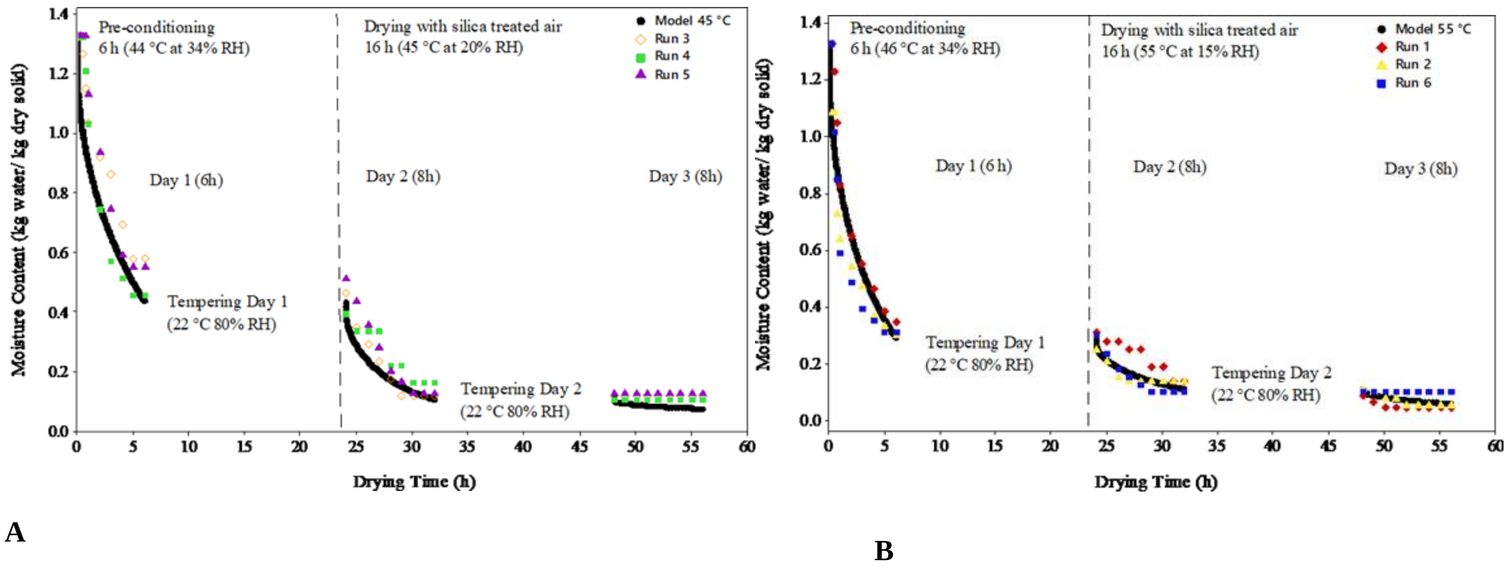


Figure 4.6. Drying curves for experimental data fitted with model at A. 45 °C and B. 55 °C. Initially, each drying run had a 6 h pre-conditioning period where wet fermented cocoa beans were pre-dried at conditions set at 44-46 °C under 32-34% RH. Second day of drying resumes after an overnight resting period of 18 h under ambient conditions at an average air velocity of 0.15 m/s ± 0.10. Each drying run has two overnight resting period, except for run 3, which terminated upon reaching a constant weight.

The moisture content equilibrated to the dryer conditions on Day 3 of the drying cycle (Figure 4.6). The model predictions for the final moisture content were 7% (w.b), while the final dried moisture conditions for experimental data was around 10% (w.b) for 45 °C and 55 °C treatment. The deviations in final dried moisture content between the experimental data and model predictions were caused by lumping the parameters for moisture diffusion within the bean. The final moisture content for the experimental data for both treatments were close to the results from literature (Kongor *et al*., 2016; Lopez and Elsa, 2018; Abhay *et al*., (2016)).

In addition to moisture content, the model predicted water activity (a_w) in cocoa beans during drying to be 1. This prediction in a_w was also reported by Hii et al. (2009). This is a critical point where contamination from *Aspergillus* sp. and *Salmonella* can occur. Mycotoxic mould, such as *Aspergillus* sp. can contaminate the dried product with ochratoxin A (OTA) and cause serious human problems (Nwagu and Ire, 2011). Evidence of mould growth has been reported in cocoa beans with a_w between 0.80 to 0.70. In Brazil, Copetti et al. (2012) detected *Aspergillus* sp. of mould in cocoa beans from 29% of cocoa processors. The a_w in sun-dried Brazilian cocoa beans were between 0.8 and 0.7. The high a_w (0.70-1.0) during pre-conditioning and overnight resting is concerning. The risks for mould growth are higher during overnight resting period. A possible solution to minimise mould contamination could be to introduce low RH into the drying process after pre-conditioning the cocoa beans.

4.3.2 Temperature and relative humidity profile

Temperature gradient is the driving force for moisture evaporation during initial stages of drying but reducing the RH enhances drying. In the drying experiments, the temperature and RH of drying air stream at tray inlet were kept constant. There were deviations between the experimental temperature and RH profiles with model predictions. Temperature profile of air stream at 45 °C treatment showed variations across the drying chamber (Figure 4.7). Fluctuations in the temperature profile of the dying air stream was also evident at 55 °C treatment (Figure 4.8).

In drying treatment at 45 °C, the air temperature at tray inlet in Figure 4.7 A was comparable to model predictions during the 56 hours of drying. The only exception was a sudden increase in the air temperature for drying run 4 on day three of drying. This may have been caused by equipment handling error. Temperature profile of air stream at tray center and outlet along the drying chamber was lower than model predictions at 45 °C. At the end of drying, the air temperature for drying runs 3 and 4 on day three at the tray center was comparable to model predictions (Figure 4.7 B), while temperature profile of air at tray outlet on day 3 was lower for all drying runs (Figure 4.7 C). Air temperature for run 5 was 40 °C at tray centre but cooled to 30 °C towards tray outlet. Lower tray outlet temperature may imply a high moisture content in the product as the dry air absorbs moisture from wet cocoa beans as it passes through the drying chamber (Toneli *et al.*, 2013).

Variations in air temperature was also observed in drying treatment at 55 °C (Figure 4.8). Air temperature profile for drying run 6 was stable at tray inlet (Figure 4.8 A), tray center (Figure 4.8 B), and tray outlet (Figure 4.8 C). Temperature profile of the drying air stream for all drying runs fluctuated at tray inlet during day two and three of drying. The drying temperature for day two and three for all drying runs was between 45 to 55 °C at tray inlet and center. Temperature of air decreased at tray outlet for runs 1, 2, and 6 to 30 °C, which was close to ambient conditions (Figure 4.8 C).

Relative humidity conditions for the drying treatments also fluctuated along the drying trays. As drying progressed to day three, RH at the tray center declined to between 25 to 35% for both treatments (Figure 4.9 A and Figure 4.10 A). Moisture accumulation was more evident at tray outlet due to the high RH (65%) throughout the drying cycle for treatments at 45 °C (Figure 4.9 B) and at 55 °C (Figure 4.10 B).

Temperature and RH control during drying was challenging. Variations may have been caused by moisture absorbed by the marine ply used to fabricate the drying chamber. Condensation of moisture from overnight resting may have been absorbed by the drying chamber walls. Therefore, excess moisture during experimental runs may have had a cooling effect on the air stream and cocoa beans. The problem of moisture retention in the dryer walls can be resolved by applying varnish to the wood or by replacing the material with stainless steel. Thermal properties of the drying chamber fabricated with stainless steel would change and this would affect the drying kinetics of wet fermented *Theobroma cacao* beans.

An average air velocity of 0.25 m/s within the dryer may have been too low to push moist air through the drying chamber during the first two days of drying. This would have caused ‘dead zones' in the dryer. In the experimental drying runs, air flow was improved by applying a stator (motionless fan) along the exhaust pipe. Another future consideration could be to insert a blower in the dryer. A blower can overcome the pressure drop caused by packing of silica gel in the desiccant tube and increase drying air velocity to 1 m/s. Other possibilities for variations in the drying conditions are design flaws in the dryer, temperature and RH fluctuations during silica gel replenishment, and measurement errors. Developing a numerical simulation to predict moisture accumulation and poor air flow in the dryer could identify and limit the problem.

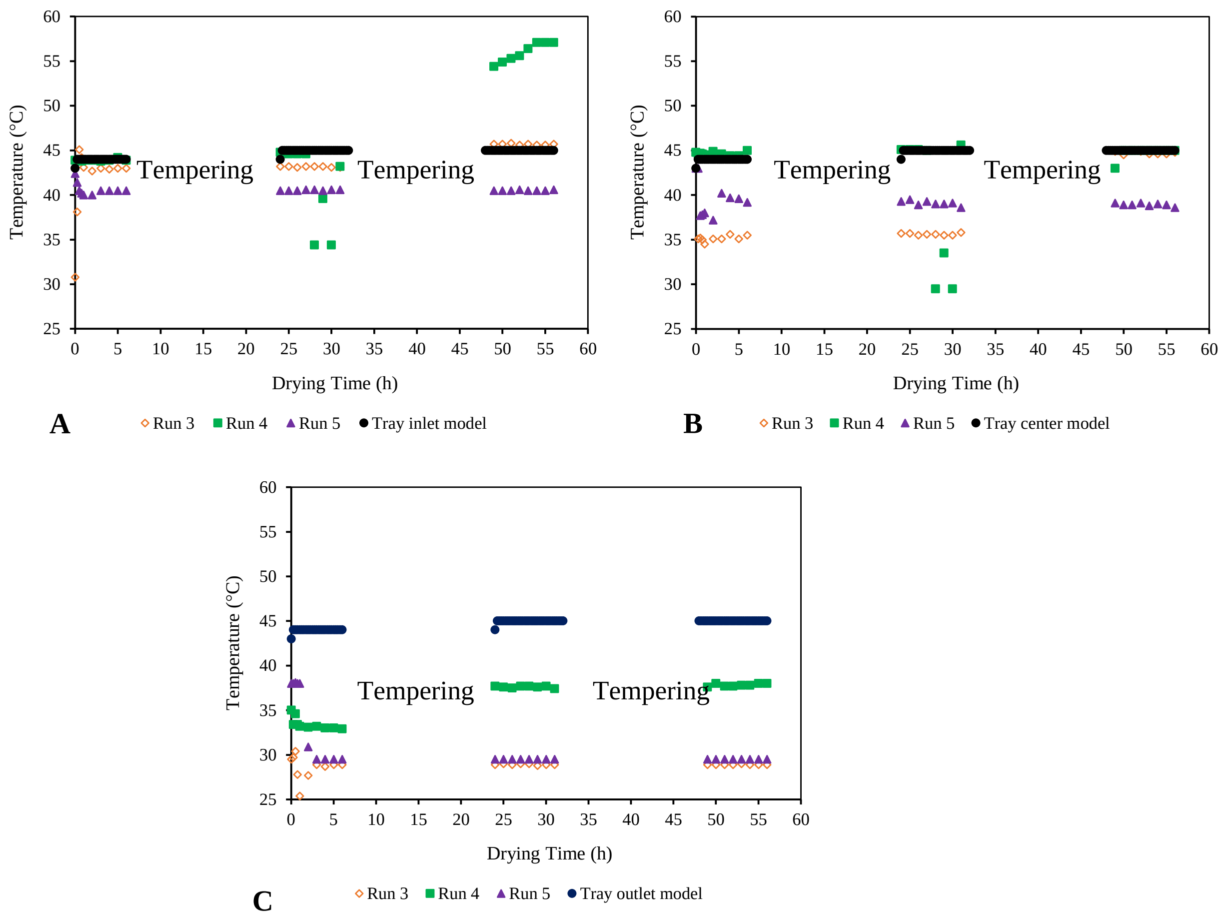


Figure 4.7. Temperature profile of air stream during drying fermented *Theobroma cacao* bean at 45 °C A. Tray inlet temperature profile, B. Tray centre temperature profile and C. Tray outlet temperature profile. Average experimental data from three drying runs are fitted with an average predicted temperature.

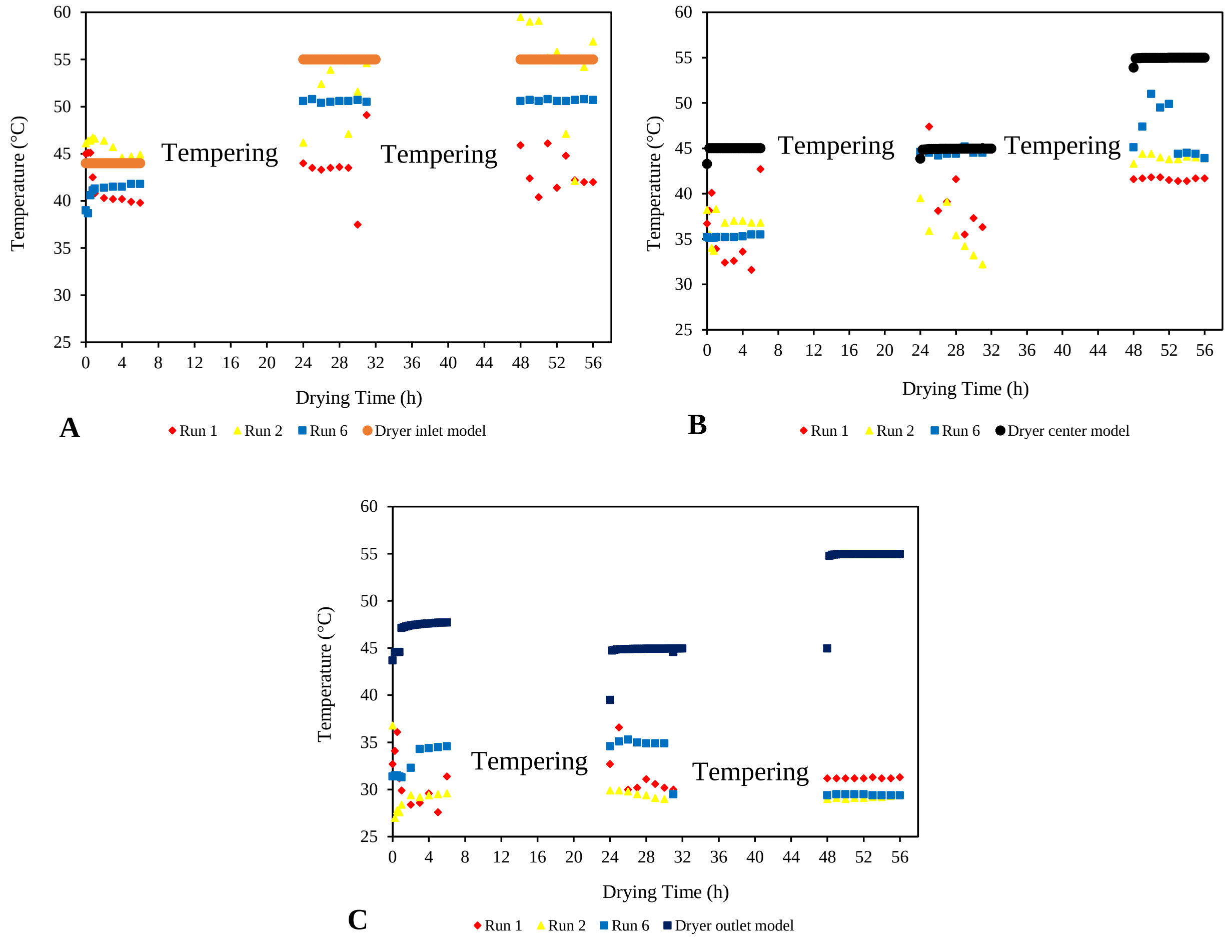


Figure 4.8. Temperature profile of air stream during drying fermented *Theobroma cacao* bean at 55 °C A. Tray centre temperature profile, B. Tray outlet temperature profile and C. tray outlet temperature. Average experimental data from three drying runs are fitted with an average predicted temperature.

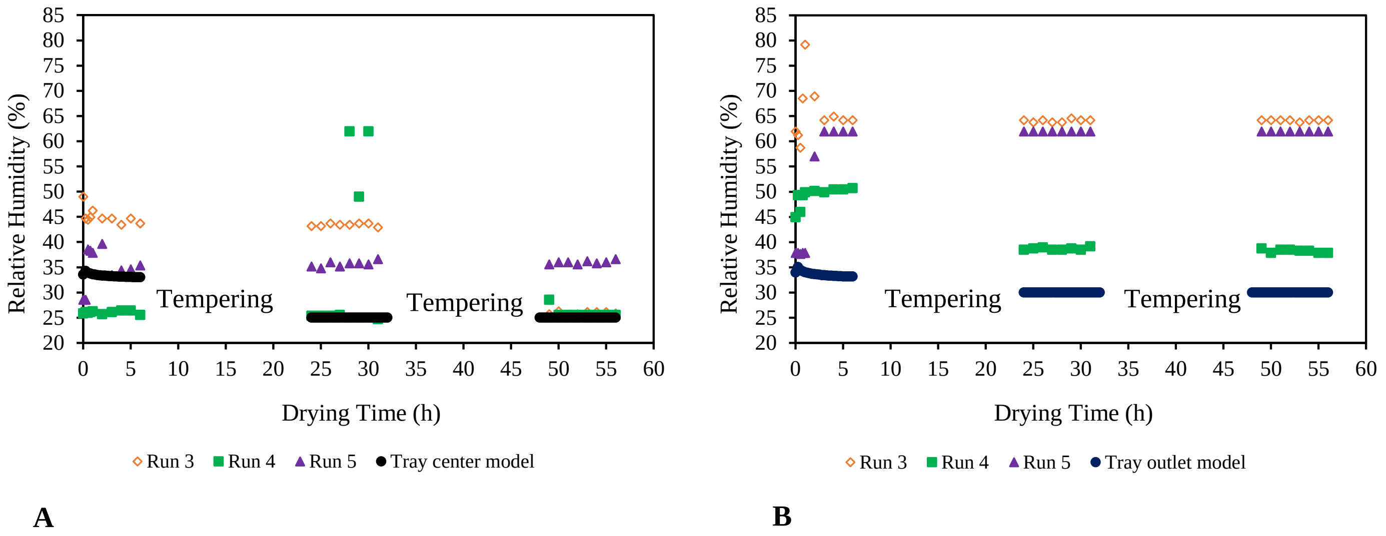


Figure 4.9 Relative humidity profile of air stream during drying at 45 °C A. tray centre and B. tray outlet.

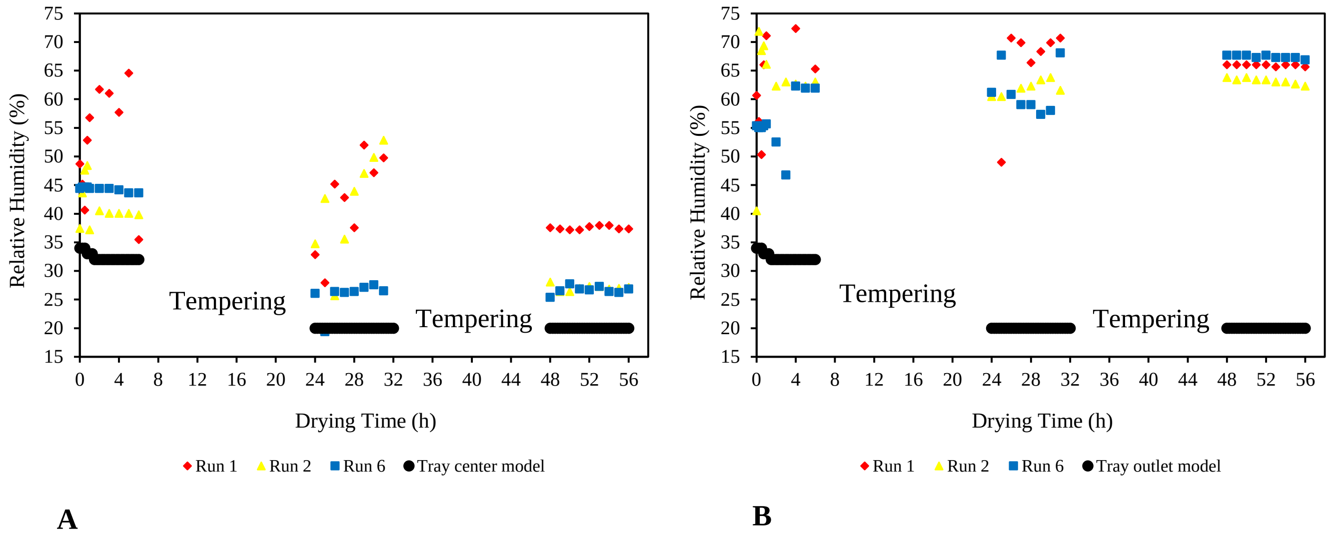


Figure 4.10. Relative humidity profile of air stream during drying at 55 °C A. tray centre and B. tray outlet.

4.4 Conclusion

Modelling and simulating the drying process can be used to explore various dryer designs and control the drying process. The mechanistic drying model developed for fermented cocoa beans was able to predict moisture loss and temperature of dry air stream for 56 hours of targeted drying time. The model solved the drying equation by simulating heat and mass transfer in dry air stream in the dryer, between dry air and bean surface along drying tray, as well as within the bean. While the model output for moisture loss was comparable to experimental data, acceptable levels of deviations were observed between predicted and experimental data. These deviations are common when moisture transport is lumped in the model. When the model assumes a lumped parameter and Fick's second law of diffusion then effectivity diffusivity is estimated by curve fitting using experimental data. The model assumes that there is no shrinkage and moisture migration is homogenous therefore the predictive model deviates from the experimental data towards the end of the drying.

Deviations between model and experimental temperature and RH were also recorded at different locations on the drying tray. These deviations increased at tray centre and outlet. Model equations considered average values of real ambient temperature and RH, therefore some variability in temperature and RH was present. While real time ambient conditions may have caused temperature variations in the drying system, the uneven moisture evaporation from cocoa bean between the drying trays can be another factor.

While the drying conditions were mild, a high thermal gradient enabled heat and mass transfer between cocoa beans and dry air stream. The model was simplified with a one-dimensional heat and mass transfer process in the bean. This could be further improved by considering a spatial distribution of temperature and moisture content within the bean. Overnight tempering in between drying enables temperature and RH gradients for the next drying cycle. This facilitates moisture loss by re-established boundary layer within the tempered cocoa beans.

The mechanistic model developed in this study for fermented Fijian *Theobroma cacao* beans can be used to predict drying time required to reach a safe acceptable moisture content of <10% (w.b) and a_w <0.65. This is possible between 45-55 °C and when the RH is consistently below 15%. Controlling the moisture content and a_w of cocoa bean before overnight resting can prevent product contamination from *Aspergillus sp.* and *Salmonella*.

The mechanistic model can be useful to determine optimum operating conditions for the desiccant based solar dryer. The drying conditions can be predicted based on variations in the daily solar cycle in Fiji and moisture content of wet fermented cocoa beans. The impact on these conditions on quality is reported in chapter 5, while the model sensitivity to input variables are reported in chapter 6.

Chapter 5. Impact of drying conditions on polyphenol and methylxanthine content in Fijian *Theobroma cacao* beans

5.1 Introduction

Organoleptic attributes, such as colour, aroma, and flavour are key quality parameters in dried *Theobroma cacao* beans. Some of these quality parameters are assessed by analysing moisture content, colour, bioactive components, and bean shape. Drying conditions, such as temperature and relative humidity (RH) enhance moisture loss and enable biochemical reactions that develop flavour and colour in cocoa beans. Various chemical compounds of interest, such as theobromine, caffeine, polyphenols, sugars, fats, and protein interact during drying to form key flavour precursors. The changes in these key chemical components during fermentation and drying are given in Table 5.1.

Table 5.1. A summary of key chemical composition of fresh and dried fermented *Theobroma cacao* bean

Cocoa Bean	Fresh bean composition %	Dried bean composition %	Dried fat free bean %
Water	32-39	4	-
Starch	4-6	6	14
Pentosans	4-6	1	3
Sucrose	2-3	2	4
Fat	30-32	53	-
Proteins	8-10	4	9
Theobromine	2-3	2	4
Caffeine	1	0.1	0.2
Acids	1	0.3	0.7
Polyphenols	5-6	6	17

*Source: Afoakwa et al. (2008)
*Percentage values are derived from dry bean weight

Fermented cocoa beans have a moisture content of 57-60% on a wet weight basis (w.b) (Bharath and Bowen-O'Connor, 2008). This is the initial moisture content of cocoa beans before drying. Effective drying reduces moisture content in cocoa beans from 60% to 6-8% (w.b). This deters mould growth and ensures safe storage. Moisture content is one of the key quality indicators of dried cocoa beans. Beckett et al. (2017) recommends drying cocoa beans to between 6-8% moisture content for long term safe storage, but in some cases the ideal moisture content for export quality cocoa beans could be 7% (w.b) (Kumar *et al.*, 2016). A list of standard moisture content by various organisations are presented in Table 5.2.

Table 5.2. International standards for moisture content in dried *Theobroma cacao* beans

Moisture content (w.b)	Reference
<8 %	FAO, Code of Practice for the Prevention and Reduction of Ochratoxin A Contamination in Cocoa (Cac/Rcp 72-2013)
8-55%	Philippine National Standard, 2019 (standards, 2019) World bank, 1985

Sun drying in the open for 14 days reduces the moisture content in cocoa beans to 16-10% (w.b) (Puello-Mendez *et al.*, 2017). Moisture content can be reduced to 7% (w.b) within 168 hours of drying using a simple solar dryer. This reduction in moisture content was reported for solar dried Columbian cocoa beans by Puello-Mendez et al. (2017). Drying conditions, such as temperature and RH can be manipulated to reduce the drying time required to reach a final dried moisture content of 7% (w.b). A combination of high temperature and low RH can reduce moisture content within a short drying period. This is critical towards controlling mould growth, but the adverse effects are quality issues, such as case hardening, shrivelling, and thermal degradation of key bioactive components.

Cocoa beans are thermally sensitive, and the biochemical quality deteriorates easily under rapid (McDonald *et al.,* 1981). High temperature conditions limits oxidation and impedes biochemical reactions that form flavour precursors and brown bean colour caused by tannins and quinones. A decline in quality parameters can have a negative impact on Fijian *Theobroma cacao* beans dried for commercial export markets. Suggesting the application of solar dryers may be a hygienic solution to reduce the drying time but the temperature profile in simple solar dryers could exceed 60 °C, which has been mentioned in chapter 2 to be detrimental on the bioactive components and physical integrity of the cocoa beans. A review of literature presented in chapter 2 suggests that low RH during drying improves the drying kinetics of *Theobroma cacao* beans. The impact of reducing RH under mild temperature conditions on key bioactive components that form flavour precursors during downstream processing of chocolate have not been extensively reported. Several studies have briefly reported a positive impact of mild temperature on heat sensitive bioactive compounds in cocoa beans (Hii *et al.*, 2011; Hii *et al.*, 2009; Menon *et al.*, 2017; Teh *et al.*, 2016). However, these studies did not reduce the RH conditions during drying.

Low RH increases the vapour pressure gradient between cocoa bean and the drying air stream. This accelerates diffusion of internal moisture and acetic acid to the bean surface. While there are several technologies mentioned in chapter 2 that can reduce the drying time, the desiccant wheel technology (DWT) driven by solar collectors could be a better solution for drying heat sensitive food. The effects of pre-estimated drying parameters on moisture and polyphenolic compounds in Fijian cocoa beans were simulated from a desiccant based drying system in this research. Variations in these key quality parameters in cocoa beans dried under dehumidified and mild temperature conditions need further investigation.

The key quality parameters in dried cocoa beans are final dried moisture content and bioactive compounds that develop flavour precursors during roasting. The drying conditions with a six-hour pre-conditioning phase followed by a 12 h overnight resting and drying under dehumidified conditions for eight hours were tested in this study. The impact of various temperature conditions at <20% RH on selected quality parameters was tested analytically. The objective of this chapter was to test the impact of selected drying conditions estimated from a theoretical desiccant wheel based solar dryer model on polyphenolic compounds and methylxanthine content in fermented Fijian cocoa beans. The bioactive components of interest were total extractable polyphenols, theobromine, and caffeine.

5.2 Materials and method

Mature and ripe *Theobroma cacao* beans (30 kg) of the Forastero variety were naturally fermented at the Fiji Ministry of Agriculture's Naduruloulou research station in Suva, Fiji. Drying tests were conducted at the Institute of Applied Sciences (IAS) at the University of the South Pacific (USP). Prior to drying tests, fermentation was conducted for six to seven days in wooden boxes (0.1 m^2) that were 0.3 m deep. Further details on the dimensions of the wooden box given in Table 5.3. Fermentation was conducted under ambient Fijian weather conditions. Cocoa beans were extracted from cocoa pods harvested late in the season in November 2018 for drying experiment 1 and between April to May for drying experiment 2.

Table 5.3. Dimension of fermentation box used for fermenting *Theobroma cacao* beans

Dimensions	Measurements	Unit
Width	0.5	m
Length	0.5	m
Depth	0.3	m
Area	0.2	m^2
Volume	0.1	m^3

*A wooden fermentation box was used

5.2.1 Quality analyses protocol

Quality attributes of fermented and dried *Theobroma cacao* beans were analysed at the food chemistry laboratory and Riddet Institute at Massey University in Palmerston North, New Zealand. Other analyses, such as moisture content and cut test during fermentation and drying were analysed at IAS, USP in Suva, Fiji Islands. A summary of quality analyses is presented in the concept flow diagram in Figure 5.1.

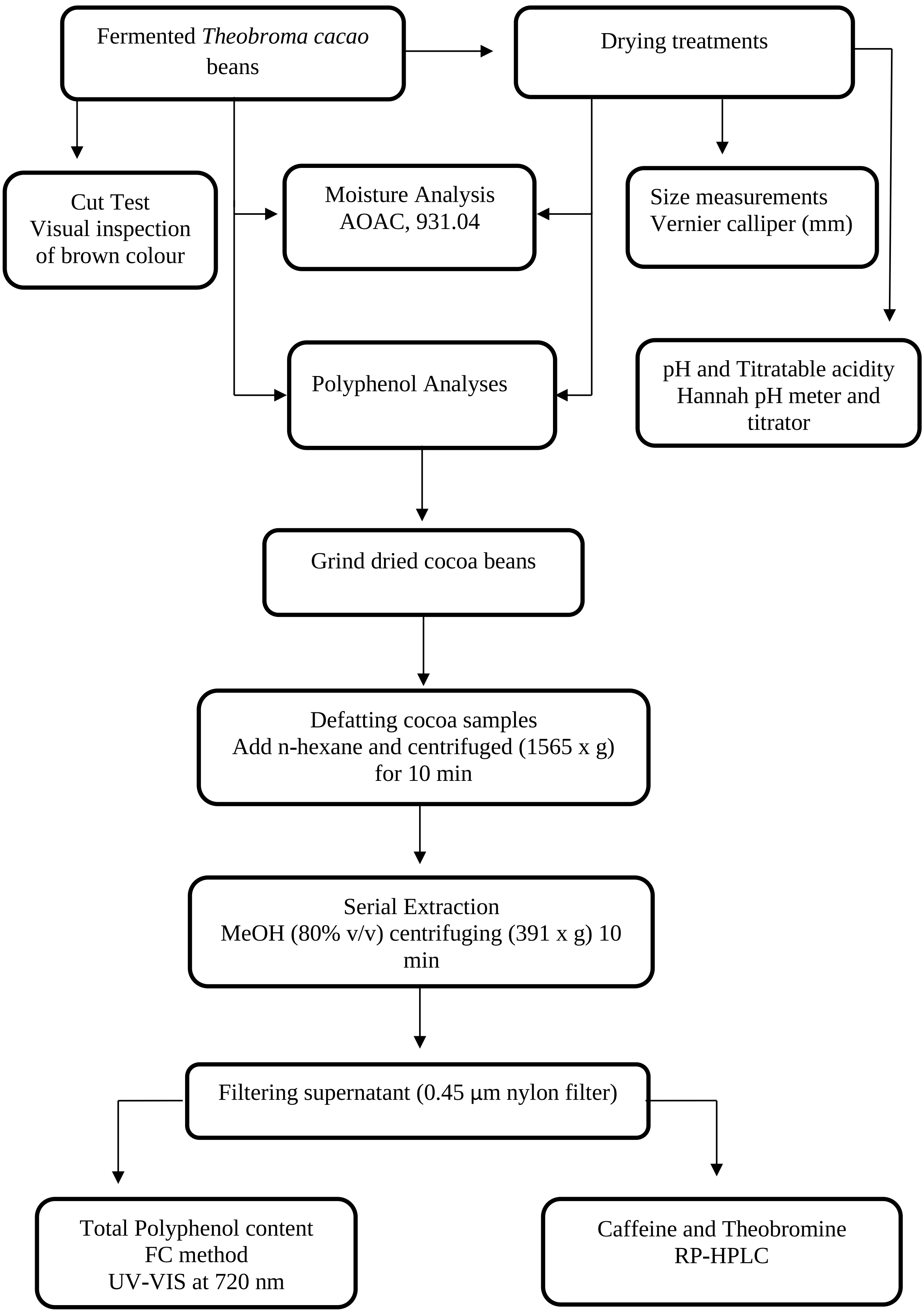


Figure 5.1. Conceptualised flow chart of analytical procedures for quality analyses of fermented and dried *Theobroma cacao* beans

5.2.2 Cut test assessment on fermented *Theobroma cacao* beans

Quality control of cocoa beans during fermentation was visually conducted using a cut test using protocols from Camu et al. (2007) and Schwan et al. (1995). A longitudinal incision along the cotyledon (bean) was conducted for a visual assessment of colour. A total of 300 cocoa beans per fermentation batch were assessed for colour change. These scores for each colour were later converted to a percentage value to demonstrate fermentation intensity. The colour profiles noted were:

1. Brown beans – fully fermented
2. Partly brown or partly violet/ purple beans – under fermented
3. Fully purple – unfermented
4. Slaty beans – spoilt beans

The proportion of fully fermented beans was calculated as a percentage.

5.2.3 Fermentation index

Fermentation index is a colorimetric assessment of anthocyanin pigments after fermentation. Sub-samples (n = 50) from three batches (25 kg) of fermented cocoa beans over two harvest seasons were tested for fermentation index (FI). The procedure was adapted from Misnawi (2009). The pigments from fermented and dried cocoa beans were extracted using a standard extraction protocol. A mixture of MeOH: HCl solution (97:3 v/v) was used for extraction. Cocoa extracts were measured at 420 nm and 560 nm to detect presence of anthocyanins. FI was calculated using the following formula:

$$FI = \frac{Absorbance\ value\ at\ 420\ nm}{Absorbance\ value\ at\ 560\ nm} \quad (1)$$

5.2.4 Drying treatments

Details of dryer and experimental design have been discussed in chapter 4. Drying experiments consisted of three drying runs for each temperature treatment (30, 45, and 55 °C) at <20 % RH with an average air velocity of 0.25 m/s. Details of experimental runs and drying conditions are mentioned in Table 5.4. During the drying process, the cocoa beans were sampled before drying runs at 0 h and after drying terminated at 56 h. This was done to prevent disturbance to the drying process. Samples were collected from top, middle, and bottom trays at inlet, center, and outlet areas.

Table 5.4. Drying tests on Fijian Forastero *Theobroma cacao* beans in Fiji

Drying Run	Recorded Temperature °C	Recorded Relative Humidity (%)
1	47 ± 8	42 ± 3
2	48 ± 6	32 ± 8
3	40 ± 8	30 ± 9
4	45 ± 10	27 ± 3
5	36 ± 7	28 ± 6
6	40 ± 9	25 ± 1

*Average values of temperature and RH are reported with standard deviation

5.2.5 pH and titratable acidity

Dried cocoa beans (5-10 g) were finely ground and homogenised in 100 mL of hot boiling deionised water. The solution was mixed for 30 seconds. The cooled mixture was filtered using a No. 2 Whattmans® filter paper with a vacuum pump. The procedure was adapted from Afoakwa et al. (2013) and AOAC 42.1.04 (1995).

Cocoa bean pH was measured using Hannah professional titrator (HI901, Indonesia). The equipment was sensitive to the pH range of ± 2 with a resolution of 0.1, 0.01, and 0.001. Accuracy of pH measurement at 25 °C was ± 0.001. The standard pH analysis involved using a pre-calibrated probe to measure pH of a solution made from pulverised cocoa beans dissolved in hot distilled water, cooled to room temperature (25 °C).

Titratable acidity (TTA) was measured using 25 mL of aliquot (filtered CE). This was titrated to an endpoint of pH of 8.1 with 0.1 N NaOH. Titratable acidity was expressed as milliequivalent of NaOH per g of dry sample.

5.2.6 Preparation of dried *Theobroma cacao* samples for chemical analyses

Dried cocoa beans (200 mg) were ground and defatted using 2 mL of n-hexane. The mixture was centrifuged at 1565 *g* for 10 min. The supernatant was decanted, and the procedure repeated thrice. Serial extraction of defatted sample was done using 1.5 mL of methanol (80% v/v) followed by centrifuging for 10 min at 391 *g* at 4 ˚C. The supernatant was filtered for further analysis. A 1:20 dilution of filtered extracts was used for all analyses. The schematic flow chart shown in Figure 5.1 conceptualises quality analysis parameters applied on fermented and dried *Theobroma cacao* beans. The defatted methanolic cocoa bean extracts (CE) were analysed for total extractable polyphenol content (TPC) and alkaloids at the Food chemistry lab at MU in Palmerston North, New Zealand.

5.2.7 Analysis of total extractable polyphenol content

Analyses for total extractable polyphenol content (TPC) on defatted cocoa beans was conducted on a UV-Vis spectrophotometer. Gallic acid was used as a standard to calculate the TPC from CE. Stock solutions of gallic acid were prepared in 10% methanol (v/v) and stored in amber screw-capped glass vials in the dark at -20 °C. Gallic acid solution of 10 g L^{-1} was serial diluted at concentrations of 0.05, 0.1, 0.15, 0.25, 0.5, 1, 1.5, 2, 5, and 7 g L^{-1} for standard calibration curves. These standards were analysed with a benchtop UV-Vis spectrophotometer (Thermo Fisher Scientific, USA). The equation from standard curve was used to calculate total polyphenol content in fermented and dried cocoa beans (Figure 5.2).

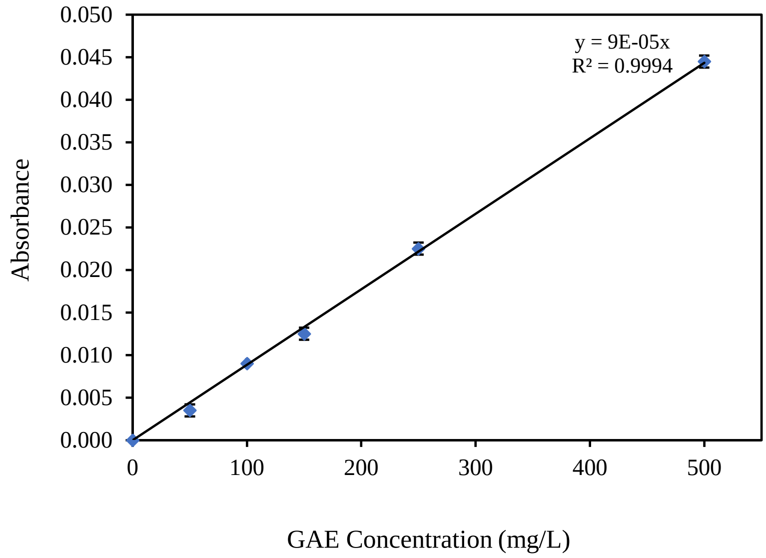


Figure 5.2. Standard calibration curve for gallic acid extract used for calculating the total extractable polyphenol content in defatted Fijian *Theobroma cacao* beans

The methanolic CE was analysed by mixing 20 µl of CE into 2 cm^3 cuvettes with 1.58 ml water and 100 µl of FC agent. This solution was left for 60 seconds in the dark and mixed with 300 µl of 20% sodium carbonate solution (w/v). This solution was incubated in the dark at 20 °C for 20 minutes. The absorbance of the incubated sample was recorded at 765 nm against a blank.

5.2.8 Analyses of caffeine and theobromine

Stock solutions of caffeine and theobromine were prepared in methanol and stored in amber screw-capped glass vials in the dark at -20 °C. The working solution for caffeine was prepared at 0.0008 g L^{-1} and theobromine was 0.0001 g L^{-1}. The calibration curves for caffeine standards were prepared at concentrations of 25, 50, 75, 100, 125, 150 and 175 µg L^{-1}. The calibration curves for theobromine standards were prepared at concentrations of 200, 400, 600, 800, 1000, 1200, 1400 and 1600 µg L^{-1}. Standard curves of caffeine and theobromine at 275 nm were established (R^2 = 0.9999).

5.2.8.1 RP-HPLC conditions

Caffeine and theobromine were identified and confirmed using RP-HPLC (Agilent Technologies) with PDA equipped with autosampler at a wavelength of 275 nm and at 10 °C. A Luna C18 reversed-phase chromatographic column (2.1 x 100 mm, 5 µm – Phenomenex, Ca, USA) operating at a temperature of 26 °C was used in the analysis of alkaloids in cocoa beans. A 1.0 µL injection volume was employed. The detailed working conditions and parameters of the RP-HPLC system used for identification of compounds are provided in Table 5.5.

Table 5.5. RP-HPLC gradient settings for caffeine and theobromine

Time (min)	%A	%B	Flow rate (mL min^{-1})
0	94	6	0.75
1	94	6	0.75
8	75	25	0.75
30	25	75	0.75
35	25	75	0.75
35.50	94	6	0.75

*Eluent solvent A – MQ H_2O + 0.1% HAC

*Eluent solvent B- MeOH 100%

Theobromine eluted first at 10 minutes followed by caffeine around 15 minutes. This was comparable to retention times found by Pelaez et al. (2016). The chromatograms of theobromine and caffeine standards are given in Figure 5.3.

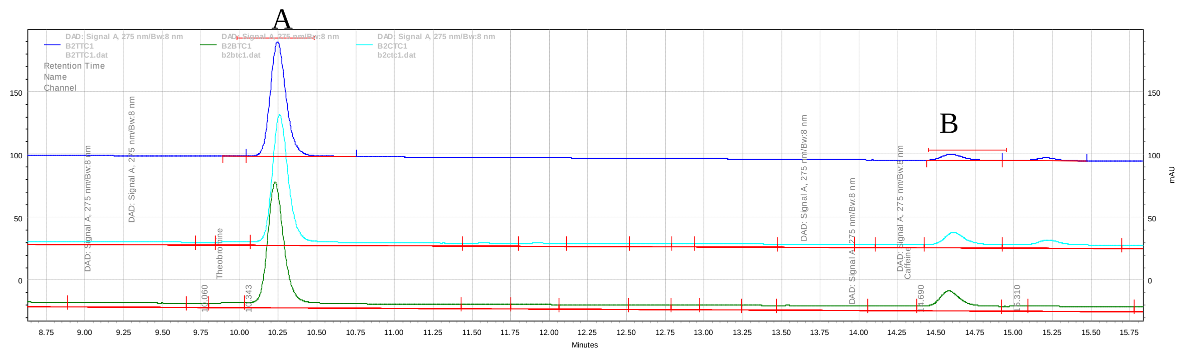


Figure 5.3. HPLC (UV–vis) chromatograms of standards. The chromatogram shows (A), theobromine (B) caffeine (275 nm).

Analytical standards (Table 5.6) were obtained from Sigma Aldrich (Saint Louis, Missouri, USA). General reagents in Table 5.7 were obtained from Merck (Kenilworth, New Jersey, USA), Thermo Fisher scientific (Auckland, New Zealand), and Sigma Aldrich (Saint Louis, Missouri, USA).

Table 5.6. List of analytical standards and compounds used in this study

Compound	CAS No.	Supplier
Caffeine	58-08-2	Sigma-Aldrich
Gallic acid	5995-86-8	Sigma-Aldrich
Theobromine	83-67-0	Sigma-Aldrich

Table 5.7. List of general reagents used for chemical analyses

General Chemicals	CAS No.	Supplier
Acetic Acid	64-19-7	Sigma-Aldrich
Ammonia	1336-21-6	Sigma-Aldrich
Ethanol	64-17-5	Sigma-Aldrich
HCl	7647-01-0	Sigma-Aldrich
Hexane	110-54-3	Sigma-Aldrich
Methanol	67-56-1	Sigma-Aldrich
Sodium carbonate	497-19-8	Sigma-Aldrich
Sodium Hydroxide	1310-73-2	Sigma-Aldrich

5.2.9 Statistical analysis

Statistical analysis of experimental data was performed using Minitab (Minitab 18, USA). All data were reported as the mean (μ) ± standard deviation (σ) from replicate analysis. Experimental data was compared for differences in means using ANOVA general linear methods with Tukey's test at an alpha value set at $p<0.05$.

5.3 Results and discussions

Theobroma cacao contains complex chemical compounds that impart sensory qualities to chocolate. The final fermented cocoa bean quality is affected by the drying conditions. Polyphenolic compounds, such as total polyphenols, caffeine, and theobromine were sensitive to drying temperature conditions and time. The best drying conditions with maximum retention of these polyphenolic compounds are identified from experimental drying conditions. Thermal processing of cocoa beans involved drying treatment at 30, 45, and 55 °C.

The bioactive components in cocoa beans are sensitive to pH during fermentation and drying (Hii *et al.*, 2009). Drying treatments had minimum variations in the final dried bean pH (Table 5.8). This may have been caused by a small sample size selected for analysis. The pH measurements of Fijian cocoa beans from this study were comparable to findings from a study by Afoakwa et al. (2015), where mixed hybrid cocoa varieties from Ghana were sun-dried for seven days. The pH of Ghanaian cocoa beans was between 5 to 6, which is considered ideal for the development of cocoa-specific flavour during roasting (Afoakwa *et al.*, 2015). Similar findings were also reported by several studies in published literature by Hii et al. (2006) for cocoa beans in Malaysia, Afoakwa et al. (2015) for Ghanaian cocoa beans and by Jinap and Dimick, (1990) and Barrientos *et al.*, 2019 for sun-dried cocoa beans from the Solomon Islands. These findings reported in literature do not specify the cultivar of cocoa. While pH may be used in various studies to express the level of acidity, TTA is a more accurate measure to assess organic acids and ionised fractions of acids (Sandler and Murphy, 2010).

Table 5.8. pH and total titratable acidity in Fijian *Theobroma cacao* beans dried at different temperature conditions

Samples from different drying conditions	pH	Standard deviation	Total Titratable acidity mEq NaOH/g dry sample	Standard deviation
30 °C	5.7a	±0.6	0.1	±0
45 °C	5.8a	±1.0	0.3	±0.2
55 °C	5.6a	±0.4	0.1	±0.1

*Values presented are average from composite dried samples with no statistical difference
*Mean values that share same letters are not statistically significantly different

In addition to chemical analyses, a visual parameter of colour change is also extensively applied to monitor fermentation quality through a cut-test. Visual assessment of fermentation quality is conducted using a cut test to measure colour change from purple to brown. The colour change observed in Fijian cocoa beans assessed by the cut test was comparable to fully fermented cocoa beans reported in literature by Niemenak et al. (2014). Brown colour change is caused by oxidation and hydrolysis of purple polyphenolic compounds to anthocyanidins. Dark coloured tannins and quinones are formed when anthocyanidins polymerise with catechins. This colour change is ideal during fermentation.

Seasonal variation was observed between biannual harvests. Fermented cocoa beans from mid-season harvest recorded a cut test percentage of 63% compared to 99% during warmer main harvest season. Rainy weather conditions with cooler temperatures from May to July mid-harvest period may be the reason for a low cut-test percentage. The cut test scores are comparable to a study by Indarti et al. (2011), which used Malaysian standards to measure fermentation quality of cocoa beans. The Malaysian standards (SIRIM) for cocoa beans to be classified as fully fermented are based on brown colour and a cut test score of more than 60% for a fermented batch (SIRIM, 2005). Conversely, some cocoa processors consider cut test score of more than 40% as a good indicator for fermentation in Malaysia (Khairul, 2014). A diagram of a cut test on fermented Fijian cocoa beans is presented in the appendix section of this thesis in Figure 20.

A more accurate technique for assessing fermentation quality is to assess colour change using the fermentation index (FI) test. The FI index provides a reliable measure for assessing fermentation quality (Shamsuddin and Dimick, 1986; Takrama *et al.*, 2006). This laboratory-based technique measures the intensity of brown colour development in methanolic extracts of cocoa beans during fermentation. The measurement is based on an absorbance ratio of 460 nm/530 nm. This absorbance range detects polyphenols and anthocyanins. Polyphenolic compounds absorb UV light more strongly at 460 nm, while 530 nm is λmax for anthocyanin spectra.

During the first 96 h of fermentation, 93% of anthocyanins are polymerised with catechins (Wollgast and Anklam, 2000). Therefore, higher FI (>1) values are expected as this indicates that anthocyanins have oxidised completely, and fermentation is complete. The average FI presented in Table 5.9 for fermented and dried cocoa bean samples from mid and main harvest seasons was greater than 1. (FI ≥ 1). An FI value of greater than 1 indicates that the cocoa beans are fully fermented. The FI value for Fijian cocoa beans in this study is the same as the FI reported in literature by Romero-Cortes et al. (2013), Racine et al. (2019), and with the Malaysian standards for grading cocoa beans (SIRIM, 2005).

Table 5.9. Fermentation index of box fermented Fijian *Theobroma cacao* beans (var. Forastero) under ambient conditions

Harvest Season	Batch No.	Fermentation Time (h)	Fermentation Index	SE
Mid-season	1	0	0.870	± 0.003
		48	0.939	± 0.009
		96	0.991	± 0.005
		168	1.048[a]	± 0.007
Main season	2	168	1.389[b]	± 0.019
	3	168	1.250[c]	± 0.015

*Values presented are average values from composite samples (n=53) or replicates from each batch for 168 h samples
*Means with different letters are statistically significantly different ($p<0.05$)
Statistical analysis using ANOVA show a difference between sample means ($p<0.05$) and F >F critical.

The FI index data for cocoa beans fermented for seven days was analysed statistically using ANOVA. Statistical analysis showed a difference between sample means, where $p<0.05$ and F>F critical. Variations between each fermented batch may have been caused by the spontaneous nature of fermentation and ambient weather conditions. Despite these variations in FI between harvest seasons, the fermentation index after seven days of fermentation was greater than 1 (FI ≥ 1). This means that the fermentation process was complete for both harvest seasons.

5.3.1 Impact of drying conditions on polyphenol and methylxanthine content

Polyphenols are the dominant compound in cocoa beans (Rusconi and Conti, 2010). During downstream processing, cocoa polyphenols react with lipids and proteins to form important flavour precursors. Polyphenolic compounds are found within the chromophores in parenchyma of cocoa bean cotyledons. The disintegration of cellular membranes releases polyphenolic compounds from the chromophores as cellular fluid leaches out. The aeration process during bean rotation in the fermentation process causes oxidation of these phenolic compounds, which darkens the colour of fermented cocoa beans. These phenolic compounds can be detected in methanolic cocoa extracts (CE) using Folin-Ciocalteou (FC) method, which is a low cost and rapid colorimetric technique. The analytical protocol uses ultraviolet-visible spectrophotometer and a reference standard, such as Gallic acid.

The chemical reaction in the FC technique is explained by Blainski et al. (2013). The FC reagent reacts with polyphenolic compounds to form a blue complex, which is detected and quantified under a blue wavelength of light. Maximum retention of chromophores from CE is influenced by an alkaline pH of the solution, which deteriorates the FC reagent. Instead of using excess reagent which increases turbidity and hinders accurate detection, the reagent was mixed with sodium carbonate to allow redox reactions to occur. The application of FC reagent using UV-Vis to detect polyphenolic compounds is described to be rapid but accurate as colour change in these compounds occur based on reaction kinetics (Cicco *et al.*, 2009).

Cocoa polyphenols are temperature sensitive and generally decline during primary processing. While fermentation causes a reduction in the total extractable polyphenol content (TPC), the drying temperature and duration also have an impact on these thermally sensitive compounds and on polyphenol oxidase (PPO) (Abhay *et al.*, 2016). PPO is active between 20 to 50 °C but degrades within a short period of exposure when the temperature increases above 60 °C (Mizobusti *et al*., 2010). In this study, a drying temperature of 45 and 55 °C under 20% RH was tested on 6 ± 1 kg of fermented cocoa beans in Fiji and compared to sun-dried samples. These experimental conditions are comparable to a study by Kyi et al. (2005) on Malaysian cocoa beans where a temperature of 40 and 60 °C under 50 and 80% RH was tested on polyphenol oxidation. PPO is active at around 40 °C but is sensitive at higher temperature conditions (Abhay *et* al., 2016).

Fermented cocoa beans used for drying experiments had a 38% reduction in TPC. This reduction in TPC was caused by temperature rise and decline in pH during fermentation. Fermented cocoa beans with an average extractable TPC of 43 mg GAE/g dry bean were used for drying experiments under different treatment conditions. Table 5.10 shows the impact of drying conditions on TPC in cocoa beans under different drying treatments in Fiji. Polyphenols were sensitive to 55 °C treatment ($p<0.05$). Cocoa beans dried under milder conditions between 30 to 45 °C showed a retention in the polyphenols when compared to 55 °C treatment. Several studies report that polyphenol concentration is temperature dependent (Mizobusti *et al.*, 2010; Teh *et al.*, 2016; Abhay *et al.*, 2016; Menon *et al.*, 2017).

Table 5.10. Total extractable polyphenol content in Fijian *Theobroma cacao* beans (var. Forastero) at various treatment conditions

Treatment conditions	Run 1	SD	Run 2	SD	Run 3	SD
30 °C[1]	57	5	53	9	21	4
45 °C	59	5	42	4	35	2
55 ° C	31	8	28	2	36	2

*Results presented are average values from three experimental runs per treatment
*[1]Samples dried at 30 °C (sun dried) at 75% RH for 14 days
*SD means standard deviation

Although the drying runs were set to 45 or 55 °C, the actual temperatures achieved are showing as not significantly different. the temperature gradient may have caused deterioration of polyphenols. The total extractable polyphenols declined noticeably to 60 mg GAE/g of dry defatted cocoa bean when the air temperature was above 40 °C in Figure 5.4 for 45 °C treatment and in Figure 5.5 for 55 °C treatment. Variations in air temperature in the drying chambers at 55 °C treatment may be caused oxidation and thermal degradation of polyphenols (Table 5.12). There may have periods of time where the drying chamber experienced higher temperature, which may have caused all degradation of polyphenols in all samples (Figure 5.5). Further investigation into the drying air temperature profile could provide more insight on temperature variations during the early stages of drying. Free surface moisture during the initial stages of drying may influence polyphenol oxidation.

Temperature profile of different tray zones shows that trays in lower areas of the dryer had a cooler temperature profile when compared to upper parts. Thermal degradation was evident in cocoa beans dried on top trays at 55 °C treatment. Kyi et al. (2005) and Abhay et al. (2016) found that temperature conditions between 40 to 60 °C and a high moisture content (50-80% (w.b)) were two factors that influenced oxidation of polyphenol. Despite the decline in polyphenols based on temperature conditions, the TPC retained the ability to impart an astringent flavour to chocolate (Kyi et al., 2005). There are no set standards for TPC in dried Fijian cocoa beans but the composition of TPC in chocolate was estimated from the percentage cocoa used during processing.

In addition to residual levels of polyphenols in cocoa beans, the presence of glycoalkaloids also enhances the sensory profile by imparting the characteristic bitter flavour in chocolate. These glycoalkaloids are also classified as methylxanthines and include theobromine and caffeine. In addition to health benefits, caffeine, and theobromine have been known to have a stimulating effect, which enhances the sensory characteristics of chocolate made from good quality cocoa beans (Araujo *et al.*, 2014; Nehlig, 2013).

Table 5.11. Temperature variations on drying trays during drying cocoa beans at 45 °C

	Run 3		Run 5	
	Mean Temperature °C	SD	Mean Temperature °C	SD
Top tray	40.4[a]	5.9	44.6[a]	0.3
Centre tray	38.4[a]	5.9	30.6[b]	2.1
Bottom tray	32.2[a]	5.4	26.2[c]	0.3

*Means with different letters and numbers are statistically significantly different (p<0.05)

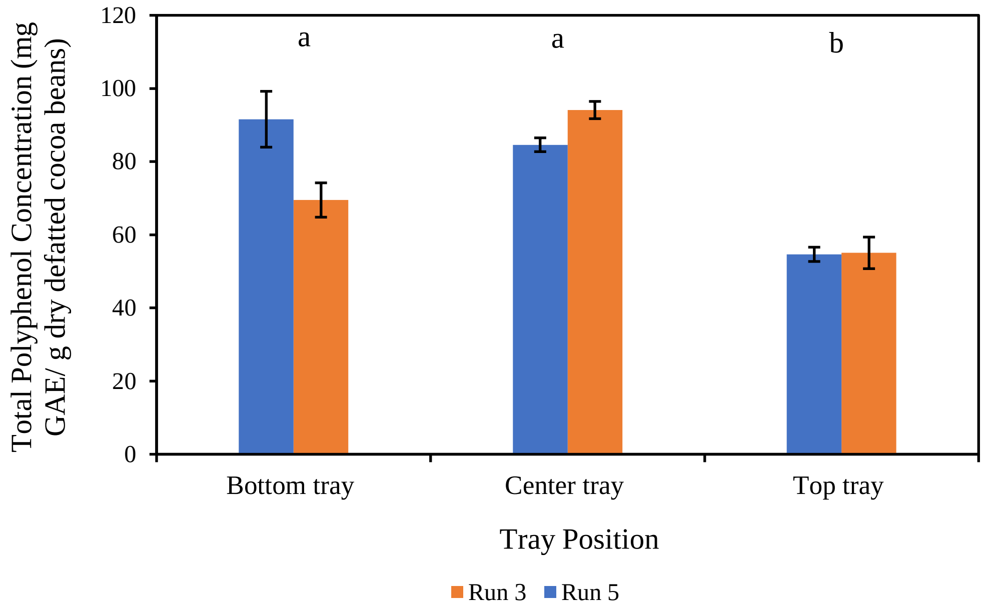


Figure 5.4. Variations in total extractable polyphenol content in Fijian *Theobroma cacao* beans (*var*. Forastero) on various tray positions in the dryer at 45 °C. Results presented are average values for samples treated at 45 °C. Means with different letters are statistically significantly different (p<0.05).

Table 5.12. Temperature variations on drying trays during drying cocoa beans at 55 °C

	Run 2		Run 6	
	Mean Temperature °C	SD	Mean Temperature °C	SD
Top tray	47.9[a]	3.0	53.2[a]	1.3
Centre Tray	43.8[b]	3.3	50.8[a]	3.0
Bottom tray	32.7[c]	1.0	34.0[c]	0.5

*Means with different letters and numbers are statistically significantly different (p<0.05)

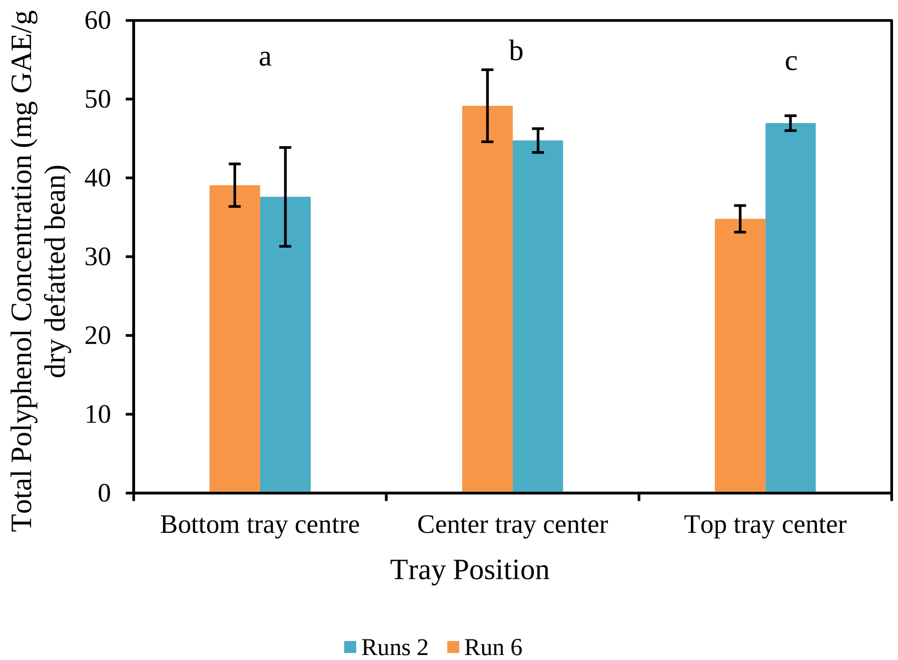


Figure 5.5. Variations in total extractable polyphenol content in Fijian *Theobroma cacao* beans (*var*. Forastero) on various tray positions in the dryer at 55 °C. Results presented are average values for samples treated at 55 °C. Means with different letters are statistically significantly different (p<0.05).

The naturally bitter flavour of cocoa beans is imparted by theobromine. The theobromine and caffeine content in cocoa beans are influenced by the variety of cocoa, maturity of the cocoa pods, geographical conditions, and processing temperature. Cocoa beans contain 2-4% theobromine by dry weight and 0.1-0.2% of caffeine (Carrillo *et al.*, 2014). Theobromine and caffeine content in cocoa beans are affected by acidification during fermentation. Acidification causes about 30% of these compounds to leach out of the bean and into the testa (Camu *et al.*, 2008). Fermentation and drying temperature conditions can reduce theobromine content by 21% and caffeine by 60% (Pelaez *et al.*, 2016).

Theobromine content in Fijian cocoa beans from three drying runs at each temperature treatment are presented in Figure 5.6. Drying temperature conditions did not show any significant impact on the theobromine concentration (p>0.05). This suggests that theobromine was relatively stable under drying conditions (30 to 55 °C). Theobromine content varies from 2 to 4% in dried cocoa bean samples (21 to 26 mg/g dry bean). In Fijian dried cocoa beans, the theobromine content was slightly higher than this range as the Forastero variety of cocoa bean generally contain the high levels of theobromine (Timbie, Sechrist & Keeney (1978)).

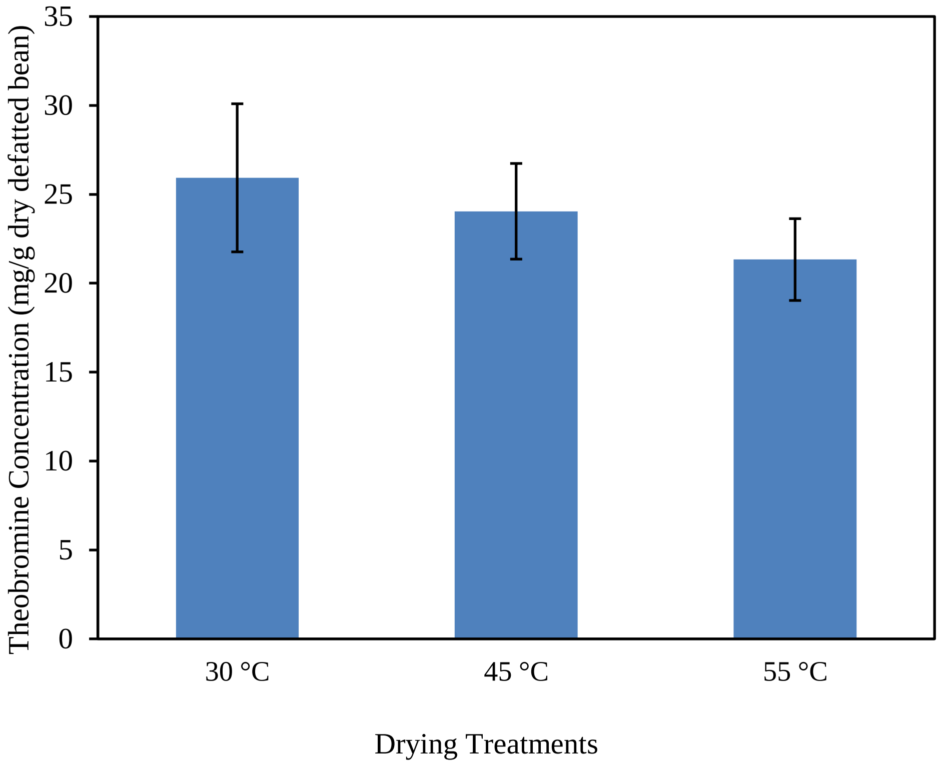


Figure 5.6. Impact of various processing conditions on theobromine concentration of Fijian *Theobroma cacao* beans (*var*. Forastero). Results presented are average values from each treatment condition for 30, 45, and 55 °C.

Another factor that may have influence the theobromine content in cocoa beans is the defatting procedure during sample preparations. This has been experienced during the processing of cocoa liquor by Gil (2012), Deus et al. (2018), and Biehl (1973). Theobromine is hydrophobic and fat removal during sample extraction could have caused losses in the lipid portions. Biehl (1973) explains that fat isolates the hydrophilic constituents, such as theobromine in cocoa beans during fermentation. Several studies have also mentioned that free theobromine diffuses from the bean and into the testa (Brunetto *et al.*, 2009; Adeyina *et al.*, 2008). The average theobromine content in cocoa cotyledon (bean) and testa from selected drying conditions are presented in Figure 5.7. Theobromine content in the testa and bean component of cocoa beans dried at 45 °C was comparable to testa and beans sun-dried at 30 °C.

Table 5.13. Theobromine concentration in Fijian *Theobroma cacao* beans (var. Forastero) dried on various tray positions at 45 °C drying treatment

	Run 3	SD	Mean Tray Temperature °C	Run 5	SD	Mean Tray Temperature °C
Top tray	22.6^{b}	7.4	40.4	18.4^{a}	9.7	44.6
Centre tray	25.8^{b}	0.1	38.4	24.4^{b}	0.6	30.6
Bottom tray	20.4^{b}	0.7	32.2	16.8^{a}	1.4	26.2

*Results are presented as average values from two drying runs in Fiji.
*Means of theobromine with different letters are statistically different ($p<0.05$).

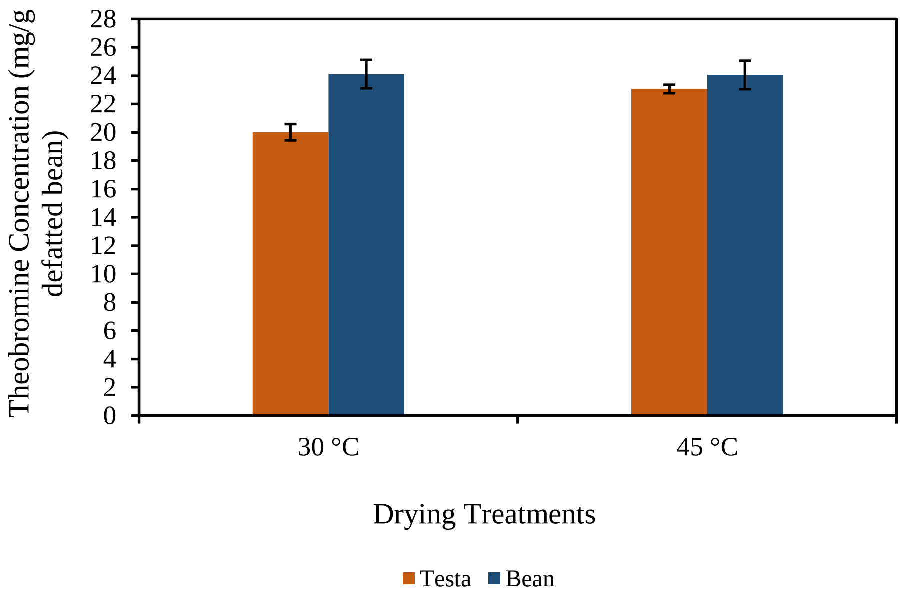


Figure 5.7. Impact of drying conditions on theobromine concentration in *Theobroma cacao* testa and bean.

Caffeine is another key alkaloid in cocoa beans that is essential for imparting bitter flavour and stimulation in chocolate. Caffeine content in cocoa beans generally declines to 0.2% during fermentation and drying (Timbie *et al.*, 1978). During fermentation, the caffeine concentration in fresh unfermented cocoa beans decreases from 4 mg/g dried defatted bean to 2 mg/g dry defatted bean. Thermal degradation during drying further decreases the caffeine content (Peláez *et al.*, 2016; Deus *et al.*, 2018).

The best drying condition that retained the most caffeine in cocoa beans was at 45 °C treatment, while cocoa bean dried at 55 °C had the lowest caffeine concentration (Figure 5.8). Caffeine is temperature sensitive and extended drying time may also affect degradation (Pelaez et al., 2016). The ideal caffeine content in dried cocoa beans is recommended to be 0.1 to 0.2% of the dried weight of cocoa bean (1 to 2 mg/ g dry bean) (Kyi et al., 2005).

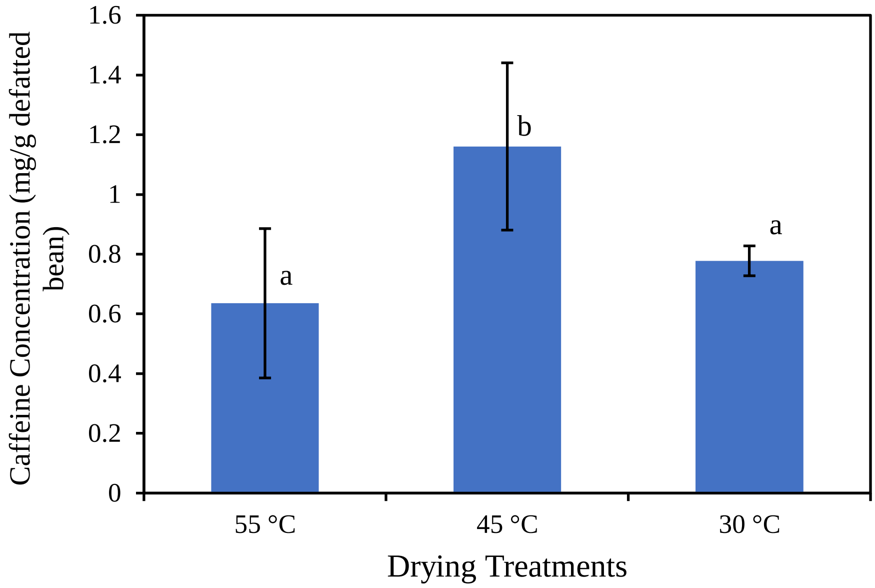


Figure 5.8. Impact of drying conditions on caffeine concentration in *Theobroma cacao* bean. Beans were sundried at 30 °C (control) under Fijian conditions over 14 days, or solar dried in under 3 days at 45 or 55 °C. Results presented here are average values from composite samples and experimental drying runs. Means of caffeine in cocoa samples that share a different letter are statistically significantly different ($p<0.05$).

The analyses for theobromine and caffeine were conducted on CE prepared from beans with the testa intact. A separate analysis of bean (cotyledon) and testa can provide further insight on the accumulation of theobromine and caffeine within the bean. Caffeine accumulated in the testa of cocoa beans during drying treatments at 30 and 45 °C (Figure 5.9). Several studies mention that fermentation causes disintegration of cellular components that causes caffeine to leach out of the cotyledon and into the testa (Ozturk and Young, 2017; Pelaez *et al.*, 2016). Moisture migration during drying may have caused caffeine to accumulate in the testa as it is water soluble (Shalmashi and Golmohammad, 2010). A shorter drying time at 45 °C may have retained more caffeine inside the bean when compared to sun dried cocoa beans ($p<0.05$). Drying at 45 °C is ideal as cocoa beans retained a higher concentration of caffeine in the cotyledons.

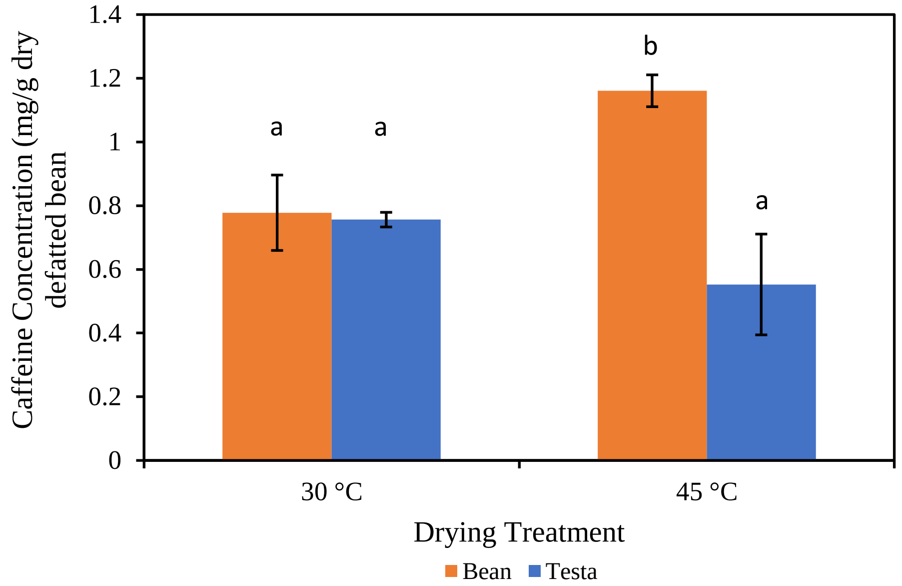


Figure 5.9. Impact of various drying conditions on caffeine concentration in *Theobroma cacao* bean testa and bean. Results show caffeine content after sun drying at 30 °C with two drying runs and under solar drying condition of 45 °C with three drying runs. Means of caffeine in cocoa samples with a different letter are statistically significantly different ($p<0.05$).

5.4 Conclusion

Phytochemical retention in *Theobroma cacao* beans during drying is critical for flavour development for chocolate production. Retention of these phytochemicals can be encouraged by maintaining a mild drying temperature or reducing the RH. The findings from this chapter demonstrate that the polyphenols, caffeine, and theobromine are mainly temperature and pH sensitive. Polyphenol concentration in fresh cocoa beans is naturally higher than caffeine and theobromine (Andújar *et al.*, 2012). Fermentation causes a rapid decline in these bioactive compounds before the commencement of the drying process.

In the drying experiments, thermal degradation of caffeine and polyphenols was observed at 55 °C treatment, while theobromine was found to be stable. Theobromine is essential for the desirable bitter taste in cocoa beans while caffeine acts as a stimulant. These are also key flavour components in chocolate. Drying tests showed that the best treatment condition for retention of bioactives in Fijian cocoa beans was at 45 °C. However, drying at 55 °C also retains the bioactive components if the temperature variations are minimised. Temperature and pH are the two main factors that affect the composition of bioactives during drying.

The desiccant based solar dryer can be an ideal solution for improving the drying conditions and quality of cocoa beans in Fiji. The desiccant-based system lowers the RH of ambient air for drying cocoa beans. Dehumidification of the drying air stream reduces the drying time from 14 days to three days. If the fermentation is reduced to four days, then three days of drying could provide consistent supply of dried cocoa beans after weekly harvest. The mild drying conditions in the desiccant-based dryer would retain the thermally sensitive bioactive components in cocoa beans. The drying model developed in chapter 5 can also be used to predict the bioactive quality in cocoa beans based on fermentation quality and drying conditions. Deviations in these input variables and the impact on cocoa bean quality can be further understood after conducting sensitivity analysis of the model. This is discussed in chapter 6.

Chapter 6 Sensitivity analysis of the drying model for *Theobroma cacao* beans

6.1 Introduction

The drying model has been validated in chapter 5 using the experimental drying data. The model will be used for selecting/determining the drying conditions for 100 kg of wet fermented Fijian *Theobroma cacao* beans in a theoretically designed solar dryer integrated with desiccant wheel (DW). The drying process is influenced by various conditions, the determination of which may be subject to uncertainties. Oberguggenberger (2004) recommends that these uncertainties in the drying conditions of a mathematical model should be captured and formulated using mathematical terms for proper assessment of variability in the model output. The sensitivity of model outputs to the variations in the drying conditions can be determined through sensitivity analysis (SA). Makokha, Muchilwa & Melly (2021) recommends sensitivity analysis to establish the impact of measurement errors during drying experiments. The study used variance-based statistical methods to determine that the moisture ratio was sensitive to drying rate coefficient and to the falling rate time during drying of maize seeds.

Local SA can be used to identify the input parameter that is most influential to the model output. There are several screening techniques that can be used for SA of a model. A simple screening technique is the one factor at a time (OAT) method for identifying the most sensitive parameter and the variations in other input variables that can affect the drying model. The main advantage of the OAT approach is that variations in the model output can be attributed to the single parameter that was changed while other parameters are unchanged. Conversely, the OAT approach does not show interaction between variables.

There is limited published literature on sensitivity analysis of a drying model as it is not necessary. The drying models for cocoa beans are generally validated using experimental data (Nwakuba, Ejesu & Okafor, 2017; Cordoba, 2018). This study is the first to report SA for a drying model developed for Fijian cocoa beans. In addition to the uncertainties in a model, sensitivity analysis is also important to accurately predict the performance of the drying system and operating parameters. In this chapter, sensitivity analysis is used to determine the effect of variations in input factors on the quality of dried Fijian cocoa beans. This would provide an insight into the impact of drying conditions from DW on the drying kinetics for Fijian *Theobroma cacao* beans.

6.2 Materials and method

Screening (factor fixing) was used to identify and eliminate input parameters that have insignificant impact on variations in the drying model output. Selection of significant input parameters was done using the one (factor) at a time (OAT) technique by changing selected operating parameter values across an acceptable range. Screening and OAT showed that the wet cocoa bean moisture content, bean length, RH, and air stream temperature had significant impacts on the drying process. This approach was adapted from Patel and Chen, (2008).

The drying model for cocoa beans developed in chapter 4 considered average values of various input variables. These input variables are:

1. temperature,
2. relative humidity (RH),
3. air velocity,
4. initial wet moisture content, and
5. size of the bean.

The values for the input variables and operating conditions for the Fijian *Theobroma cacao* drying model are provided in Tables 1 and 2. The model simulation should be able to operate across a range of realistic values for each input variable of about ± 20% variation for each input variable. These variations were incorporated in the model equations and tested by running simulations on the MATLAB software. In the actual model, the fixed set of input values for model operating parameters are given in Table 6.1.

Table 6.1. Input data used to simulate drying model for fermented *Theobroma cacao* beans

Variables	Description of variables		Unit
M_{dt}	Wet product weight	10	kg
M_{ic}	Initial wet moisture content	57	%
D_{be}	Cocoa bean size	20	mm

Table 6.2. Operating conditions during drying simulations

Variable	Description of variable	Value	Unit
T_{ai}	Ambient temperature	30	°C
T_{ai1}	Day 1 drying air temperature at the inlet	55	°C
T_{ai2}	Day 2 drying air temperature at the inlet	55	°C
T_{bi1}	Initial bean temperature	28	°C
T_{bi2}	Tempered bean temperature (overnight)	25	°C
X_{ai}	Ambient humidity	22	g moisture/ kg dry air
X_{ai1}	Day 1 humidity of air at inlet	15	g moisture/ kg dry air
X_{ai2}	Day 2 humidity of air at inlet	15	g moisture/ kg dry air
u	Velocity of air stream	0.25	m/s

6.2.1 Variations in moisture content of beans

The first simulation was conducted for drying 100 kg fermented *Theobroma cacao* beans with an average bean size of 20 mm under DW conditions. Drying tray dimensions were kept constant. These conditions were selected based on parametrisation of the drying model using experimental data from drying fermented cocoa beans under Fijian weather conditions. Average moisture content from experimental runs was 57% (w.b). In the simulation, inlet moisture content of wet fermented beans varied from 37-77% (w.b) as in practice the fermented bean moisture content varied.

6.2.2 Variations in fermented cocoa bean diameter

The second simulation was conducted for drying 100 kg of wet fermented cocoa beans with an average inlet moisture content of 57% (w.b). Inlet temperature was set at 55 °C and inlet RH was set at ± 20%. Average inlet air velocity was fixed at 0.25 m/s with tray dimensions kept constant. Bean diameter was varied based on experimental data on fermented Fijian cocoa beans. In model simulations, inlet bean length varied using realised values from 5 to 45 mm (0.5 to 4.5 cm). Bean size is dependent on variety of cocoa, pod size, and maturity.

6.2.3 Variations in inlet air stream temperature, relative humidity, and air velocity

The air temperature at the dryer inlet was set between 35 and 75 °C in the third simulation. Other inlet operating parameters were kept constant. The model did not simulate drying when the inlet temperature was below 35 °C. This may be because heat and mass transfer were limited due to decline in temperature gradient between bean and air stream. The temperature of fermented cocoa beans was 28 °C before drying. There must be a 10 °C difference or a percentage difference of more than 30% between bean and air stream for heat and mass transfer by convection.

6.2.4 Relative humidity of drying air at the dryer inlet

RH at dryer inlet was fixed between 5 and 45% in the fourth simulation. Drying terminated when the RH was >45% as this condition did not provide sufficient vapour pressure gradient for heat and mass transfer to occur. Drying conditions under 5% RH can be simulated by the model but the lowest possible RH of the drying air from a desiccant wheel would be around 5% at 45-60 °C. This can be achieved on a clear sunny day during the main harvest season.

6.3 Results and discussions

Sensitivity analysis can be used to test and apply the drying model as a tool to study dryer performance. These variations that are predicted can be used to control the drying process and dried cocoa bean quality. Drying time for a selected range of parameters, where the parameter values increase by ± 20% was analysed using the model simulation.

Table 6.3 shows the effect of varying some key input variables on the drying time of fermented *Theobroma cacao* beans. Control of these input variables, such as moisture content, bean diameter, temperature, and RH are critical to improving cocoa bean quality and drying time. Drying can be as short as 10 h when cocoa beans that are 20 mm in size are dried at 75 °C or under 5% RH at 55 °C. Other conditions that can reduce drying time to 10 h are when the initial moisture content of wet fermented cocoa beans is 37% and the cocoa beans are dried at 55 °C under 15% RH.

Table 6.3 Variations in input variables on the drying time for *Theobroma cacao* beans

Input parameter	Drying time (h)
Initial Moisture Content (%)	
77	48
57	30
37	10
Cocoa Bean Length (mm)	
18	34
20	48
30	58
Drying Temperature (°C)	
35	56
55	32
75	10
Relative Humidity (%)	
5	10
25	28
45	48

6.3.1 Variations in inlet moisture content on drying profile of *Theobroma cacao* beans

Fermented cocoa beans had an initial moisture content of 57 to 60% as input moisture content for the drying process. Initial moisture content for Fijian cocoa beans fermented for six days was comparable to findings from Bharath and Bowen-O'Connor (2008). Fermented sub-samples (n = 25) from different batches (n = 3) over two harvest seasons showed variation in moisture content. Average moisture content of 57% (w.b) was considered as the model input value with average bean length set at 20 mm and temperature at 55 °C.

Sensitivity analysis showed the expected positive correlation between drying time and initial moisture content. Wet fermented cocoa beans with a moisture content of 77% (w.b) had a longer drying time (50 h) at 55 °C. Generally, fermented cocoa beans have a moisture content of 45- 60%. A scenario where moisture content could be 77% (w.b) is when the beans are unfermented with pulp intact or when fermented beans are soaked and washed with water.

The model predicts that a raised moisture content (77% w.b) in cocoa beans extended drying time (50-56 h) at mild temperature conditions (55 °C and 20% RH). Rapid drying conditions at high temperature (>60 °C) can improve drying time but this can also cause case hardening and shrinkage. Therefore, high temperature drying is not recommended as it causes mechanical and thermal damage. Knapp (1924) explains that removal of pulp by washing causes the seed coat to become more fragile to drying conditions. This leads to breakage and fissures along the seed coat during rapid drying.

6.3.2 Variations in *Theobroma cacao* bean diameter on drying profile

Chocolate manufacturers prefer plump or spherical dried cocoa beans to flat beans. Dried cocoa beans can shrink anisotropically and become flat if germination stops abruptly. This can occur during fermentation due to acidification and thermal stress (Lopez and Dimick, 1995). Physiological changes in size and shape of cocoa beans can affect drying kinetics and quality aspects. Drying at high temperature in electric dryers causes a visco-elastic matrix in the seed to shrink into cellular spaces. Additionally, overnight tempering contributes to shrinking as the cocoa beans suddenly cool to ambient temperature. Shrinkage affects physical quality by reducing bean diameter and sphericity.

Sphericity is an important physical quality parameter for downstream processing. Spherical beans are dehulled efficiently with minimum transfer of testa into the nibs. Sphericity is measured using bean diameter. Mathematical equations for diameter and sphericity in Forastero variety of cocoa beans are discussed in chapter 5. The equations were adapted from Koua et al. (2017) and Ndukwu et al. (2012). In the drying experiments, diameter of fermented and dried cocoa beans was comparable to findings from Koua et al. (2017) and Ndukwu et al. (2012). Sphericity was calculated from a ratio of bean geometric diameter over length.

Spherical geometry is classified as beans having a value of 0.50 to 1.0. Flat beans have a sphericity value below 0.50. Mass of flat cocoa beans declines after roasting, which limits the commercial value. Chocolate manufacturers tend to reject a batch with less than 5% flat beans. Cocoa farmers sometimes include flat beans to improve product weight for profit. An acceptable limit set by the cocoa industry for flat beans in a batch of dried cocoa beans is less than 5% of batch weight.

Several studies mentioned in chapter 2 literature review show particle size has an influence on drying kinetics as well as heat and mass transfer coefficients (Mohseni and Peters, 2016; Heidarshenas et al., 2019). Fermented cocoa bean shape was considered spherical with a standard diameter of 20 mm (2 cm). Various external factors, such as the variety of cocoa, pod size, and maturity influences the size of the cocoa bean. Variation in bean size at a standard wet moisture content of 57% (w.b) was tested using the drying model. The model calculated a higher heat and mass transfer coefficient in smaller beans (18 mm) when compared the beans that had a larger size (>20 mm).

Model predictions were comparable to findings from a study by Onwuka and Nwachukwu (2013) where drying time was shorter (6 h) in smaller sized cocoa beans (11.57 to 13.60 mm). In this study, the cocoa beans were dried in sweat boxes with a 400-watt bulb as heatsource. During solar drying, air temperature and RH have a more significant impact on the drying time than does bean size.

6.3.3 Variations in inlet air temperature on drying profile of cocoa beans

Zanoni et al. (1998) mentioned that air temperature and product thickness have an impact on final moisture content. Inlet temperature is more effective in determining drying constants and drying rate than air velocity (Ndukwu, 2009). An air velocity above 2 m/s has limited additional impact on the drying rate. Experimental drying on figs showed that increasing air velocity to more than 2 m/s at constant temperature did not have a significant impact on drying rate (Babalis and Belessiotis, 2004).

Drying at low temperature and high air velocity has been shown to improve evaporation rate. Drying rate under low air velocities can be improved by increasing air temperature. Additionally, in early stages of drying when mass transfer is controlled by external resistance, high air velocity at low temperature can improve drying rate. Air temperature and RH remains the driving force for drying due to internal resistance to mass transfer. Sensitivity analysis of air temperature validates these findings.

Sensitivity analysis was conducted for inlet temperature at 20% RH, air velocity of 0.25 m/s, and 20 mm bean diameter. Other inlet variables remained fixed. Inlet temperature of fermented cocoa beans, warmed to room temperature was 28 °C. Model simulations was sensitive to inlet air temperature of less than 55 °C. Temperature gradient between bean and air stream should be more than 10 °C to facilitate heat and mass transfer. This is achieved by increasing drying air temperature.

Reduction in drying time was noted with increase in temperature. An increase in temperature to 75 °C shortened drying time by 79 % (12 h) when compared to drying at 38 °C (56 h). Drying temperature of 55 °C showed 36% improvement while 45 °C improved drying time by 11%. These findings are comparable to a study by Banboye et al. (2020), where increasing drying temperature using fleece reduced drying time. Shorter drying time at high temperature was also reported by Deus et al. (2018) in cocoa beans. Several studies show a positive correlation between drying temperature and effective diffusivity (Chinenye *et al.*, 2010). This is mentioned in the literature review section in Chapter 2 of this thesis.

Temperature variations impact relative humidity but not absolute humidity of an air stream during drying. While absolute humidity remains the same, RH of air changes. High temperature and low RH improves moisture evaporation rate unless impeded by case hardening. Relative humidity also influences equilibrium moisture content of the product.

6.3.4 Variations in relative humidity profile on drying regime for cocoa beans

Variations in RH at a fixed temperature of 55 °C, 0.25 m/s air velocity and 20 mm bean size were tested for impact on drying time. A reduction of 64% in drying time was estimated at 25% RH. Reduction in RH to 5%, reduced drying time by 79% (12 h). Sensitivity analysis showed drying time when RH was limited below 25%. This was comparable to findings by Sigge et al. (1998). The study tested relative humidity of 15 to 40% at various drying temperature. Findings revealed that 15% RH at 55 °C and 65 °C improved drying rate and time (2-3 h) in green bell peppers with 62% moisture content (w.b). While moisture content of bell peppers was comparable to fermented cocoa beans, drying time was 75% shorter at 55 °C. This is attributed to product geometry, where cocoa beans are spherical in shape while bell peppers were cut into 100 mm^2 cubes.

Additionally, relative humidity influences equilibrium moisture content (EMC) of cocoa beans. The cocoa beans equilibrate to the vapour pressure of the drying system. Dried cocoa beans stored at 25 °C and at 75% RH had an EMC of 6 to 8% (w.b) (Henderson, 1984). During air drying of mung beans, a combination of high temperature and low RH influenced EMC during drying (Silakul and Jindal, 2002).

While drying time was shorter for step up technique, beans dried using step down technique showed lower moisture content (0.06 g water/ kg dry solid). Additionally, the study reports better quality beans were dried using step up approach. In this treatment, fermented beans were exposed to conditions of 31 °C at 61% RH for 24 h. This may have facilitated better oxidation in the bean. Cut test showed darker bean colour when compared to beans from other treatment.

Sensitivity analysis shows that change in input variables by ± 20% affects drying kinetics but a clear interpretation and relationship of this data to change in quality composition is essential. Drying model was reliable in predicting the drying kinetics of cocoa beans between 5 and 45% RH at fixed input parameters. Limiting RH to 5% demonstrated a decline in drying time by 79% when compared to a drying time of 56 h at 45% RH.

The drying time under 45% RH was longer than drying under 5% RH. This difference was smaller (43%) between 25 and 45% RH, while between 5 and 25% RH the percentage difference was 100%. These RH values are estimated from desiccant wheel used to dehumidify ambient air for drying cocoa beans as shown from 1 to 2' in Figure 7.1. Variations in desiccant wheel RH output is between 75 and 5 %. This can be taken into consideration when designing the drying system for cocoa beans.

Sensitivity analysis showed that many of the variables, such as wet cocoa bean weight, tray dimensions, tray load, tray gap, drying chamber size, and bean size did not have a big impact on the drying time. The variables that had a significant impact in limiting drying time were temperature and RH of the drying air stream, bean size, air flow, and initial moisture content of wet fermented cocoa beans. During drying the air flow should be between 0.5-1.0 m/s to improve the moisture evaporation during the first six hours of drying.

6.4 Conclusion

Sensitivity analysis using OAT was effective in predicting the effect of changing selected input variables on drying time. A positive interaction was observed between RH, bean size, and moisture content of wet cocoa beans with drying time. Other parameters, such as tray size, tray number, tray load, and tray gap did not show significant impact on drying time, heat, and mass transfer coefficients.

The experimental input variables were compared against the drying model using sensitivity analysis. The experimental input variables were within a 20% difference from the mean value. This can be useful to predict drying time and product quality. However, most of these variations in variables, such as temperature, RH, and initial moisture content are limited within ±20% deviations from the input value. The model was sensitive to smaller bean length of 18 mm. The information from this study is the first to report information on the sensitivity analysis of drying model for Fijian cocoa beans. The sensitivity analysis can be improved further by a global sensitivity analysis (GSA) to identify the most significant model input parameters.

Chapter 7 A conceptual design for a solar dryer integrated with a desiccant wheel

7.1 Introduction

Quality problems in sun dried Fijian *Theobroma cacao* beans can be caused by intermittent ambient conditions in Fiji. The concept of a solar dryer system with solar collectors and a desiccant wheel (DW) is proposed to provide better control of the drying process in this work, including continued operation during rain. The solar collectors considered are flat plate collector and parabolic trough collector for improving ambient air temperature for desiccant regeneration. The test dryer built in this study is intended to test low RH conditions on the drying kinetics of wet fermented cocoa beans under moderate temperature conditions. These temperature conditions are calculated and tested based on the temperature of drying air stream anticipated from DW.

The objectives of chapter 7 were to design a hypothetical drying system with a desiccant wheel and integrate this design into a drying model for predicting the drying kinetics. A conceptual design was developed for drying 100 kg of wet fermented Fijian *Theobroma cacao* beans under seasonal conditions in Fiji. The drying model developed in chapter 4 was integrated with air temperature variations from solar collectors and DW for a more accurate prediction of drying conditions in the dryer based on seasonal variations.

Several studies have integrated a solar dryer with desiccant materials for reducing the drying time and enhancing conditions for cocoa beans by limiting humidity of drying air. Dina et al. (2015) tested adsorbent (molecular sieve 13 x ($Na86[(AlO_2)86.(SiO_2)106].264H_2O$) and absorbent ($CaCl_2$) as desiccant thermal storage materials in solar dryers during drying tests on cocoa beans. That study found that under favourable ambient conditions, the maximum temperature in the solar dryer system was between 40 to 54°C. This was ideal for drying Indonesian cocoa beans. Lower and inconsistent temperature conditions during off-sunshine hours caused drying problems. A recently published literature also mentions integrating solar dryers with liquid calcium chloride as a desiccant material for effectively reducing the drying time for ginger (Sabareesh et al., 2021).

Mixed mode solar dryers with thermal storage are recommended by Adeyemi et al. (2020) for cocoa beans but the study did not elaborate on the material used for thermal storage. The importance of integrating a simple solar dryer design with thermal storage for improving drying conditions was emphasised. While simple solar dryer design can be modified with various types of desiccant material, the key point to consider is the ease of maintenance and cost of modification. Farm based dryers must be simple and low cost to operate for small scale cocoa farmers. Solar energy can be utilised in many ways using the suitable components of the solar dryer to improve drying. One example is operating the dryer under active convection using fans operated by solar photovoltaic (PV) panels. In the Fiji Islands, solar PV systems have been in use for around 30 years for electricity production (Raturi and Prasad, 2014). Therefore, solar PV panels can be used to provide electricity to operate the fans and other components of the dryer. Direct connection of PV panels to fans with no intervening controller has the advantage of speeding air flow at exactly the times when solar air heating is greatest.

On average, the solar insolation on a horizontal surface in Fiji is estimated to be around 5.4 kWh/m^2/day from historical data reported by Prasad et al. (2017). Seasonal variation affects the intensity of solar insolation during cocoa harvest season, where mid harvest season (May to July) has an average of 4 kWh/m^2/day and main season harvest (October to December) has 6 kWh/m^2/day (Johnston, 2004, Prasad *et al.*, 2017). Average solar insolation data on a horizontal surface in Fiji over a period of ten years is presented and discussed in chapter 2. The high solar insolation (6 kWh/m^2/day) during main harvest may heat ambient air to a high temperature by the solar collector system. This depends on design specifications from the thermal properties of ambient air and manufacturing materials for solar collector.

7.2 Materials and method

Key components of the proposed solar dryer system are presented in Figure 7.1. These design components consisted of:

1. Solar collectors – size of FPC and PTC was established based on thermal properties of ambient air and air volume required to dry 100 kg of wet fermented cocoa beans within two 12 h drying cycles. Collector size was determined through iterative calculation of mass and energy balance equation (Pandey & Chaurasiya, 2017; Duffie & Beckman, 1974) on MS Solver®.

2. Desiccant wheel – size of the desiccant wheel (DW) has a standard dimension from the supplier (Cooke Industries Ltd, New Zealand).

3. Drying chamber – size of the drying chamber was specified by iteratively solving the mass and energy balance equations using MS Solver®.

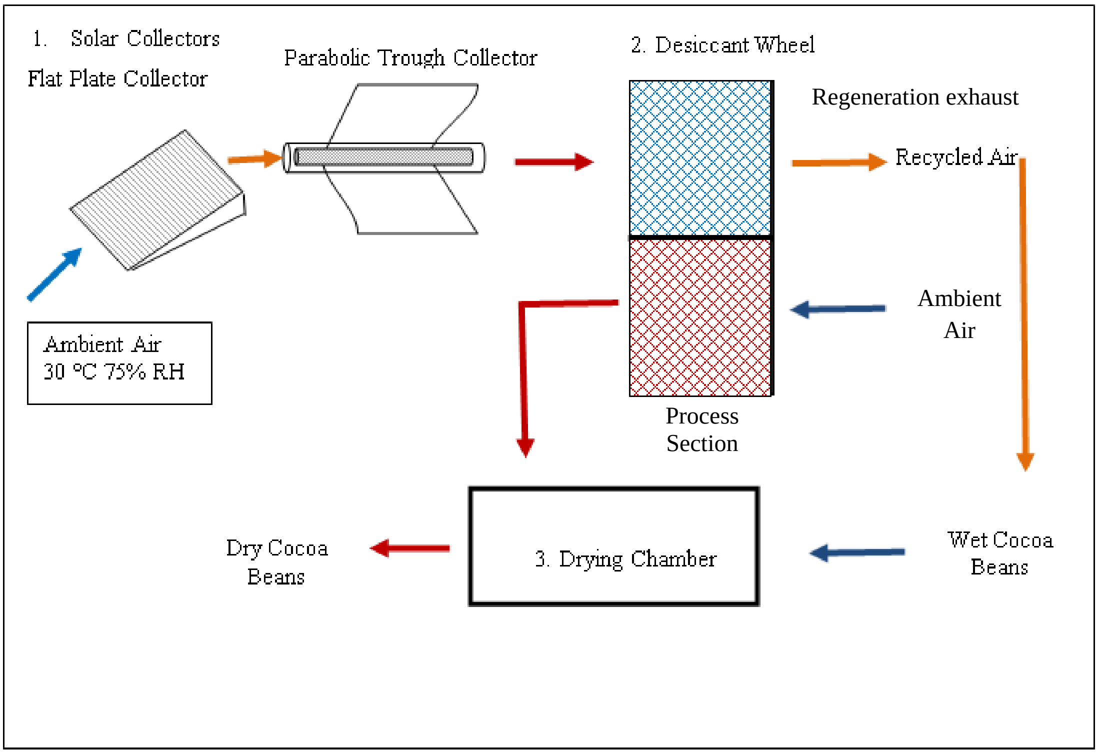


Figure 7.1. A conceptual layout of solar drying system with a rotary desiccant wheel for drying *Theobroma cacao* beans

7.2.1 Collector design

Temperature output from a simple flat plate collector (FPC) is generally between 30-80 °C, but this alone is insufficient for desiccant regeneration, as ambient RH is very high (75 to 80%) in Fiji. Desiccant regenerated by this humid air at 80 °C may not be able to dehumidify the drying air to a low RH (<10%) for effective drying. Following a FPC by a PTC can potentially improve desiccant regeneration temperature up to 120 °C. Temperature output from the solar collector train can be calculated. Mathematical equations for predicting temperature of air for desiccant regeneration from the solar collectors were based on the following considerations:

1. Air flow is one dimensional.
2. Solar absorption is by absorber plate.
3. Air temperature gradients do not exist in directions perpendicular to flow direction.
4. Heat losses to ambient air are from collector inlet, outlet, edges, back insulation, and topcover.
5. Irradiation losses from top cover is to the sky.
6. Longitudinal dispersion of heat is negligible.
7. Dust and dirt on collector surface are negligible.
8. Shading of absorber plate is negligible.

7.2.2 Flat plate collector

Figure 7.2 shows a schematic illustration of flat plate collector design. A simple FPC consists of an absorber plate on a concrete base with insulation and transparent double glass cover. Width and length of the collector is determined by a set of values to begin iterating the calculations. This was done to check and ensure the air temperature out of FPC was more than 50 °C for PTC input. Thermal properties of inlet air, materials used for fabricating the collector cover, absorber plate, and insulation were considered in the mathematical equations for FPC design. These equations calculated the heat transfer between glass cover and absorber, which was mainly through convection and radiation. External factors, such as solar influx and glass cover temperature cause temperature variations inside the solar absorber. Some design specifications, such as double glazing (two glass cover), glass thickness, absorber material and thickness, air channel depth, air velocity and length of FPC, also influences air temperature and heat transfer efficiency of the design.

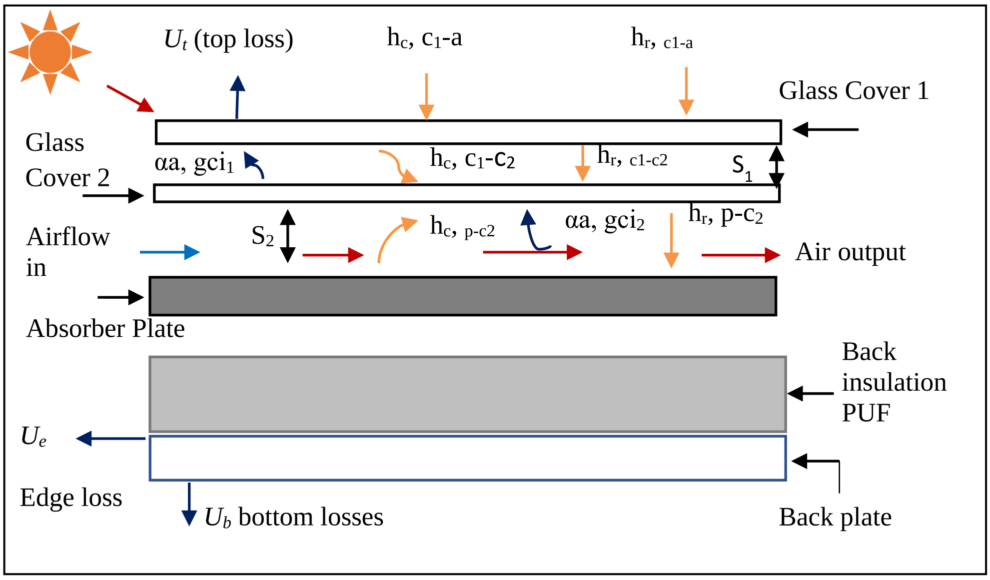


Figure 7.2. Schematic illustration of the components of the flat plate collector. The diagram shows heat transfer and heat losses between air stream, glass covers, absorber plate and back. Glass cover 1 shows top losses (U_t), convective, and radiative heat transfer from air stream to glass.

Energy balance equations were adapted from Duffie and Beckman (1974) and Mc. Adams, (1954). A measure of collector performance is the thermal efficiency describe by Duffie and Beckman (1974) as the ratio of useful heat gain (Q_u) over time to solar insolation on the area of solar collector. The thermal efficiency (η) is calculated as:

$$\eta = Q_u/(L \times W \times It) \quad (1)$$

Where: Q_u is the useful heat gain, *It* is the solar insolation on a horizontal plane, L is the length and W is the width.

These equations were used to set the FPC size to achieve the outlet air temperature required for a PTC to achieve outlet temperature recovery for desiccant regeneration. The solar absorber in FPC is assumed to be made of polished steel. The solar radiation that is absorbed by steel plate heats ambient air to 50 °C. This air is then further heated by PTC to 90-120 °C for desiccant regeneration.

7.2.3 Parabolic trough collector

The linear parabolic trough solar collector (PTC) design consists of with a cylindrical absorber made with glass set in a reflective trough made of polished aluminium (Figure 7.3). The PTC was designed based on mass flow rate of air and estimated regeneration temperature required by the DW. The linear PTC operates by reflecting solar insolation into the receiver, which absorbs the solar energy for heating air from FPC. A single axis tracking can be used to focus solar radiation parallel to the collector axis. Equations from Duffie and Beckman (1974) were used to determine collector dimensions and thermal efficiency (η). First the size and dimensions of the PTC were guessed and then energy balance equations from Duffie and Beckman (1974) was used to calculate the size of PTC absorber and tube.

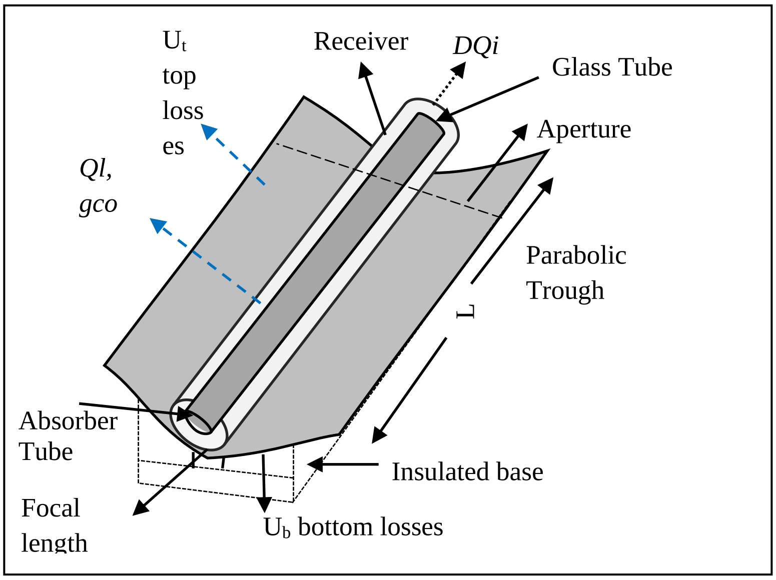


Figure 7.3. Schematic illustration showing major components of parabolic trough collector. Heat losses from top of aperture (U_t), bottom (U_b) and glass cover *(Ql, gco)* are demonstrated in the diagram.

Parabolic geometry of the PTC is significant for operating efficiently. Thermal efficiency (η) of PTC represents the ability of the design to transfer heat energy to the air stream for desiccant regeneration. This is calculated using the useful heat gain (Q_u), solar insolation (*It*), and area of aperture (*Aa*).

$$\eta = Q_u/(It \times Aa) \tag{2}$$

7.2.4 Design of drying chamber

Dimensions of the drying chamber were calculated using the quantity of wet fermented *Theobroma cacao* beans per drying cycle. Physical properties of wet fermented *Theobroma cacao* beans (100 kg) were considered in calculating the area of drying tray (Table 7.1). For drying 100 kg wet Theobroma cacao beans, with a bulk density of 593 kg/m^3, at a bean bed thickness of 0.006 m, a total tray area of 28 m^2 was calculated. The width and length of a single tray were set using guesses of dimensions. The standard length was set at 0.8 m for a dryer with 1 m length. This length was used to understand the drying problems along the dryer. The parameters used in the following equations are presented in Table 7.1.

Table 7.1. Physical properties of *Theobroma cacao* bean

Variable	Description	Value	Unit
Adry			
ρ_b	bulk density of cocoa bean	593	kg/m^3
V_b	volume of coca bean per kg	0.0017	m^3
t_b	thickness of bean bed assumed	0.006	m
Wtray or W_T	Width of single tray	0.4	m
L_T	Length of single tray	0.8	m

The area for one drying tray (A_{tray}) was calculated using the following equation:

$$Atray1 = W_T \; x \; L_T \tag{3}$$

Number of trays (Nt) required for drying 100 kg of wet fermented *Theobroma cacao* beans was calculated by the following equation:

$$Nt = Adry \; x \; Atray1 \tag{4}$$

Where *Adry* is the drying area for wet cocoa beans.

Tray gap was fixed for the drying trays, and this was used to calculate the drying chamber design specifications. The drying inner chamber height (H*inch*) and width was calculated using the following equations:

$$Hinch = gtray\ x\ Ntray + gtop \tag{5}$$

Where: *gtray* is the gap between tray (m) and
gtop is gap at the top of the first tray and drying chamber (m).

The width of the drying chamber (W*inch*) was estimated by:

$$Winch = Wtray + (gs\ x\ 2) \tag{6}$$

Where: *gs* is the gap between tray and side wall (m). and
Wtray is the width of the drying tray (m)

The length (*Linch*) of drying chamber was calculated by:

$$Linch = Ltray + 2x\ 0.1 \tag{7}$$

Where: Ltray is the length of drying tray (m)

The spacing between the sides, top, and bottom of the drying trays were standard fixed values. Clear area for air flow (A*f*) inside the drying chamber was estimated using inner chamber dimensions and tray dimensions.

$$Af = Winch\ x\ (Hinch - htray\ x\ (Nt - 1)) \tag{8}$$

Where: *htray* is the height of the drying tray (m)
Based on the wet bean quantity, the mass flow rate (F*dm*) of air inside the drying chamber was estimated from the quantity of air required over a 24 h drying period. This was calculated from the following equations:

$$Fdm = Qa/dtime \tag{9}$$

Where: Q_a is the mass flow rate of air (kg/kg) and
dtime is the drying time (h)

The heat transfer from drying air to the bean based on tray area is calculated using the following equations:

$$Q = dT x \, h_c \, x \, Atray \, x \, Nt/1000 \tag{10}$$

dT = dt 1- dt 2/ ln (dt 1/ dt 2) (11)

$$h_c = Nu \times \lambda_a/(gtray - htray) \tag{12}$$

$$Nu = 0.664 \times Re^{0.5} \times Pr^{0.33} \tag{13}$$

$$Re = \cup_a \times (gtray - htray)/va \tag{14}$$

Where: Q is heat energy (kW)

dT is temperature difference between dryer outlet (*dt2*) and cocoa bean temperature (°C)

dt2 is temperature at dryer inlet

LN is natural log

Nu is Nusselt number and Re is Reynolds number. These are dimensionless quantities.

$\cup_a$ is air velocity (m/s)

υ_a is air viscosity (Pa)

The abbreviations for some of the parameters are mentioned in Table 7.3. Mass diffusion (*Mdiff*) was calculated using the following set of equations:

$$Mdiff = D \times Sh/(gtray - htray) \tag{15}$$

$$D = Sc/\, va \tag{16}$$

$$Sh = 0.664 \times Re^{0.5} \times Sc^{0.33} \tag{17}$$

Where: *D* is the diffusion coefficient for moisture (m^2/s)

Sc is the Schnell’s number and *Sh* is the Sherwood’s number. These are dimensionless quantities.

7.2.5 Integrating solar collector and desiccant wheel into the drying model

The drying model for wet fermented Fijian *Theobroma cacao* beans developed in chapter 4 was modified by integrating temperature and relative humidity output from solar collector train and desiccant wheel (DW) equations. The initial temperature conditions from solar collectors were based on ambient conditions in Fiji, which influences the regeneration and process (R/P) air temperature in DW. In the drying model equations presented in chapter 4, the temperature and RH values for each drying cycle were integrated with process air temperature and humidity from DW simulation.

A schematic illustration of DW given in Figure 7.4 shows the desorption and adsorption process. The DW is divided into regeneration and process sections (R/P) with an area ratio of 1:3. Ambient air heated by solar collectors to 60-120 °C is used for regeneration of desiccant material. Moisture from the solid wet desiccant is evaporated by this hot air, which exits from the regeneration exhaust section of DW. Ambient air passes through the process section of DW and is dehumidified by the solid desiccant material (silica gel).

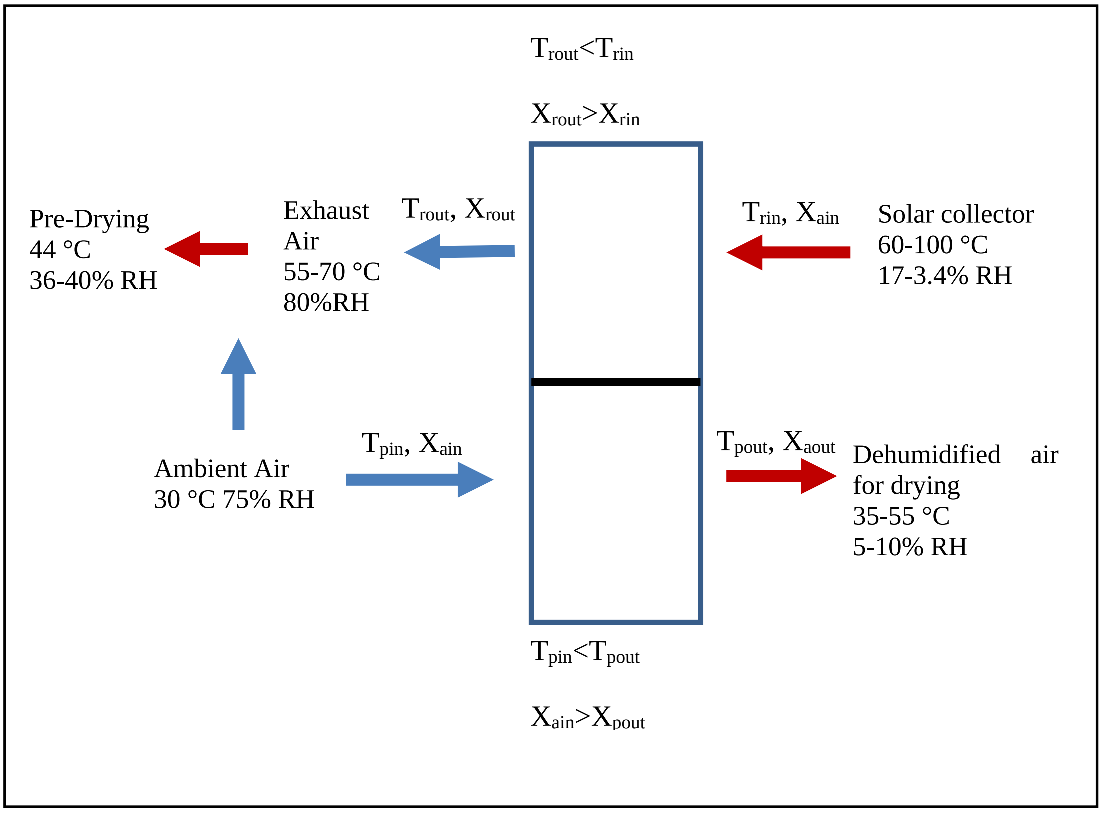


Figure 7.4. Schematic illustration of air flow through a conceptual desiccant wheel (DW) design. The DW design was used in the model equations for predicting drying outcomes on fermented *Theobroma cacao* beans. T_{rin} is the regeneration temperature and X_{ain} is the humidity of air from solar collector. T_{rout} is the temperature of exhaust air and X_{rout} is the humidity of exhaust air from regeneration side. In the process section, T_{pin} is the temperature of process air from ambient conditions and X_{pin} is the humidity of ambient air. T_{pout} is the temperature and X_{pout} is the humidity of dehumidified process air for drying cocoa beans.

Temperature output that was calculated from the solar collector train was an input for regeneration temperature for the desiccant wheel. Flow rate (Fa) for regeneration air was determined using 1:3 ratio (R/P) between the regeneration and process air flow rates of DW. The desiccant wheel performance was simulated by a code developed by Chen et al. (2018).

7.2.6 Estimation of cost for the solar dryer system

The cost of fabricating and investing in the desiccant based solar dryer system is important to determine the cost of production and the profit obtained for a cocoa farm in a Fijian village. The processing time for 100 kg of wet fermented cocoa beans is limited to three solar cycles in the drying model, which is a significant improvement when compared to sun drying for 14 days. Costing for the solar dryer system was adapted from a study by Heid (1978). The price of each solar collector was calculated based on cost of material per area of the equipment. Capital investment cost was calculated from the prices given at a local hardware store in Fiji, Vinod Patel®. The prices for hardware materials were advertised in 2021.

7.3 Results and discussions

7.3.1Collector output based on design parameters

Temperature and energy output from solar collectors were calculated based on thermal and physical properties of ambient air conditions in Fiji. Thermal properties of construction materials for solar collector were considered in energy balance calculations. Temporal variations in heat transfer coefficients due to change in input solar radiation and ambient air conditions was considered in collector design. Daily variations in ambient temperature, RH and radiation levels also have an impact on temperature and RH output from solar collectors. Additionally, energy efficiency and optimum design parameters can be determined from variations in daily solar radiation levels. Variations, such as cloud cover have been known to affect the intensity of solar radiation. Partially cloudy weather conditions experienced during mid-season could improve solar radiation intensity by reflecting the solar insolation (Matuszko, 2011). This improvement has been attributed with convective cloud cover during humid conditions.

Another factor to consider is the number of sunshine hours based on day length. Mid-season harvest has shorter day length when compared to the main harvest season. Based on the solar cycle, maximum solar insolation is between from 10 a.m. to 2 p.m. for 4 to 8 hours. Operation of solar collectors can be hindered by rainy weather conditions when the cloud cover is more than 87%. These variations in solar radiation in Fiji have been reported in a study by Prasad et al. (2017).

7.3.2 Flat plate collector

Flat plate solar collectors (FPC) operate by using solar radiation to heat ambient air for the drying process. FPC has a simple design that can be low cost to fabricate and easy to maintain. This study considered some of the advantages of FPC suggested by Ojike, 2011, such as:

1. Ability to utilise beam and diffuse solar radiation.
2. Operates without orientation to the sun.
3. Low maintenance.

Table 7.2 shows the design specifications for FPC in this study. Dimensions of FPC were initially guessed for 100 kg of wet fermented cocoa beans. The size (Le) of FPC calculated for 100 kg of wet bean was 2.2 m. Additionally, materials with high thermal properties, such as glass and steel were considered in the conceptual design. Gap sizes in between glass cover and absorber plate were adapted from Kumar and Mullick (2012). The spacing between absorber plate and glass collector was set at 20 mm and spacing in between glass covers was set at 10 mm.

Based on literature values, glass thickness of 4 mm and double glazing was considered to enhance heat transfer. Glass that is low in iron and less than 4 mm is more susceptible to damage (Bakari *et al.*, 2014). When glass thickness between 3-6 mm was tested by Bakari et al. (2014) on FPC, the best results were obtained using 4 mm thick glass with 35% efficiency, while collectors with 6 mm thick glass had limited thermal efficiency (28%). Garg and Prakash (2006) recommend using at least 3.3 mm thick glass cover. Double glass cover is an important component for improving heat transfer between absorber plate and drying air stream.

In the design, spacing between glass covers was set at 10 mm to minimise radiative and convective heat losses. Several studies also recommend using glass as it transmits 90% of short-wave radiation to absorber plate (Kabeel and Abdelgaied, 2016, Leon et al., 2002, Ekechukwu and Norton, 1999). Clear glass with low iron content is preferred for solar covers. Other materials, such as polycarbonate is more durable and cheaper when compared to glass. While transmissivity of polycarbonate is comparable to glass, this declines with long term use. Replacing glass with polycarbonate may improve thermal performance of FPC, but glass is a better option based on its resistance to high temperature.

The dimensions of FPC with specifications are mentioned in Table 7.2. Insulating materials considered in FPC design was polyurethane foam (0.02 W/m K) on a concrete base (1.7 W/m K), while polycarbonate absorber and glazing has also been suggested by Pandey and Chaurasiya (2017) as a low cost and light weight alternative to using metal absorbers. However, the conceptual design considered double glazing with 4 mm glass and steel absorber plate with a thickness of 0.02 m for better thermal efficiency. Thermal properties of polished steel were emissivity of 0.88 andthermal conductivity of 52 W/m K as suggested by Agbo and Okoroigwe (2007). The base insulation for the FPC was 0.25 m and the edge insulation was set at 0.15 m. Based on design specifications in Table 7.2 and clear weather conditions with a solar insolation of 6 kW/h/m^2 in a day, the heat exchange coefficient was 17 W/m^2 K.

Overall thermal performance of FPC can be described by useful heat gain (Q_u) as well and this is also influenced by daily solar insolation. Fluctuations in daily solar insolation causes variations in thermal efficiency. Thermal efficiency for FPC designed for DW regeneration in this study was estimated to be 0.72 (72%). Thermal efficiency could improve with further adjustments to the design. One example is improving the pressure drop through the collector, which was estimated to be 16 Pa as the system operates on passive convection. An increase in air flow could be made with solar powered fans to control air velocity.

Table 7.2. Input parameters for flat plate collector

Symbol	Description	Value	Unit
θt	Tilt angle	10	°
W	Width of collector	2	m
L	Length of collector	2.5	m
Le	Characteristic size	2.2	m
s_1	Spacing of plate to cover 2	20	mm
s_2	Spacing between cover 1 and 2	10	mm
s_3	Air channel depth	10	mm
δ_{gc1} δ_{gc2}	Thickness of outer and inner glass cover	4	mm
t_2	Thickness of collector plate	0.02	m
t_3	Back-insulation thickness	0.25	m
t_e	Edge thickness	0.15	m
λ_b	Insulation thermal conductivity (PUF)	0.02	W/m K
ε_p	Emissivity of collector plate, polished steel	0.88	
a_p	Absorptance of collector plate	0.92	
ε_{gc}	Emissivity of glass	0.91	
λ_{gc}	Thermal conductivity of glass	1	W/m K
τ_{gc}	Transmittance of glass	0.82	
a_{gc}	Absorptance of glass	0.11	
r_{gc}	Reflectance of glass	0.07	
λ_a	Thermal conductivity of air	0.03	W/m K
T_a	Temperature of ambient air	30	ºC
X_a	Humidity of ambient air	20	g/kg
RH_a	Ambient air relative humidity	75	%
X_{pda1}	Humidity at inlet	22	g/kg
T_r	Air temp out of FPC	55	°C
h_c	Heat exchange coefficient	17	W/m² K
Q_u	Useful heat gain	1747	W
η	Efficiency	0.72	
dP	Pressure drop	16	Pa

Temperature output from FPC was calculated based on an average daily solar insolation of 5 to 6 kW/ m^2 with varying cloud cover. Temperature output and thermal efficiency were also considered for conditions with heavy precipitation and cloud cover. The FPC was mounted East to West and tilted at 10° based on the latitude of 18° from the equator. Variations in the average temperature profile over the number of sunshine hours on a given day is worth a consideration as it determines temperature output from FPC and into the PTC for desiccant regeneration.

Figure 7.5 shows the air temperature variations in the FPC based on average solar insolation on a given day during harvest seasons. Temperature lifts at 0700 h for mid-season harvest with 50% cloud cover (45 °C) and for 87% cloud cover (40 °C). During main season temperature variation begins at 0600 h from 45 °C until a maximum temperature of 65 °C is attained by mid-day (1000 to 1400 h). These seasonal temperature fluctuations influence temperature output from FPC. These findings were comparable with studies by Seco-Nicolas et al. (2020).

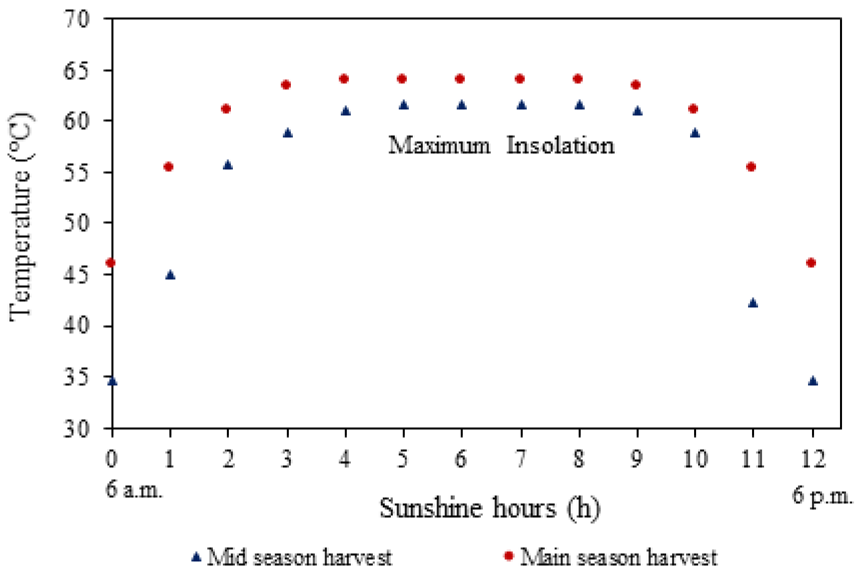


Figure 7.5. Mean plate temperature of flat plate collector on a given day. Temperature variations during A. mid-season harvest (May to July) B. main season harvest are demonstrated.

Seasonal variation in collector temperature influences thermal performance. This can be described assessed by calculating useful energy gain (Q_u). These values reflect fluctuations in daily solar insolation and FPC temperature output. Heat transfer coefficients and losses were comparable between main and mid harvest season. However, 87% cloud cover during rainy weather may limit heat transfer and increase heat losses.

Another improvement can be to increase the air channel depth to more than 10 mm to extend and stabilise temperature output during rainy season. Increase in air channel depth decreases air velocity along the collector. Slower air flow allows increases in temperature along length of collector by allowing more efficient heat transfer. Lower air flow allows better heat transfer from collector plate to the drying air stream. This improves thermal efficiency and heat gain, but overall heat loss coefficient decreases. Different design dimensions demonstrate balancing of equilibration of efficiency and heat gain as reported in literature. A rough corrugated metal sheet can be applied to improve air turbulence and convective heat transfer coefficient between plates (Gao *et al.*, 2007). Corrugations also increase area available for convective heat transfer for a given plan area.

Heat loss can be minimised by application of back insulation beneath absorber plate. In the conceptual design, polyurethane foam (PUF) with a thermal conductivity of 0.02 W/m K was assumed. A thickness of back insulation of 250 mm with an edge thickness of 150 mm minimized heat losses and allowed thermal efficiency (η) of 0.72. Total heat loss transfer coefficient (U_L) of this design was 0.53 W/m^2 K. Total heat loss is an estimate and may vary with weather exposure during field-testing. Heat loss from back (U_b) and edge (U_e) of FPC are mainly through conduction. In a well- designed FPC, edge losses should be negligible. In this simple design, edge loss was 0.13 W/m^2 K, which is negligible. Heat loss from the back can be minimised by applications of back insulation beneath absorber plate. Bottom loss coefficient (U_b) is calculated from thermal conductivity and thickness of insulation (250 mm).

In the conceptual design, polyurethane foam (PUF) with a thermal conductivity of 0.02 W/m K was considered. Improving thickness of back insulation to 250 mm with an edge thickness of 150 mm minimised heat losses with thermal efficiency (η) of 0.72. Total heat loss coefficient (U_L) of this design was 0.5 W/m^2 K (Figure 7.6). It is noteworthy that total heat loss and heat removal factor are not constant values and will vary with sun exposure during field-testing. In Figure 7.6, there is a strong negative linear relationship between overall heat loss coefficient and plate temperature. This is comparable to findings by Sivakumar and

Sivaramankrishnan (2012), where an increase in plate temperature reduced overall heat loss coefficient. Temperature variations along collector also influences heat loss coefficient.

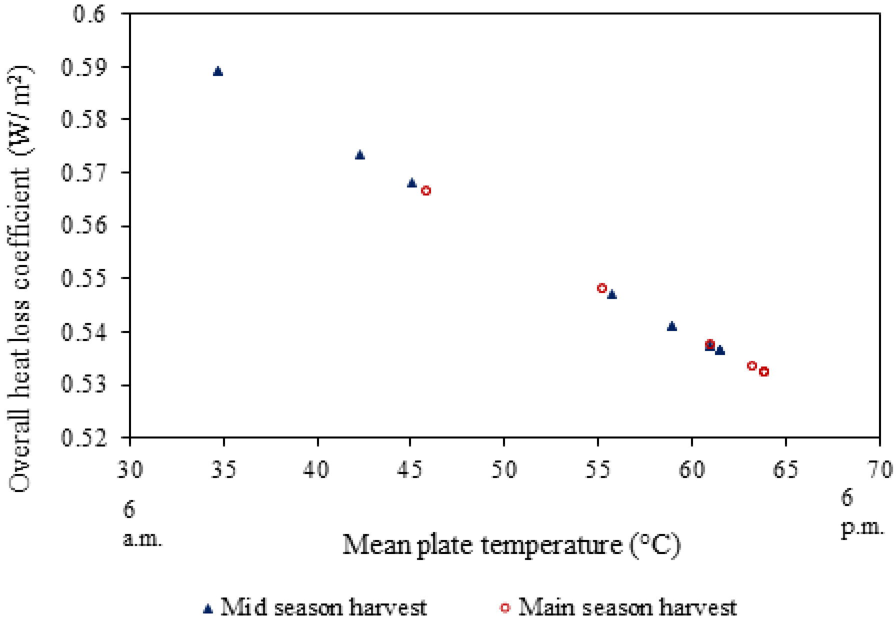


Figure 7.6. Overall heat loss coefficient of air stream in flat plate collector during main season and mid-season.

Gao et al. (2007) recommends minimising heat loss by considering surface properties of absorber plate material. Radiation heat transfer coefficient can be improved by applying non-selective coating on absorber plate. Additionally, rough surface and fins can be added to improve convective heat transfer coefficient (Gao *et al.*, 2007). Careful FPC design is critical to provide a temperature output of more than 50 °C, which is the required input air temperature input for the parabolic trough collector.

7.3.3 Parabolic trough collector

Assumed parameters for PTC are given in Table 7.3. PTC dimensions such as, aperture width (2.5 m) and collector length (2.7 m) were fixed values. The focal length of 0.7 m determines the size of PTC system. Arc length (2.7 m) and height (0.5 m) are calculated from focal length. Maximum focal length can be 1.7 m with a maximum aperture width of 6 m. Another important parameter is the rim angle as it determines design characteristics of PTC, such as concentration ratio. Rim angle was set to 80 °, which is ideal for a parabolic trough. Rim angle above 90 ° has high investment costs and low energy efficiency. The shape of parabola is difficult to manufacture at lower rim angles.

Table 7.3. Input parameters for parabolic trough collector

Abbreviation	Details	Value	Unit
W_a	width of aperture	2.5	m
L	length of collector	2.7	m
φr	rim angle	80	°
K	ratio of real diameter to theoretical one	7	
δr	thickness ratio	5	
δgc	thickness of glass cover	4	mm
νa	ambient air viscosity	0.000018	Pa
Pr	Prandtl number	0.7	
Cpa	heat capacity of air	1.01	kJ/kgK
λa	thermal conductivity of air	0.03	W/mK
λt	thermal conductivity of carbon steel (<0.5%C)	54	W/mK
εt	emissivity of rolled steel	0.6	
εgc	emissivity of glass	0.9	
λgc	thermal conductivity of glass	1	W/mK
T_{sky}	sky temperature	2	°C
T_{amb}	ambient temperature	30	°C
U_{wind}	wind speed	1.5	m/s
$\nu a\ g_{co}$	viscosity of air outside glass cover	0.00002	m^2/s
$\lambda a\ g_{co}$	thermal conductivity of air outside glass cover	0.026	W/mK
$\nu a\ g_{ci}$	viscosity of air inside glass cover	0.00002	m^2/s
$Pr\ g_{ci}$	Prandtl number of air inside glass cover	0.7	Pa
e	roughness	0.25	
QPC_{a1}	air into PTSC	5025	kg/batch
$XPC_{a,i}$	humidity of air in PTSC	22	g/kg
$TPC_{a,i}$	Temperature of air into PTSC	55	ºC
$RHPC_{a,i}$	relative humidity of air into PTSC	57	%
Qu	useful energy gain	2110	W
η	thermal efficiency of PTC	0.71	
ΔP	pressure drop through the tube	128	Pa

Input variables and design parameters of PTC are provided in Table 7.5. Linear dimensions, such as aperture width and length were used to calculate surface area (7 m^2), receiver area (0.7 m^2) and concentration ratio (9.3). Surface area estimates the quantity of materials required for fabrication. A schematic illustration of PTC showing design components is given in Figure 7.3. The base of the collector is designed with a wooden frame with metal brackets for support. Glass cover around receiver tube was 4 mm thick.

Energy balance calculations showed that the glass cover minimised convective heat losses and reduced total heat loss coefficient (U_L) to 8 W/m^2 K. Setting the gap between glass cover and receiver tube to 16 mm minimised convective losses and improved collector efficiency (F') to 0.8. Receiver thickness was calculated using a thickness ratio of five. Cross-sectional area for air flow was 0.004 m^2 and at a volumetric flow rate of 0.1 m^3/s, air velocity inside receiver tube was estimated to be 1.5 m/s. This can be facilitated using a blower or axial fan.

Design features show main collector components and heat losses from receiver tube, aperture and back. At an average solar insolation of 6 kW/m^2 the total heat loss coefficient (U_L) was 9 W/m^2 K. Radiation and convective heat losses are mainly from the glass cover around receiver tube. Useful heat gain was 2109 W with a maximum outlet temperature of 94 ˚C. Under these conditions, the thermal efficiency of PTC is 71%. Variations in inlet temperature and solar radiation affect thermal performance and energy output.

Temperature profile of PTC is determined by concentration ratio, which is calculated from rim angle and focal point. Regeneration of solid desiccant material, such as silica requires temperature above 80 °C. Under ambient Fijian conditions (30 °C, 80% RH), adsorption capacity of silica is 20% water/ kg dry silica gel. When temperature rises above 50 °C, adsorption capacity declines to less than 5% and the maximum temperature of the receiver tube increases to 112 °C during main season harvest (Figure 7.7). Peak solar insolation is 6 kW/m^2 with 10% cloud cover during main season cocoa harvest. Since solar insolation declines to around 3 kW/m^2 during rainy weather conditions, a decline in temperature (76 °C) is also observed with an increase in cloud cover to 87%.

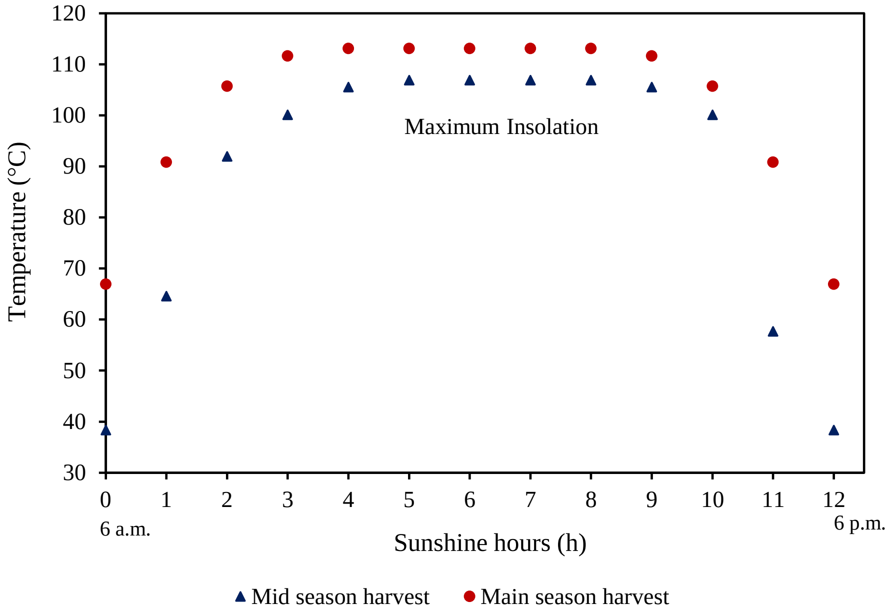


Figure 7.7. Mean temperature in absorber tube of parabolic trough collector during mid-season harvest and main season harvest. Temperature output from flat plate collector was used for parabolic trough collector inlet.

During the mid-season harvest between May to June, the average receiver temperature can increase to 107 °C with a regeneration temperature of more than 80 °C for desiccant regeneration. The average receiver temperature was estimated to be 94 °C with a regeneration temperature of 92 °C during main season (October to December) harvest. Cooler collector temperature profile can be caused by high precipitation and cool air conditions. This is less effective for desiccant regeneration. The PTC can operate at optimum capacity when cloud cover is 10% during main season harvest. Solar insolation during the main season is also high, which would allow the PTC to operate at high capacity (Figure 7.7). Improvements in aperture width and thermally efficient insulating material can maximise temperature output from PTC. These modifications can minimise the effects of seasonal variations and improve desiccant regeneration temperature (Pramuang and Exell, 2007).

7.3.4 Drying chamber design

A schematic illustration of drying chamber is given in Figure 7.8. Drying trays are vertically stacked on a drying shelf fitted with wheels for easy transport between drying chambers. Mass flow rate (Q_a) of air was estimated to be 5025 kg/100 kg for fermented cocoa beans with a volumetric flow rate of 0.1 m^3/s. Drying chamber size was estimated using tray specifications required to dry 100 kg of wet fermented product. Tray size was set at 0.3 m^2 and number of trays required was estimated by depth of bean bed. This was calculated using volume of beans.

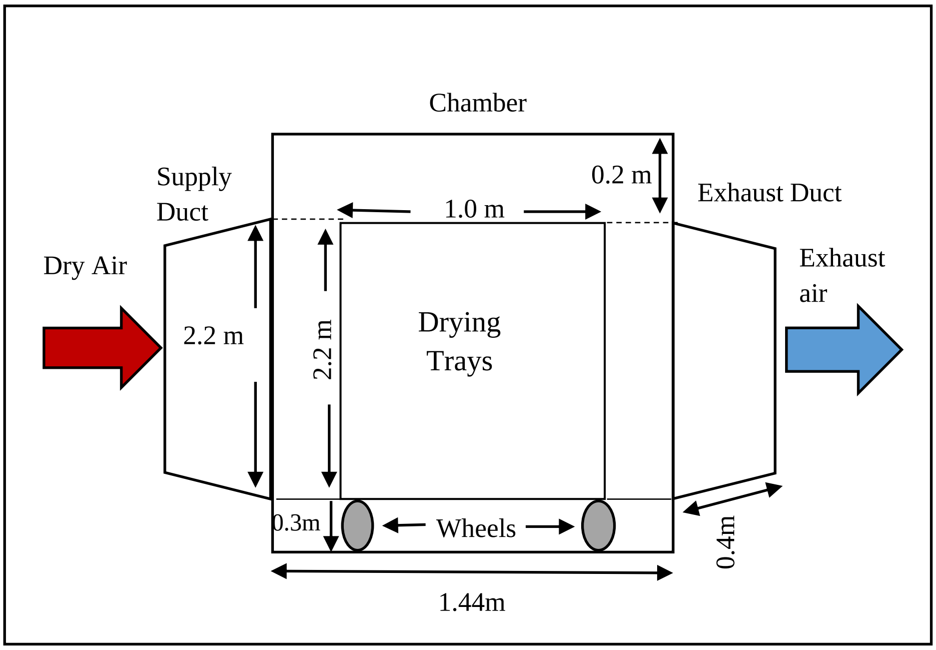


Figure 7.8. Dimensions of the drying chamber for drying 100 kg of wet fermented *Theobroma cacao* beans.

A drying chamber size of 3 m^2 was estimated for 100 kg of drying fermented cocoa beans with a clear area for air flow of 0.4 m^2. Mass flow rate of air inside drying chamber was estimated to be 0.8 kg/s with a volumetric air flow of 1.2 m^3/s and superficial air velocity of 0.3 m/s. Air velocity estimated from dryer design is comparable to realised air flow during drying experiments in Fiji. The Reynolds number of 491 under these conditions indicated slow laminar air flow. Mass transfer coefficient of air was also low (0.01 kg/s) under these conditions.

Improving air flow increases mass transfer coefficient between wet bean and dry air stream. This can be achieved by increasing tray size and drying chamber dimensions. Heat exchange coefficient was estimated to be 19 W/m^2 K. Improvement in Reynolds and Nusselts number when modifying dryer size increases heat transfer coefficient, which improves the drying process. Based on temperature output from desiccant wheel into dryer inlet, thermal efficiency of drying chamber was estimated to be 90%. Further work is needed to consider these design improvements.

7.3.5 Integrating the solar dryer desiccant wheel model into the drying model

A desiccant wheel can be effectively re-used during the drying cycle by regenerating the solid desiccant material. The study considers silica gel as representative of the solid desiccant material. Silica gel can be effectively regenerated above 80 °C. These regeneration temperatures can be achieved by using a FPC followed by a PTC. The FPC can be used to heat humid ambient air from 30 °C at 75% RH (20 g/ kg d.a) to around 55 °C at 25% RH (1-2). When this heated air is passed through a PTC, the air temperature increases to 120 °C at 5% RH (2-3). This is a suitable temperature for desiccant regeneration. The thermal treatment of ambient air does not alter humidity ratio. Air flow through the solar collectors can be increased by using a blower or a fan. The details of this design feature have been mentioned in chapters 1 and 2.

The drying model was integrated with a desiccant wheel (DW) model. The model was used to simulate the dehumidified air stream from the process section of DW for drying fermented cocoa beans. An area ratio of regeneration to dehumidification of 1:3 (R/P) can be used for a regeneration temperature of 60 and 120 °C. Milder regeneration temperature (60-80 °C) can be achieved with a split ratio of 1:1. This means that the DW regeneration/Process ratio can be designed to vary between 1:3 and 1:1 to provide better control of desiccant regeneration based on ambient conditions.

Desiccant wheel rotation speed also demonstrates an effect on temperature of process air and bean temperature. Figure 7.9 shows the impacts of DW rotation speed on drying temperature output. When DW is at 30 rph, the process air temperature for drying is around 55 °C and when rotation speed declines to 10 rph, air temperature is around 45 °C. These results are also reported by Rambhad et al. (2016) and Yadav and Bajpai (2011), where silica gel based DW is more efficient from 20 to 30 rph.

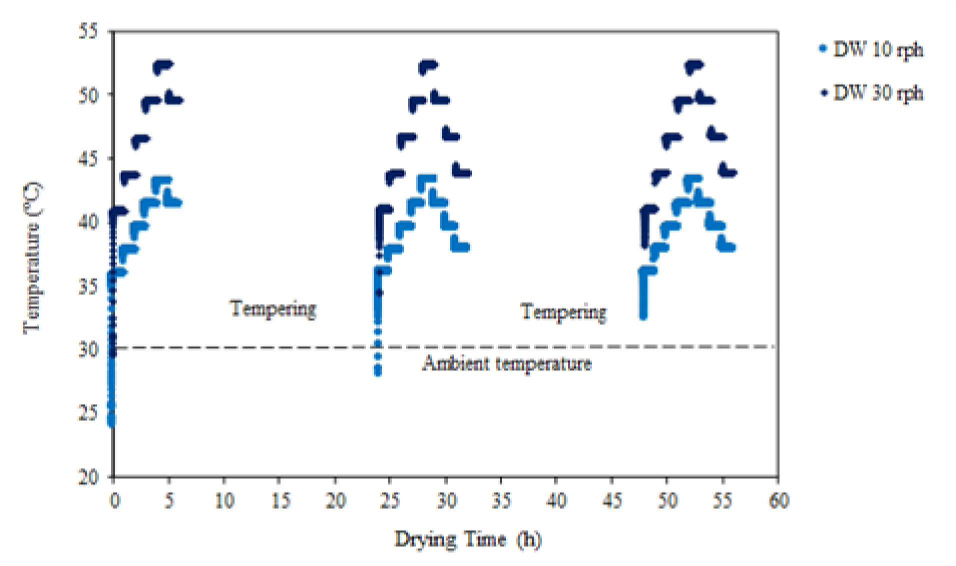


Figure 7.9. Daily temperature profile of process air at 10 rph and 1:1 regeneration ratio and 30 rph at 1:3 ratio predicted by desiccant wheel integrated drying model for dehumidified drying at 55 °C. Tempering period in between drying runs occurred overnight. Drying ceased and moisture equilibration occurred.

Variation in process air temperature also has an impact on bean temperature as shown in Figure 7.10. Bean temperature is comparable to process air temperature at each DW rotation speed. These findings reflect the variations expected in a solar dryer system based on solar radiation on a given day. If DW motor is DC and solar powered, the intensity of solar radiation can influence wheel rotation and dry air temperature and RH conditions.

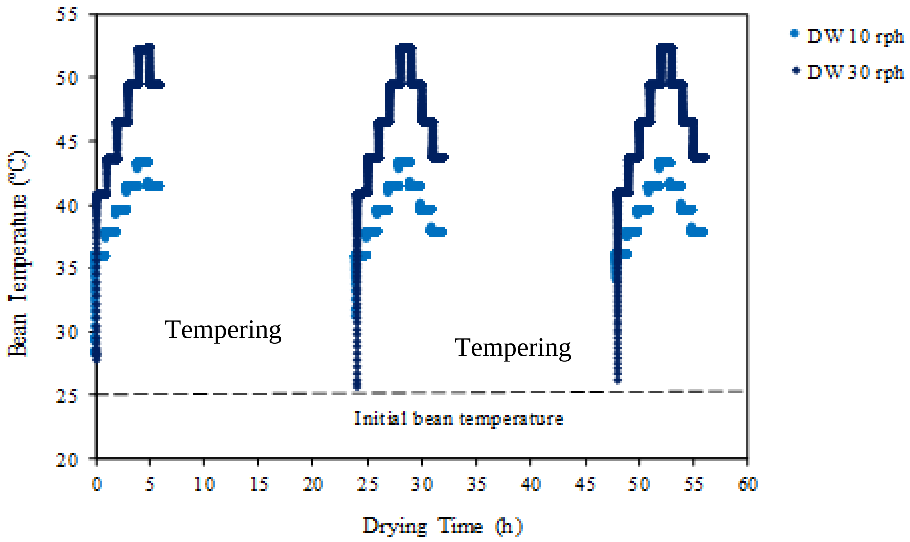
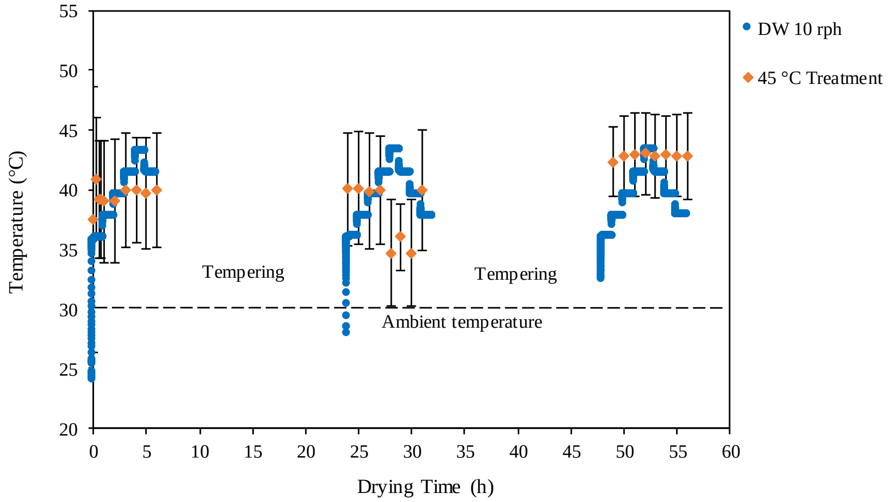


Figure 7.10. Bean temperature simulated by the model during drying cycles under dehumidified conditions at 10 rph and 1:1 regeneration ratio as well as 30 rph at 1:3 ratio.

Variation in temperature and relative humidity were observed when DW rotation speed was adjusted with an area ratio of the regeneration section to the process section (R/P) of 1:1. When DW rotation was 10 rph, the calculated temperature output was comparable to experimental drying data from 45 °C and 55 °C treatments (Figure. 7.11 A for 45 °C and B for 55 °C). The relative humidity output was also comparable with experimental data (Figure 7.12). At a slower rotation speed of 10 rph the ambient air flow through the DW has more contact with the desiccant material when compared to a DW rotation speed of 30 rph. Desorption is also complete at a rotation of 10 rph and this reduces the RH of drying air stream. The predicted RH of air stream from DW process section at 10 rph was comparable to 45 °C drying treatment (Figure 7.13). Model predictions on the rotation speed of DW at 1:1 R/P ratio was also close to the results from a study published by Kabeel and Abdelgaied (2016).

The model was able to accurately predict the temperature and RH output from a solar assisted DW dryer relatively well. In model simulation, exhaust air from DW regeneration section is used for bean pre-conditioning and the dry air from process section is used for drying. Drying experiments on Fijian cocoa beans were designed to test these theoretical desiccant wheel conditions based on daily solar cycle in Fiji. The variations predicted by the model can be used to adjust the drying process to preserve cocoa bean quality parameters. These quality parameters, mainly relating to polyphenolic compounds that are sensitive to temperature variations are described and discussed in Chapter 5. Additionally, further insights on the effects of input variables on drying kinetics of cocoa bean can be provided by a sensitivity analysis of the model, discussed in chapter 6.



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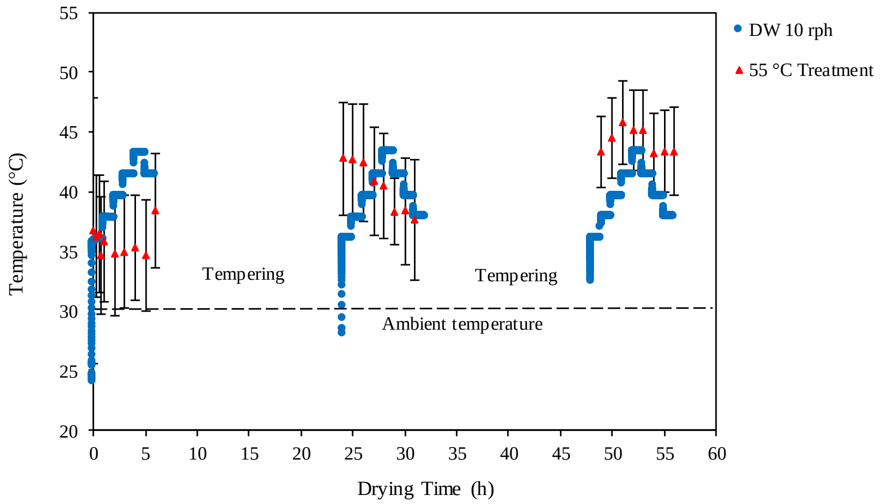

B

Figure 7.11. Temperature profile of air stream predicted by desiccant integrated drying model at 10 rph and 1 :1 R/P ratio. The model predictions are overlaid with experimental data A. 45 °C treatment and B. 55 °C treatment. The errors bars are standard deviations from drying runs.

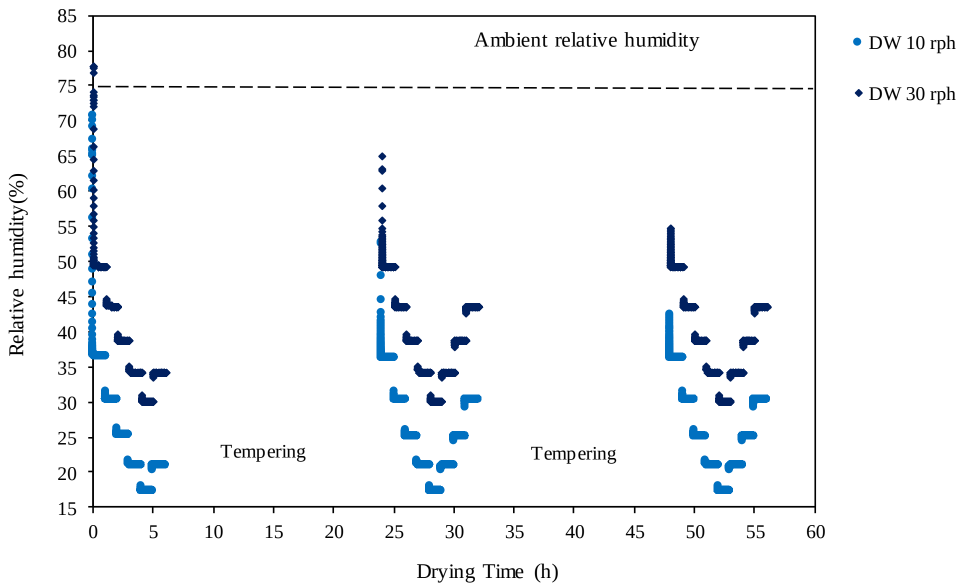

Figure 7.12. Relative humidity output from desiccant wheel indicated by model at 10 rph with R/P 1:1 and 30 rph and R/P 1:3.

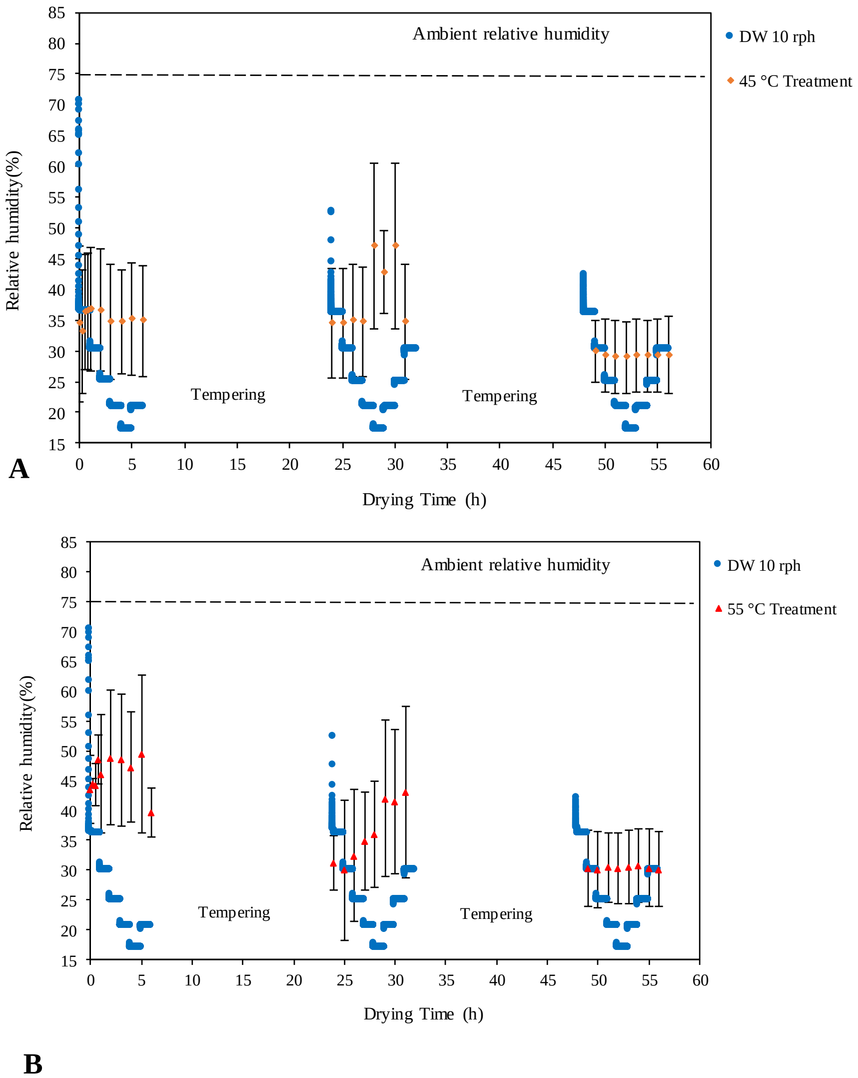

Figure 7.13. Relative humidity profile of desiccant wheel as predicted by the model at DW 10 rph and 1:1 regeneration ratio in comparison to the experimental data at A. 45 °C treatment and B. 55 °C treatment.

Energy balance equations characterise solar collectors and drying chamber for a specific quantity of fermented cocoa beans. Input quantity and thermal properties of feed material may vary between harvest seasons. Additionally, cost of materials, investment, and labour costs for dryer fabrication must be feasible for small-holder cocoa farms in a Fijian village. A socio-economic analysis of the drying system can provide insights on the benefits of investment and maintenance cost for a village setting.

7.3.6 Socio-economic implications of desiccant based solar dryer for *Theobroma Cacao* beans

In Fijian cocoa farms, freshly harvested cocoa is fermented, and sun dried on-site. This primary processing stage is labour intensive and time consuming. In Fijian villages, labour cost is minimised by involving the community. A large amount of time and labour is required for harvesting the cocoa beans and carrying the fermented cocoa beans (20 to 60 kg) to the drying platforms. Sun drying is unreliable with numerous quality issues in the dried product. Additionally, farmers lack of training and postharvest processing knowledge. Barbour and McGregor (1998) explain that in the past, more emphasis was placed on cocoa production rather than on quality aspects.

Quality is an important parameter for dried cocoa beans destined for international markets and can be a significant determinate of economic return. Fermentation and sun drying is a time consuming and labor-intensive process, which is costly to cocoa farmers. Additionally, farmers may not know the actual moisture content of sun-dried cocoa beans. Drying on-farm adds value to fermented cocoa beans and improvement in drying technology not only improves dried product quality but also maintains consistency in quality output.

In addition to energy analysis, economic cost can also be used to assess solar dryer performance. Costing is important as many farmers in the village may not be willing to invest in dryers. Veronice (2014) identified the following constraints faced by cocoa farmers in West Sumatra, Indonesia in adopting technology for fermentation and drying:

1. Additional labour time of 10 days for mixing beans during fermentation and drying.
2. Lack of price variation between fermented and unfermented cocoa beans.
3. Sales by farmers to middlemen for cheaper prices.

This situation is relatable to Fiji, but further socio-economic information is required to validate these constraints. Labour intensive tasks in a Fijian village is allocated to males, while the female members usually assist in monitoring the drying process. The division of labour may influence the cost for processing cocoa beans. Traditionally, women in a village setting perform domestic tasks with little or no incentive. In this case, labour cost by the village is at risk of being disregarded. The labour hours of eight hours per week for three months from literature was considered in calculating bean cost (Tables 7.4, 7.5 and 7.6).

Table 7.4. Capital cost for desiccant wheel based solar dryer system

Capital cost	Price FJD	Total cost FJD
Flat plate collector	1,074	
Parabolic collector	1,132	
Drying chamber	1,463	
Cost of installation	200	
Overhead	500	
Desiccant wheel	8,000	
Cost of Capital		12,369

Table 7.5. Annual operating cost for 5 Mt of dried cocoa beans by desiccant wheel based solar dryer

Annual Operating cost	Price FJD	Total cost FJD
Depreciation*	1237	
Maintenance	500	
Labour	780	
Energy consumption	2952	
Losses	500	
Total		5,969
Cost per kg of cocoa bean		1.20

*Depreciation is calculated as 10% per annum

Table 7.6 Annual operating cost for 5 Mt of traditional sun-dried cocoa beans

Annual Operating cost	Price FJD	Total cost FJD
Depreciation*	0	
Maintenance	100	
Labour	1559	
Energy consumption	0	
Losses	2000	
Total		3,659
Cost per kg of cocoa bean		0.73

The capital cost of installing a desiccant based solar dryer is given in Table 7.4. The DW can be used for drying cocoa beans for about 10 years. The solar collectors and DW is estimated to depreciate by 10% per annum. This depreciation value is considered in Table 7.5 for the annual operating cost for 5000 kg or 5 Mt of dried cocoa beans per year using a desiccant based solar dryer. In addition to depreciation of 10%, there is also estimated labour costs, maintenance cost for equipment, energy consumption, and losses caused by physical damage from cyclones. The labour costs and losses for desiccant based solar dryer is lower when compared to the annual operating cost for sun-drying cocoa beans given in Table 7.6. Sun-dried cocoa beans do not have a depreciation value and energy costs but the labour cost at a minimum wage of 2.32 FJD per hour in Fiji is higher than the labour cost for desiccant based dryer. Sun-dried cocoa beans require frequent monitoring and mixing during the solar cycle of eight hours for the whole week during three months of harvest. The harvest season is biannual in Fiji. Introducing the desiccant-based dryer is expected to reduce labour cost by 50% as only four hours of the day can be dedicated to loading and unloading the dryer and other routine maintenance tasks.

The cost of cocoa beans from the desiccant-based dryer is 1.20 FJD per kg when compared to sun-dried cocoa beans, which is 0.73 FJD per kg. Product loss is expected to be as high as 40% in sun-dried cocoa beans. Based on the estimated price of cocoa beans, if a village were to produce 5000 kg of dried cocoa beans per year and contributed 40% of the revenue towards the capital cost then the capital cost can be paid off within five years. Application of this solar technology is a long-term investment where drying can be more efficient with lower cost. The solar dryer with the desiccant wheel can be operated for 10 years. The desiccant wheel system is more reliable than sun drying and has the potential to add value to dried cocoa beans for quality chocolate production.

7.4 Conclusion

Energy balance equations are useful for estimating thermal efficiency of solar dryer components. However, mathematical models can be usefully applied with validation from field data. While solar insolation and air temperature are critical input variables, thermal and properties of materials can also improve heat transfer within solar collectors and in the drying chamber. Temperature and air flow estimated in the drying chamber are comparable to values measured in drying experiments. Improvements in collector dimensions and materials can improve temperature output for desiccant regeneration and minimise heat losses. Therefore, there is scope for testing and refining mathematical models using analysis of solar dryer components. While there are many types of solar dryers, an effective design has not been developed for *Theobroma cacao* beans. There are many theories and recommendations that need further testing. Further work needs to be conducted by developing a reliable and robust mathematical model for collector design and testing its performance under Fijian conditions.

Chapter 8 General discussions, conclusions, and recommendations

8.1 General discussions

In Fiji, fermented and dried *Theobroma cacao* beans are an economically significant commodity, which provides Fijian village communities with a lucrative source of income. Currently, the global demand for exotic Pacific cocoa beans, mainly for single origin chocolate markets is on the rise. Dried Trinitario cocoa beans from Samoa are used by Whittakers®, NZ for chocolate production. Additionally, Pacific Islands nations such as Solomon Islands, PNG, and Vanuatu are also producing dried cocoa beans for the chocolate industry.

Fermentation and gentle drying conditions are known to develop flavour profiles. Spontaneous fermentation in Fiji could potentially be controlled by introducing starter cultures. This approach has been successful in improving cocoa bean quality in several studies reported in literature. These studies are mentioned in detail in chapter 2. While starter cultures have not been tested on Fijian cocoa beans, a scientific trial to test the influence of starter cultures on cocoa bean quality in Fiji would validate the technique under Fijian conditions. This may help control microbial diversity between batches and in between different farm locations. Further insights on the microbial succession and the impact of microbial enzymes on flavour precursor formation during fermentation of Fijian cocoa beans could provide new information to scientific literature.

The drying process in Fiji is mainly open-air sun drying. While there are no energy costs associated with sun drying, cost is incurred in the form of labour. Inconsistent weather patterns not only disrupt sun drying, but it also reduces the commercial value of dried cocoa beans. Labour is required to constantly monitor the drying process and to rake the cocoa beans during all 14 days of drying. Simple solutions, such as covering the heap of cocoa beans with tarpaulin or plastic may seem low cost, but condensation of excess moisture trapped in the beans often causes mould growth. The growth of mycotoxic mould is a concern to human health and could also lead to tonnes of sun-dried cocoa beans being rejected for export. This study addresses the problem of solar drying under humid conditions by integrating a desiccant technology into the solar dryer design. This concept can be a food-safe approach to dry the fermented cocoa beans under controlled drying conditions.

Solar dryers have been proven to improve the drying process and product quality and the integration of a desiccant wheel to this system further reduces drying time. Dehumidification of drying air stream has been demonstrated to significantly improve the drying kinetics of many food products as mentioned in chapter 2. Experimental trials involving large quantities of wet fermented cocoa beans with desiccant wheel and solar dryer are costly and time consuming. Therefore, a drying model was developed in this thesis to predict the drying kinetics of freshly fermented cocoa beans based on variations in Fijian drying conditions.

The two-key objectives of this PhD were:

i. to understand how a desiccant wheel can be introduced into a solar dryer system to dry wet fermented cocoa beans under low RH but moderate temperature and

ii. to develop a mechanistic model that can accurately predict the drying kinetics for a quality dried product.

A mechanistic drying model was developed for predicting the drying kinetics of *Theobroma cacao* beans by simulating variations in drying conditions inside a solar assisted desiccant-based dryer set-up in Fiji.

Parameterisation of mechanistic drying model for Fijian *Theobroma cacao* beans and analyses of key quality composition addressed the following key research questions of this PhD:

1. Can the theoretical output air from the desiccant wheel be used to achieve cocoa bean drying within one pre-drying and two drying days, under Fiji conditions?

2. Can a mechanistic model simulate drying kinetics of Fijian *Theobroma cacao* beans in a solar dryer integrated with a desiccant wheel under Fiji weather conditions?

3. What are some changes that occur in the quality composition of fermented *Theobroma cacao* beans when dried under the likely range of conditions in these scenarios?

The first step to answer these research questions, was to design a small-scale preliminary experimental set up for testing the effects of relative humidity conditions on the drying kinetics of a seed at mild drying temperature. *Cucurbita moschata* seeds were selected based on seasonal availability in New Zealand. The *C. moschata* seeds were used for understanding the impacts of altering relative humidity (RH) conditions on the drying time and final moisture content in a dried seed. A review of literature on drying cocoa beans suggested that cocoa beans are temperature sensitive, and the drying kinetics can be improved by dehumidifying the air stream. Based on this information from several studies, low RH and mild temperature combinations were tested on wet fermented Fijian cocoa beans in a large-scale drying system (6 ±1 kg of wet beans), which was a bench top dryer. Details of the drying experiments are presented in chapter 3. The conceptual dryer design was modified from Duffie and Beckman, (1974) to fabricate a bench scale experimental set up for drying experiments in the Fiji Islands.

The drying trials showed a high level of variability in dry bulb temperature and RH profile in between drying runs. While the drying conditions were not consistent during the experiments, the cocoa beans were able to be dried to a safe moisture content of less than 10% (w.b) in three drying cycles. Variations in temperature and RH profiles at tray inlet and outlet and from the top tray to bottom tray were experienced during the drying runs. Chapter 2 mentions that a safe level of a_w can be achieved during drying if the RH of drying is less than 65% between 40 to 60 °C. Therefore, fluctuations in RH were below 65% for each temperature treatment.

Data points from the best three drying runs on fermented Fijian cocoa beans at 45 and 55 °C treatment was used to validate the mechanistic drying model in chapter 4. Several input parameter values were selected from experimental conditions in Fiji and from the literature mentioned in chapter 2 and chapter 3 of this thesis for model parameterisation. The one-dimensional drying model was in agreement with the experimental drying data at 45 and 55 °C. Further drying runs could be tested but restrictions in time and limited availability of fermented cocoa bean samples prevented further experimentation. The model was useful in predicting drying time, but quality data were needed to assess the possible impact of these drying conditions on temperature dependent compounds that affected the bioactive quality of cocoa beans.

Analyses of key bioactive components, such as total extractable polyphenols, caffeine, and theobromine are discussed in Chapter 5. These bioactive components were analysed using a standard protocol from literature as mentioned in chapter 5. While the anthocyanin content was not analysed using HPLC-DAD, the fermentation index (FI) was used to estimate the level of anthocyanins detected in the fermented and dried cocoa beans. Anthocyanins are sensitive to temperature and pH during postharvest processing. A further decline in the anthocyanin content is expected during downstream processing due to temperature conditions. The thermal degradation of anthocyanins affects the flavour profile of cocoa beans.

Other compounds that contribute to a desirable bitterness in dried cocoa beans are caffeine and theobromine. These glycoalkaloids were analysed in the cocoa extracts (CE) using reverse phase chromatographic separation with ultra-violet absorbance detection (RP-HPLC/DAD) (Brunetto *et al.*, 2009). Several parameters, such as sample size, volume of extracted solvents and extraction time were used to optimise and validate performance of the analytical procedure. Key performance indicators, such as good selectivity, sensitivity, and recovery of analytes demonstrated that the method was accurate and reliable for simultaneous analysis of theobromine and caffeine in CE. Caffeine demonstrated temperature sensitivity at 55 °C treatment, while theobromine remained relatively stable. However, theobromine content declined in cocoa beans exposed to 105 °C in an air dryer. This temperature condition is expected during downstream processing of fermented and dried cocoa beans. The study findings show that degradation of polyphenols, caffeine, and theobromine content exhibit temperature dependency. The drying model can be used to predict the impact of drying conditions on these bioactive components. A sensitivity analysis of the model provided further insights.

The sensitivity analysis of the drying model to variations in drying parameters was discussed in chapter 6 of this PhD thesis. A one at a time parameter (OAT) approach was adapted from Patel and Chen (2008) to test model parameters with 20% variation. The model was sensitive to variations in the dry bulb temperature at drying tray inlet, RH at drying tray inlet, cocoa bean diameter, and initial moisture content. Temperature is the key parameter that influences the bioactive composition in cocoa beans during drying. The key findings from chapter 3, 4, and 5 address significant research questions of this PhD and are discussed in the sections below.

8.1.1 Development of a mechanistic model for predicting drying kinetics and impact on the quality of Fijian *Theobroma cacao* beans

A drying model was initially developed using ordinary differential equations (ODEs). The ODEs are limited in describing the drying kinetics as the equations consider only one variable. This is not sufficient to accurately describe the drying process. The relationship between multiple variables affecting the drying kinetics can be described by using partial differential equations (PDEs). The numerical solution used to solve the PDEs was the finite difference method (FDM). There are other numerical solutions that can be used for future work. The FDM was used to approximate solutions to the PDEs using derivatives with finite differences. The spatial and temporal domains were discretised into such small scales that the numerical dispersion was minimised. An implicit method was used to solve the one-dimensional heat and mass transfer equation with a upwind scheme. The PDEs were solved and the drying process was simulated using the Matlab software.

The input variables for the model were considered from the drying trials conditions in Fiji. Variables, such as cocoa bean morphology, dryer length, air flow, as well as temperature and RH variations were used in the model equations. Drying experiments were conducted in a custom-made bench top dryer from preliminary experiments at MU. There were several minor design flaws in the bench top dryer used for drying tests in Fiji. It is worth considering that air flow and uniform drying are difficult to achieve even in the most sophisticated drying equipment. Realised conditions at tray inlet, such as average temperature, RH, air velocity, and product weight measurements from experiments in chapter 3 were used as input parameters for model development in chapter 4. The drying model for cocoa beans accurately predicted the drying kinetics under varying input parameters but neglected the overnight resting period (tempering) as overnight moisture loss was negligible.

The product moisture content at the end of drying provides further insight on the a_w. The model predicted the a_w of pre-conditioned cocoa beans to be 1. This increases the risk of mycotoxic mould growth overnight that causes product spoilage. Mycotoxins released from mould, such as *Aspergillus* sp. are a risk to human health. While the growth of mycotoxic moulds was reported to be evident in food samples with a_w above 0.65, production of mycotoxins occurs mainly between a_w of 0.81 to 0.83. The mycotoxin of concern in *Theobroma cacao* beans is ochratoxin A (OTA) produced by *Aspergillus* species.

Phytosanitary practices during primary processing can influence the growth of these mould species. Currently, there is no information on the levels of OTA in dried Fijian *Theobroma cacao* beans. While the detection of OTA in dried cocoa beans was outside the scope of this study, further work could be conducted to identify the exposure to OTA along the processing chain. The mathematical model developed in chapter 4 can be a useful tool in estimating the risk of OTA contamination in Fijian cocoa beans dried for export. It can also be used to virtually test the drying conditions and design conditions for a desiccant wheel (DW) system, estimate achievable air flows, temperature, and RH.

Control measures for a_w are critical during the pre-drying stage as the humid overnight tempering conditions for 12 hours could cause mould growth in the product. In overnight conditions, the temperature range is between 20 and 30 °C and the a_w in cocoa beans is 1. These are optimum conditions for mycotoxic mould to proliferate in the product. Preventative strategies suggested were terminating pre-drying at six hours and introducing dehumidified drying conditions, improving air flow in the dryer (0.5 to 1 m/s), and enabling drying under overnight conditions. Air flow during overnight resting can be improved using a fan driven by lithium batteries that can be charged using solar energy through a solar PV unit.

Another suggestion is to open the drying chamber during overnight resting to the clear night sky so the drying chamber walls cool. This causes temperature and vapour pressure gradients which facilitate moisture loss. The drying model can be further developed using Newton's law of cooling to further estimate moisture loss during overnight resting phase (tempering). While the details of these recommendations are discussed in chapter 4 and 7 of this PhD, the variations in temperature, and RH in the solar dryer integrated with a DW are discussed in chapter 6.

This PhD study recommends comparing the OTA levels in sun dried cocoa beans with samples that are solar dried under dehumidified conditions. Control measures, such as antifungal compounds and biocontrol agents can inhibit growth of *Aspergillus* mould and mycotoxin contamination in the product. These are a better option when compared to high drying temperature conditions that may destroy the bioactive active constituents in the dried product.

The mechanistic model for drying Fijian *Theobroma cacao* beans developed in this thesis can predict the time to achieve a final moisture content of 7% (w.b) based on varied input parameters. The model is a low cost and effective tool for controlling drying conditions to retain the quality of the dried product. The model can reliably prevent product contamination with mould by estimating the drying conditions that can limit a_w to <0.65 at the end of day one. Total drying time can be limited to two drying days, where the product dries to a final moisture content of 7% (w.b). Model predictions can be used to adjust the DW regeneration section or wheel rph to achieve the desirable drying conditions for maintaining cocoa bean quality.

The model also estimates DW regeneration temperature able to be generated by the parabolic trough collector (PTC) based on temperature output from the upstream flat plate collector (FPC). Under optimum ambient conditions of 30 °C, the temperature output from FPC is estimated to be 55 °C, which allows temperature output from PTC of 95 °C. This is discussed in detailed in chapter 7. Temperature output from the FPC is limited to about 55 °C, which is adequate for sun drying but not sufficient for desiccant regeneration. This temperature was improved by attaching a PTC for desiccant regeneration. Seasonal variations will likely affect the regeneration temperature profile, which also influences pre-drying conditions during the initial stages of drying. The model considers these variations and can estimate the drying conditions and drying time during based on seasonality.

Another point to consider is that desiccant regeneration is mainly effective during the mid-day period when insolation increases, and solar collectors achieve peak temperature profile. These variations are discussed in chapter 7. Therefore, pre-drying is limited to less than six hours of the first drying day. Overnight mould growth can be prevented by introducing dehumidified drying conditions to extend drying time. This would limit a_w in cocoa beans to <0.65, which could prevent mould growth and avoid product contamination with mycotoxins. Variations in the drying conditions affects the bioactive composition of the dried product. Chapter 5 provides a description on the thermal degradation of polyphenols during drying. The best drying condition was identified to be at 45 °C treatment under 20% RH, where temperature variations in the drying chamber was between 30 to 45 °C. These drying conditions demonstrated better retention of polyphenols, theobromine, and caffeine within two drying cycles.

8.1.2 Effect of postharvest processing conditions on the bioactive composition in *Theobroma cacao* beans

The standard analytical techniques used in this study provided reliable estimates for TPC, caffeine, and theobromine in dried *Theobroma cacao* bean samples. It was evident that polyphenols and caffeine exhibited temperature sensitivity. In addition, extended drying time could also have had a detrimental impact on polyphenol content. The effects of drying conditions on the composition of these compounds in cocoa beans have been discussed extensively in chapter 5. The impact of fermentation conditions on the bioactive composition of Fijian cocoa beans (var. Forastero) has not been discussed in detail as this was outside the scope of this study.

In Fiji, the effects of fermentation and drying on the bioactive composition of cocoa beans have never been reported in published literature. The findings from this study would contribute to scientific literature by reporting changes in key bioactive components caused postharvest processing conditions. In Fiji, a high UV index and mineral-rich volcanic soil contributes to the polyphenol composition and robust flavour profile in Trinitario and Forastero varieties of cocoa bean. Bean pH is an influential factor that determines polyphenol and methylxanthine retention during drying. It is worth noting that cocoa bean pH prior to drying is influenced by the production of organic acids during fermentation, which are also responsible for development of flavour and aroma precursors during downstream processing.

In Fiji, some cocoa processors wash fermented cocoa beans with potable water to remove residual pulp and organic acids adhering to the bean surface. This may change the bean pH. In addition, excess moisture gained during washing also affects the drying kinetics by eliminating variability in moisture content within a fermented batch. A better understanding of pH variations during drying can be achieved by measuring the pH of cocoa bean matrix at certain time intervals during drying treatments. This would elucidate the effects of pH variations on cocoa bean polyphenol content during postharvest processing. Solubility of polyphenolic compounds increases when the pH is acidic (<5). Enzymes such as polyphenol oxidase (PPO) that oxidises polyphenolic compounds are active between a pH of 5 to 11 but the optimum pH is 6.5. While pH can be an indicator of enzyme activity, the acidic flavour profile is determined by the titratable acidity (TTA). In the dried cocoa beans, the TTA was above the standard value of 11 to 19 mEq NaOH/100g of dried sample. A high TTA value indicates an acidic flavour profile in dried cocoa beans, which may have been caused by excess organic acids.

8.2 Conclusion

This study tested low relative humidity conditions on the drying kinetics of fermented *Theobroma cacao* beans in Fiji under mild temperature conditions (45 and 55 °C). Low RH has been known to decrease drying time and reduce moisture content to safe levels. Conversely, rapid drying is not ideal for thermally sensitive products, such as cocoa beans. Quality issues, such as case hardening, shriveling, and destruction of bioactive components were minimised by introducing low RH at mild temperature conditions that would also limit polyphenol oxidase activity and prevent further oxidation of polyphenols. Several studies have applied heat pumps and air compressors, but these techniques are costly for cocoa farmers in a Fijian village. Introducing a DW or a molecular sieve with desiccant material could be a better cost-effective option for Fijian cocoa processors and farmers. The DW technology could be operated using solar PV panel and the desiccant material can be regenerated using solar collectors. A drying operation using these techniques would become part of a green technology that is user friendly and low maintenance. In rural areas, energy supply may not be consistent or affordable.

A theoretical design of a solar dryer with a collector system was estimated to be effective for desiccant regeneration and for improving drying conditions. Mathematical modeling provided accurate predictions of drying time, temperature, RH, and product moisture content during drying. Mechanistic models were found to be more informative about the drying behaviour of fermented cocoa beans when compared to semi-theoretical models. The model could be used for predicting the drying conditions for fermented cocoa beans based on product moisture content, seasonal variations, and dryer conditions.

Sensitivity analysis demonstrated that the drying kinetics for cocoa beans is affected by four key parameters. These were drying air temperature, RH, bean size, and wet bean moisture content. Air flow was critical only during the first six hours of drying. The mechanistic model for cocoa beans in this PhD is the first drying model developed for Fijian cocoa beans based on the weather conditions in Fiji. This mechanistic model has the potential to be used as a low-cost tool to determine drying time, risk of mycotoxic mould infestation, and quality of bioactive components as flavour precursors.

The drying model also predicted the a_w and temperature profile of cocoa beans during drying. Control of a_w during drying cycles could control mycotoxin contamination in cocoa beans, especially when a_w is higher than 0.65 during overnight resting period. This increases the risk of contamination with *Aspergillus* sp., which causes food safety and human health concerns. The overnight resting is important as it allows tempering of cocoa beans, which facilitates moisture equilibration and re-distribution in partially dried cocoa beans. Other modifications during tempering would be to increase air flow to 0.5 m/s and to expose the drying chamber walls to the clear night sky. A clear polyethylene cover can be placed above the drying chamber to condense moisture from internal air and drain off the condensate safely from the walls. This would prevent mycotoxic mould growth in cocoa beans that could lead to product spoilage and rejection.

The mathematical model provides a convenient and cost-effective tool for predicting techniques to improve the drying conditions. This model can be a strong quality control tool in situations where there are variations in drying parameters caused by seasonal variations. In a solar dryer integrated with desiccant wheel, model predictions could be used to adjust the drying conditions to improve the drying kinetics. These adjustments could be the ratio of regeneration section, DW rotation, air velocity, and RH conditions. These adjusted drying conditions could improve the quality of dried Fijian *Theobroma cacao* for export.

8.3 Future work

Future work on improving the drying process for *Theobroma cacao* beans may include but is not limited to the following:

1. Comparing seasonal variations on the drying kinetics of fermented cocoa beans. Seasonal variations have showed an impact on ambient air temperature and relative humidity during cocoa processing. Fermentation and drying are relatively slow during mid-season harvest due to cool rainy conditions.

2. Standardising the fermentation process to limit biological variability within *Theobroma cacao* beans. Controlling fermentation conditions, such as temperature and aeration would maintain consistent quality of wet fermented cocoa beans as input material for drying.

3. Investigating the application of molecular sieves from natural sources as a low-cost alternative for dehumidification of the dry air stream for village scale drying.

4. Application of computational fluid dynamics (CFD) to model the internal temperature profile of *Theobroma cacao* beans during various drying conditions based on seasonal variations.

5. The microbial analysis was outside of the scope of this PhD study, as the focus was on quality problems in the drying process rather than fermentation.

6. Fabricating a full working prototype under Fijian conditions.

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List of Appendices

1. Preliminary humidity control experiments on *Cucurbita moschata* seeds

Drying experiments were conducted in humidity-controlled chambers inside an electric dehydrator (Excalibur ®, USA) with fan forced air flow at the postharvest laboratory at MU (Figure 1). The dimensions of this dryer were 420 mm L, 360 mm H, 320 mm W with fan forced airflow. Temperature and RH conditions were simulated using a range of process temperature output from the desiccant wheel under ambient Fijian conditions. Air velocity from fans in the humidity chamber during drying tests was at 0.9 m/s. Nominal volume of humidity containers was 200 ml.

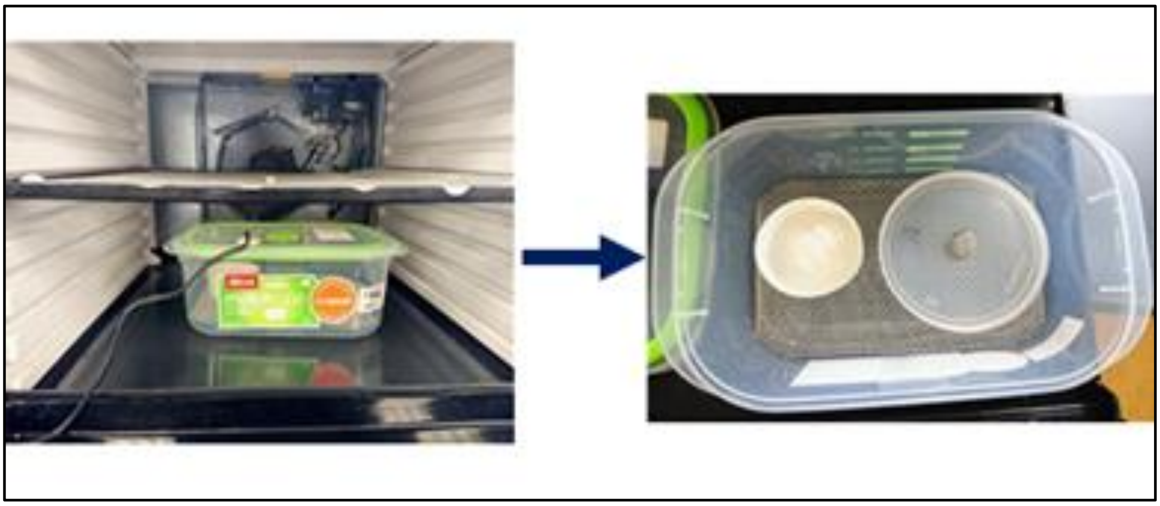


Figure 1. Set-up of humidity-control containers in an electric dehydrator. The humidity-control containers were used for drying tests on washed *Cucurbita moschata* seeds at different temperature conditions.

Selected RH conditions of 11, 33, and 75% at temperature conditions of 30, 45, and 55 °C were tested on a sample (20 g) of *C. moschata* seeds. Experimental RH and temperature conditions are presented in Table 1. Temperature and RH were measured and recorded using calibrated I-button sensors (Thermocron ®, USA). Temperature and RH setting for drying experiments are given in Table 1. These drying conditions using humidity control chambers with saturated salt solutions were adapted from studies by Misha et al. (2015) and Fudholi et al. (2011b). A schematic illustration given in Figure 2 provides a visual representation of the steps involved in humidity controlled drying tests on *C. moschata* seeds.

Table 1. Temperature and relative humidity settings for drying tests on *C. moschata* seeds

Relative humidity	11% RH	Sample size	33% RH	Sample size	75% RH	Sample size
Temperature °C	30	3	30	3	30	5
	45	3	45	3	45	5
	55	3	55	3	55	5

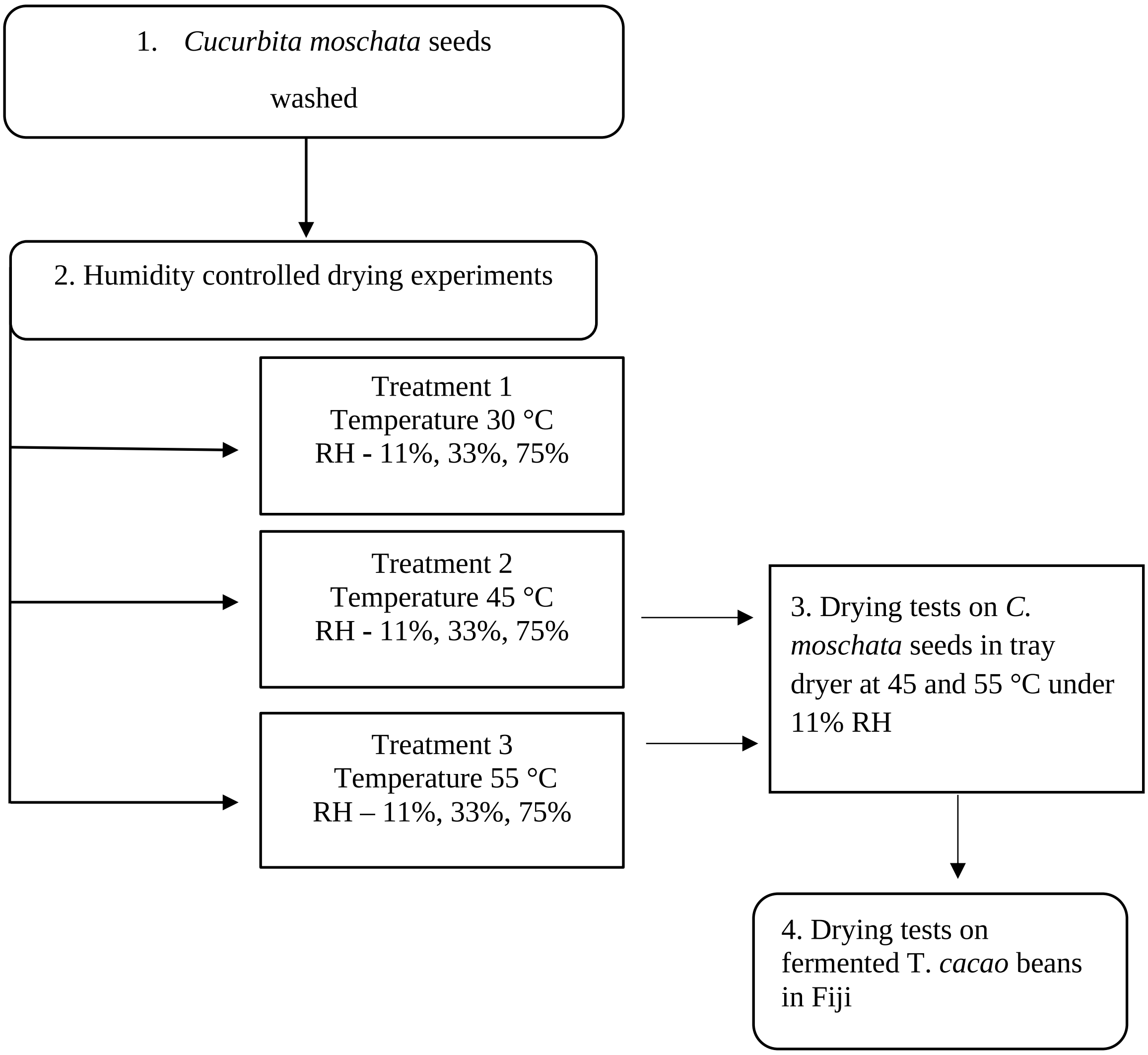


Figure 2. Schematic diagram showing design of preliminary drying conditions tested on *Cucurbita moschata* seeds for further screening during final drying tests in Fiji.

Large scale drying experiments were replicated in a tray dryer at food bioprocess laboratory, MU. The drying system were upgraded to a tray dryer for one kilogram of wet seeds. The tray dryer presented in Figure 3, consisted of a load cell connected to a computer to detect and calculate change in weight of wet seeds during drying. A blower circulated ambient air to a heater and then to the drying chamber for drying. Experimental drying conditions between 45 and 55 °C at 11% RH was tested on wet *C. moschata* seeds. The bigger system allowed a better understanding of variations in temperature, RH, and air velocity during drying tests. Additionally, a larger drying system increases air volume, which influences the drying time needed to achieve a product with a safe final moisture content.

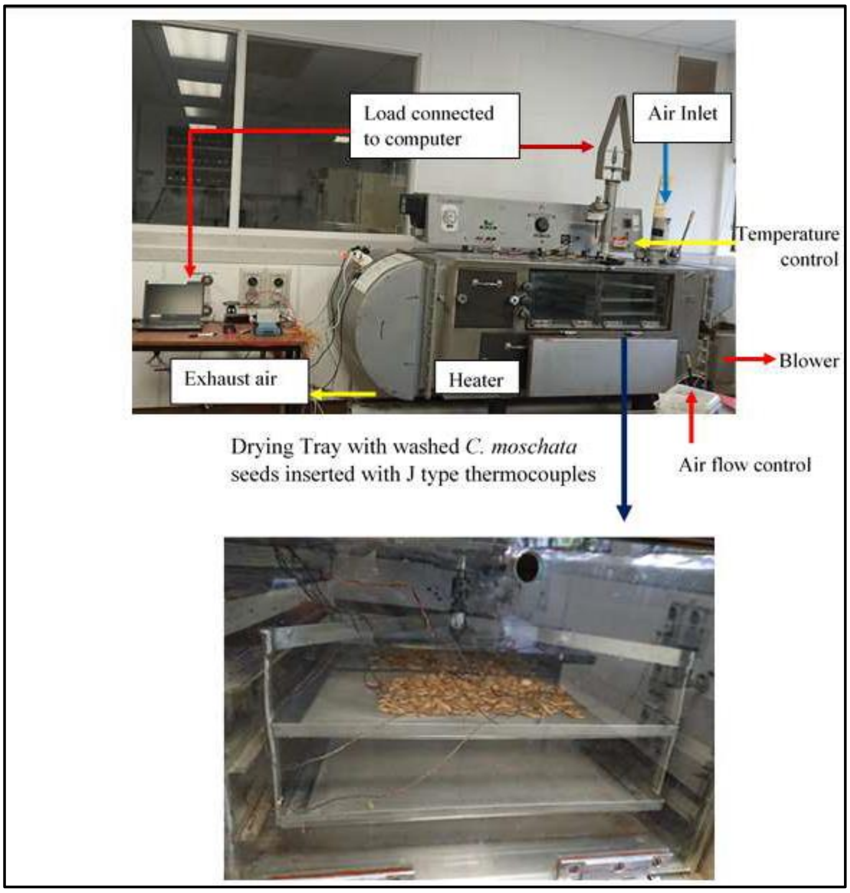


Figure 3. Tray dryer set up for testing drying conditions on one kilogram of *Cucurbita moschata* seeds at 45 and 55 °C under 11% RH. Humidity conditions was maintained using saturated lithium chloride (LiCl) solution.

2. Humidity controlled drying tests on drying kinetics of *Cucurbita moschata*

Experimental temperature and RH conditions were tested on washed pulp-free *Cucurbita moschata* seeds in small humidity-controlled containers with fans to circulate air flow. Details of the psychrometric properties of dry air stream used for drying *C. moschata* seeds between 30 to 55 °C under 11 to 75% RH provides further explanation on the drying kinetics. These psychrometric qualities of dry air stream used for drying tests are provided in Table 2. The key concept was to understand the possible effects of limiting RH using a desiccant wheel (DW) under sun drying conditions on drying kinetics of cocoa beans. Ambient Fijian conditions were simulated by using drying temperature of 30 °C and saturated sodium chloride solution for 75 % RH. The implications of reducing RH at 30, 45, and 55 °C on the drying kinetics was studied using humidity-controlled experiments on *C. moschata* seeds.

Table 2 shows that dehumidification of dry air stream lowers wet bulb and dew point temperature of dry air stream. This increases temperature gradient and improves moisture holding capacity of air. When RH of dry air is hypothetically limited to 11% using saturated lithium chloride solution at a dry bulb temperature of 30 °C, the wet bulb temperature declines to 14 °C (table 2). Washed wet *C. moschata* seeds equilibrates to wet bulb temperature of dry air during drying.

Table 2. Thermal properties of air stream used for testing various temperature and RH conditions on *C. moschata* seeds in humidity control containers

Material	Air Stream									
Stream Name	Ambient Air*	Dehydrator control	Enclosed chamber							
Dry bulb temperature (˚C)	30 ± 1	55 ± 2	55 ± 2	55 ± 2	55 ± 2	30 ± 1	30 ± 1	45 ± 1	45 ± 1	45 ± 1
Wet bulb temperature (˚C)	26	24	47	35	26	18	14	40	30	22
Dew point temperature (˚C)	24	8	46	31	14	11	-3	40	25	8
Saturation temperature (˚C)	26	24	47	35	26	18	13	40	30	21
Relative Humidity (%)	75 ± 2	7 ± 1	75 ± 2	33 ± 2	11 ± 2	33 ± 2	11 ± 2	75 ± 2	33 ± 2	11 ± 2
Partial saturation vapour (Pa)	2810	15760	14661	14661	14661	4246	4246	9593	9593	9593
Partial vapour (Pa)	2984	1092	10156	4416	1619	1279	469	7223	3178	1059
Humidity (kg/kg d.a)	0.018	0.006	0.069	0.028	0.010	0.080	0.029	0.048	0.021	0.007
Enthalpy (kJ/kg d.a)	78	73	234	127	80	51	38	169	97	62

*Ambient air conditions were 30 °C treatment at 75% RH

3. Drying kinetics of washed *C. moschata* seeds in humidity-controlled chambers

Proof of concept for improving drying potential of air using dehumidification was tested on small samples of *C. moschata* seeds using humidity-controlled chambers. These small-scale experiments on washed *C. moschata* seeds developed an understanding of the interaction between mild temperature, RH, and air flow on moisture evaporation. Effective combinations of temperature and low RH with a shorter drying time when compared to traditional sun drying of 14 days were identified from humidity-control experiments. These temperature and RH conditions were selected for further tests on Fijian cocoa beans using a customised dryer.

Experimental findings from drying tests shown in Figure 4, supports the concept that an RH of 11% improved drying time. These initial drying tests shows variations in drying time between different treatment conditions at 30, 45, and 55 °C. Drying runs shown in Figure 4 (A) at 30 °C and (C) at 55 °C were treated to an overnight resting period, whereas samples in Figure 4 (B) treated at 45 °C were dried continuously. In drying runs at 30 °C and 45 °C, *C. moschata* seeds were dried between 24 - 36 h at 11% RH conditions until constant weight was recorded. The constant weight per test sample was achieved under both treatments after 24 h of drying. Drying tests on *C. moschata* seeds at 55 °C under 11% RH was conducted on four samples of *C. moschata* seeds.

Drying curves for four samples of *C. moschata* seeds treated at 55 °C under 11% RH is shown in Figure 4 (C). The drying runs were terminated between 48-54 h with two overnight resting periods between each drying runs. Drying runs 1 and 2 were terminated after 48 h of drying, soon after overnight tempering. There was a delay in the termination of drying for samples in run 3 at 54 h and run 4 at 50 h. Drying runs 1 and 2 equilibrated within 36 h of drying but an overnight resting period was included to observe any reduction in weight the following day. The samples had achieved its target moisture content based on weight measurements therefore drying was terminated.

These variations in moisture loss may have been influenced by an influx of external air in humidity containers while rotating saturated salt solutions. The disturbance in the air profile remains for 15 minutes, and then the drying conditions stabilises. Another factor that may have caused variations in moisture loss is the residual pulp attached to the testa. Drying runs 2 and 3 demonstrates unusual patterns of moisture loss after overnight resting. Moisture content in these runs equilibrate after 12 h of drying, followed by a rapid decline after overnight resting for eight hours. Drying runs 2 and 3 commenced simultaneously at 9.30 a.m. and terminated at 9.30 p.m. during the first day and resumed around 6 a.m., the following day. Drying run 1 was continuous drying for 30 h.

Drying treatment at 45 °C in Figure 4 (B) was continuously monitored without any overnight resting period. Variations between drying runs were limited. *C. moschata* seeds equilibrated within 14 h of continuous drying at 11% RH. Moisture loss. Drying run 3 displayed a slower moisture loss when compared to runs 1 and 2. Variations in *C. moschata* drying curves were also limited at a higher drying temperature of 55 °C at 11% RH. Rapid moisture loss was observed initially for six hours of drying. The seeds equilibrated to a moisture content of 0.10 kg water/kg dry seed within 12 h of drying. Resumption of drying after overnight resting demonstrated a decline in moisture content to 0.07 kg water/kg dry seed. The RH profile for air in drying runs 1 to 4 is presented in Figure 11 (C). The drying runs were conducted under 55 °C at 11% RH. The graph shows an increase in RH during initial stages of drying. Relative humidity stabilises to 11% after 12 h of drying for drying run 1 and 4. In drying runs 2 and 3, where the RH of air was 15%, *C. moschata* seeds in these drying runs equilibrated to a moisture content of 15% or 0.15 kg water/kg dry seed. The spike in RH from 11 to 15% may have been caused by excess moisture retention in the humidity chamber or leakage of ambient air into the system.

These experiments at different temperature conditions at 11% RH developed an understanding of variations expected in the drying system. Additionally, the various stages in the drying process were identified from the drying curves between different treatment temperature conditions. In the initial stages of drying for the first six hours, external migration of moisture from seed surface is controlled by temperature and air velocity. Seed geometry and dimensions influence the rate of moisture migration from the surface. Uddin et al. (2016) explains that in a flat seed, a large surface to volume ratio facilitates this external migration of moisture.

Additionally, moisture diffusion on the lower surface of seeds on a drying tray is restricted by the tray surface. Internal diffusion of moisture within seed pores is facilitated by a vapour pressure gradient caused by reducing RH in the drying system. Temperature profile and RH conditions of the drying system in small humidity-controlled containers were relatively stable during drying tests. Variations in between drying may have been caused by biological variability in seeds, such as moisture and starch content. The variability increases after fermentation.

Improvement in drying time in *C. moschata* seeds when RH was lowered is comparable to findings by Fudholi et al. (2011). The study found that reducing RH to 10% at 60 °C with an air velocity of 1 m/s demonstrated a positive impact on drying time and final dried moisture content (<10% w.b) on seaweed. These findings are comparable to various other studies in literature, such as cassava pulp. LiCl solution was used to limit RH to 11% between 30 to 70 °C (Ratinun and Suparerk, 2019). LiCl solution limits relative humidity from 11.3 (± 0.3) to 10.9 (± 0.3) between 25 to 60 °C (Greenspan, 1976). Lower RH (0.010 kg/kg d.a) also increases seed temperature, which improves drying time (Pazyuk *et al.,* 2018).

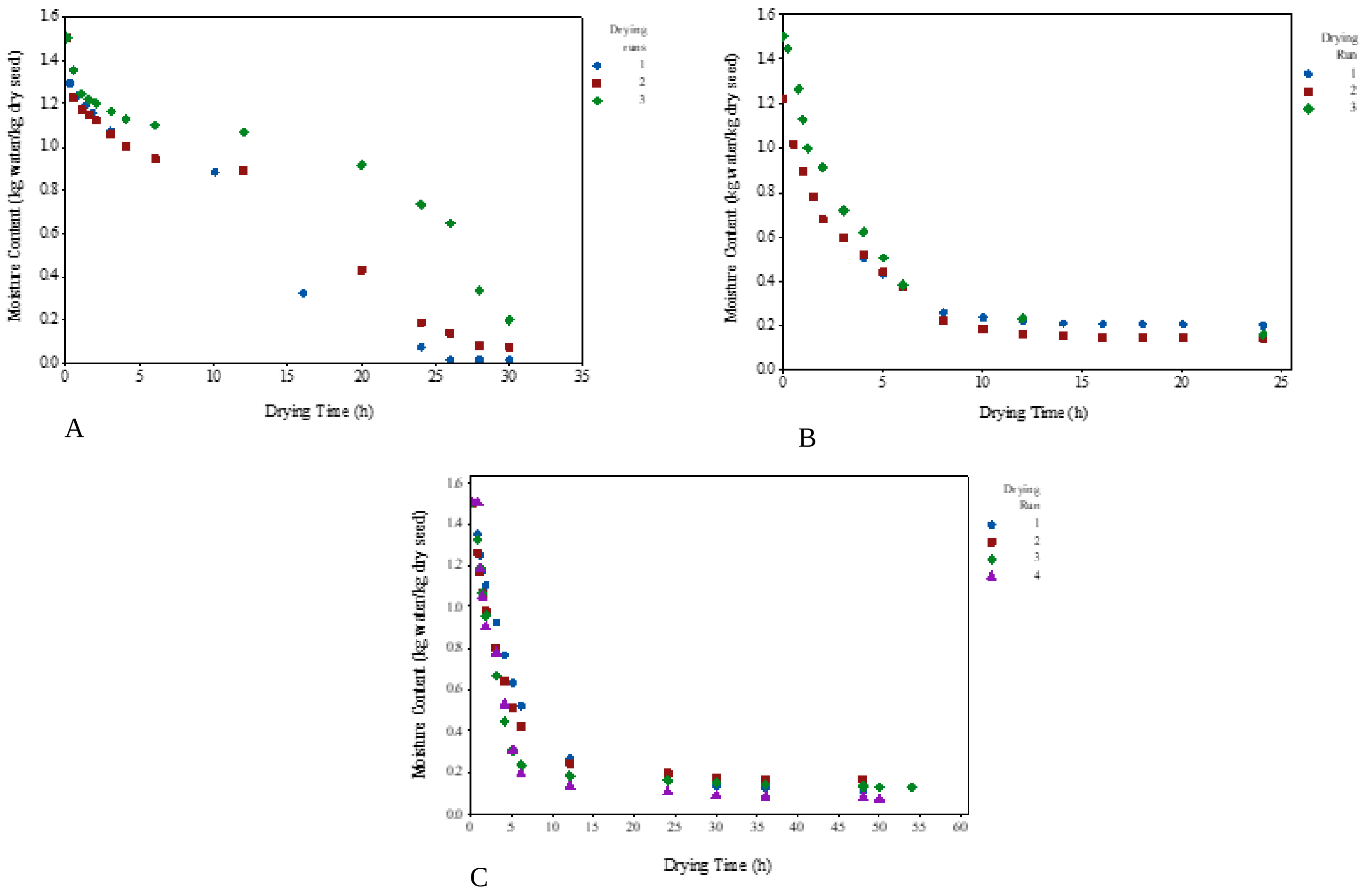


Figure 4. Drying curves for washed *Cucurbita moschata* seeds dried in humidity-controlled chambers. Drying was conducted under 11% RH at various temperature conditions presented in A. 30 °C, B. 45 °C and C. 55 °C for a drying period of 48-60 h. Drying was terminated once a constant weight was reached.

Table 3. Drying time for *C. moschata* seeds to reach moisture content of <10% w.b. under 11% RH at various dry bulb temperature

Dry bulb Temperature °C	RH %	Drying time h
30		30
45	11	14
55		12

*Average value from each drying runs are presented in this table

Moisture analysis and change in physical parameters of composite samples of *C. moschata* seeds dried at 11% RH are presented in Table 5. The whole seed consists of testa (8%) and kernel (4%). The average initial moisture content of whole seed on was 58% (w.b). The testa had a higher moisture content than the kernel. This could be attributed to the percentage composition of testa in the seed and the high fat content in the kernel. The fat content in fresh *C. moschata* kernel is around 50% (Petkova and Antova, 2015). This is comparable to the fat content in fermented cocoa beans, which varies from 45-60 % depending on cocoa varieties and geographical location (Pires *et al.*, 1998).

Drying tests on *C. moschata* seeds showed that 11% RH was effective in limiting the moisture content from 58% to 7% on a wet weight basis in less than 30 hours. This drastic reduction in moisture content at 55 °C under 11% RH showed an impact on the seed surface area from 297 to 191 m^2. The testa loses the most moisture when compared to the kernel.

Table 4. Physical parameters and moisture content of fresh and dried *C. moschata* seeds

Parameters	Average values ± SD	Units
Average weight per dry seed	0.3 ± 0.1	g
Wet seed surface area	297 ± 30	mm^2
Dried seed surface area	191 ± 9	mm^2
Fresh seed moisture content (w.b)		
Whole seed with testa	58 ± 0.3	%
Testa %	42 ± 0.7	%
Kernel %	25 ± 0.6	%
Dry seed moisture content (w.b) at 11% RH		
Whole seed with testa	7.0 ± 0.1	%
Testa	8.0 ± 0.2	%
Kernel	4.4 ± 0.1	%

*Drying temperature was 55 °C under 11% RH

4. Humidity-controlled drying experiments on *C. moschata* Seeds in a tray dryer

Experimental conditions from humidity control containers with shorter drying time were selected for further tests on a larger drying system (2 m^2) on one kilogram of *C. moschata* seeds. A tray dryer with a capacity for two kilograms of wet product and minimum air velocity of 1 m/s was used for further drying tests on washed *C. moschata* seeds. A description of the tray dryer is discussed in the methods section of this chapter. Saturated LiCl solution was used to dehumidify inlet air stream to 11% RH at 45 °C with an air velocity of 1 m/s. Seeds were dried on two trays (0.25 m^2) on a vertical drying shelf attached to a pre-calibrated load cell for weight measurements on hourly intervals.

The drying curves presented in Figure 5 shows a sharp decline in moisture content, which is visible during initial stages of drying, followed by a steep decline in moisture content after 12 h. Temperature and RH profile given in Figure 7 was relatively stable. The initial moisture loss can be attributed to a reduction in the boundary layer, followed by a slow decline in moisture content. Drying under 11% RH may have improved internal diffusion of moisture from seed pores to the surface.

Capillary diffusion of unbound moisture from pores to surface is facilitated by low RH conditions (Sigge *et al.*, 1998, Akritidis *et al.*, 1988). During the drying tests in the tray dryer, there was no fluctuation in temperature and RH conditions of dry air stream. The tray dryer is a larger scale drying system when compared to humidity control containers. Therefore, the drying time at 45 °C under 11% RH in a 2 m^2 drying system as opposed to a 0.0020 m^2 was 60% longer (25 h). These results are comparable to a rapid drying rate in studies by Pazyuk et al. (2018) and Uddin et al. (2016).

Tray dryer had a larger drying area when compared to the humidity chamber, airflow was estimated to be laminar and sample size was 400 times greater. The mass flow rate in the tray dryer was 0.25 kg/s with an air velocity set at 1 m/s. The initial wet moisture content of washed *C. moschata* seeds was 60% (w.b) or 1.32 kg water/kg dry seed. This is a small amount of moisture in relation to the humidity ratio of air at dry bulb temperature. Extended drying time in a larger drying system can be better understood by calculating the heat transfer coefficient of drying air stream.

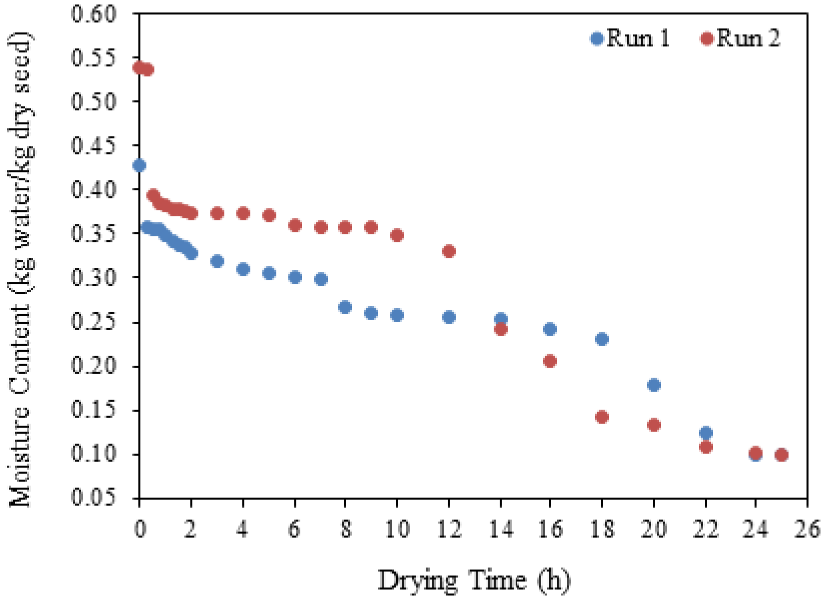


Figure 5. Drying curve for *C. moschata* seeds dried in a tray dryer at 45 °C. Drying was conducted under 11% RH and at an air velocity of 1 m/s.

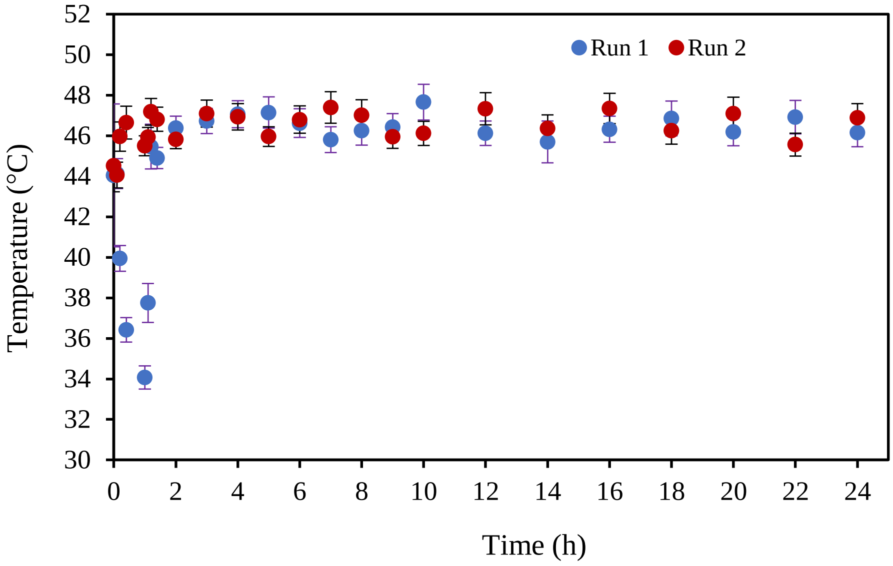


Figure 6. Temperature Profile in the tray dryer during drying tests on *C. moschata* seeds at 45 °C

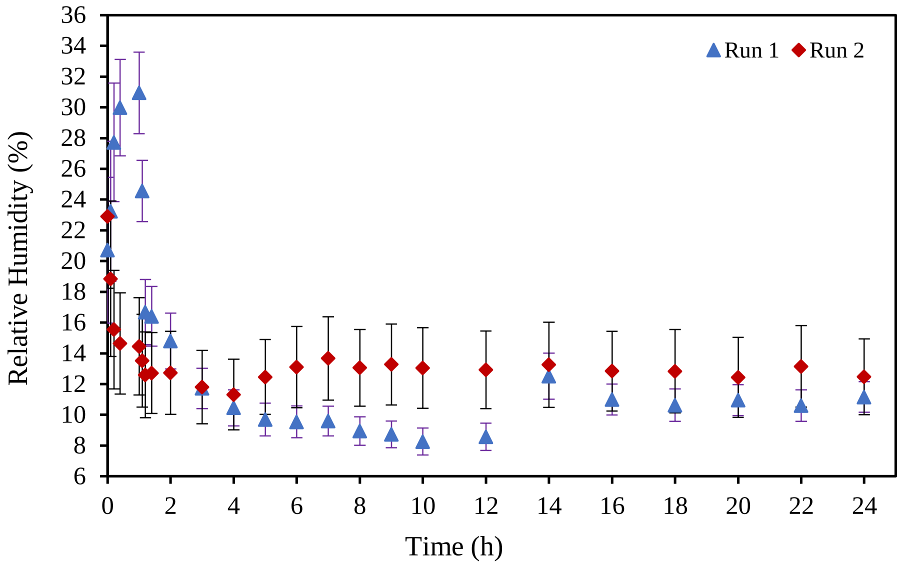


Figure 7. Relative humidity profile in the tray dryer during drying tests on *C. moschata* seeds at 45 °C

High temperature and low humidity conditions may be favourable for rapidly drying wet seeds for safe storage. However, the risk for mechanical defects, such as case hardening and fissures increases with rapid drying conditions. Defects on seeds caused by case hardening can lead to loss of quality. Additionally, seeds dried at high (75%), or intermediate (33%) RH conditions are at a higher risk of developing mould. Moisture content in seeds that are dried at high and intermediate RH achieved an EMC greater than 20% (w.b). Seeds at this moisture content have a high rate of respiration, which in addition to microbial activity can deteriorate seed quality (McCormack, 2010). These points were considered and applied to design an experimental dryer to test 10-11% RH on wet fermented Fijian *Theobroma cacao* under Fijian conditions.

Table 5. Moisture content of *C. moschata* seeds after drying under various RH conditions

Dry bulb Temperature °C	Relative humidity (%)	Initial moisture content % (w.b)	Final moisture content % (w.b)
30	11	60	12
	75	67	33
55	11	60	7
	75	58	11

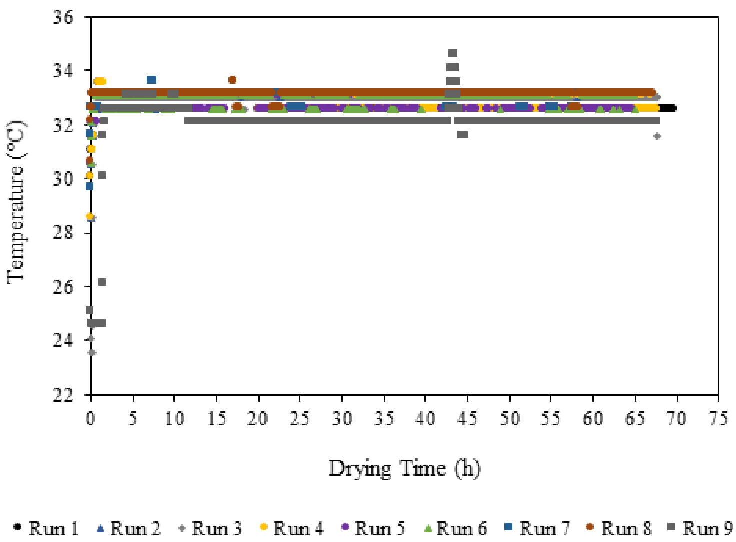


Figure 8. Temperature profile of air stream during drying tests on washed *C. moschata* seeds at 30 °C in humidity controlled chambers.

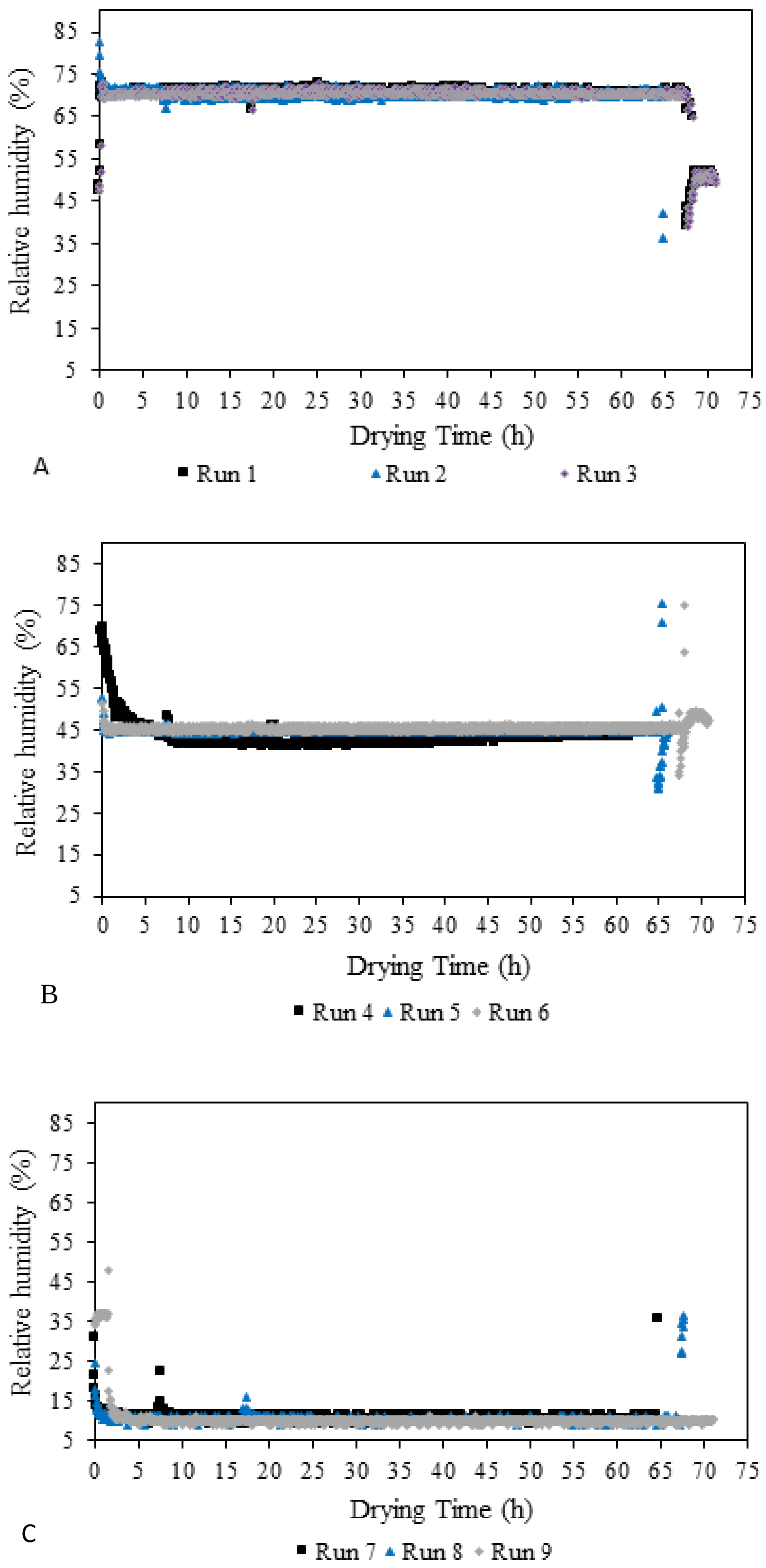


Figure 9. Relative humidity of air stream during drying tests on washed *C. moschata* seeds at 30 °C A. 75% RH, B. 33% RH and C. 11%RH.

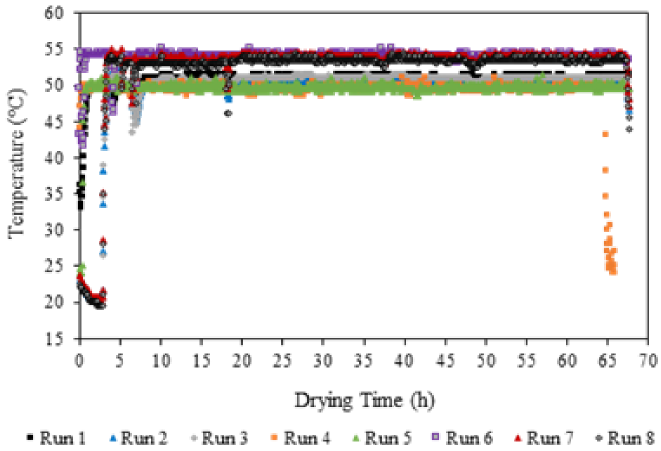
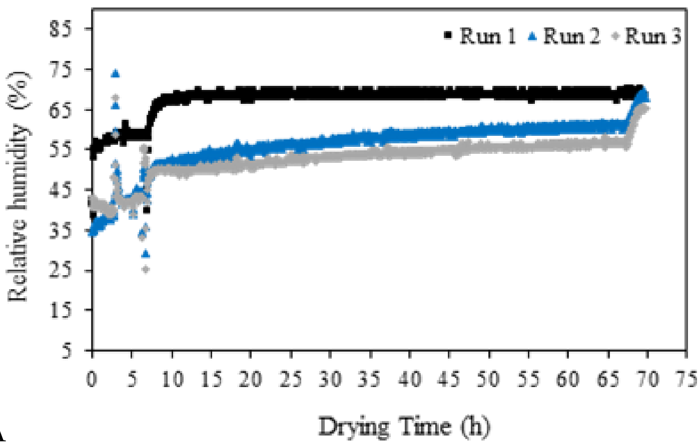
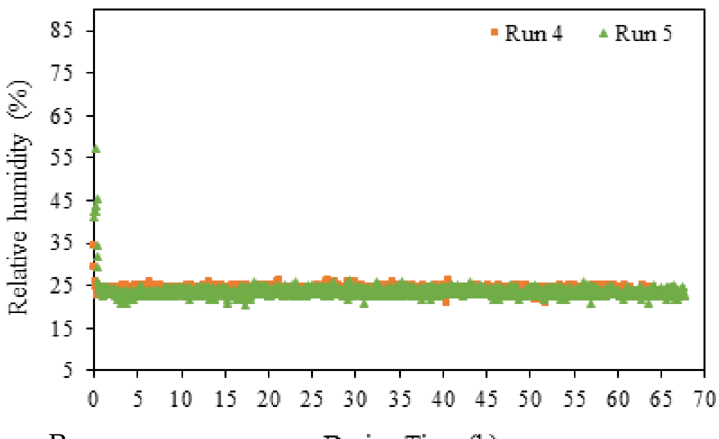


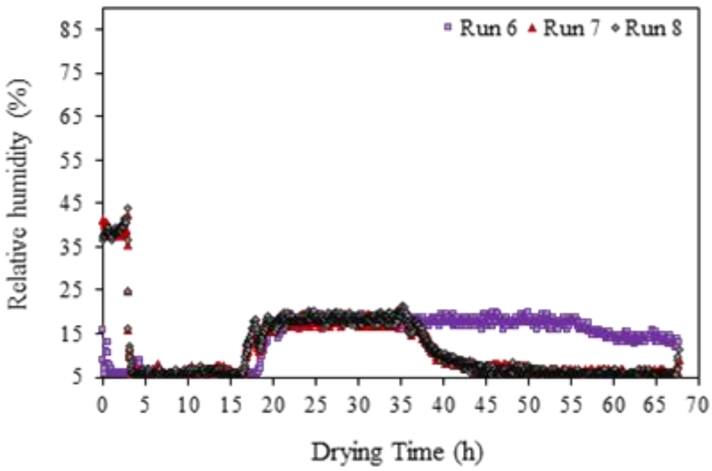
Figure 10. Temperature profile of air stream for treatment conditions set at 55°C during drying washed *C. moschata* seeds in humidity-controlled chambers.



A



B



C

Figure 11. Relative humidity of air stream during drying washed *C. moschata* seeds at 55°C under A. 75% RH B. 33% RH C. 11% RH. An increase an RH to 15% was noted between 18 to 36 h. This may have been caused by a decline in temperature and moisture accumulation in the system overnight.

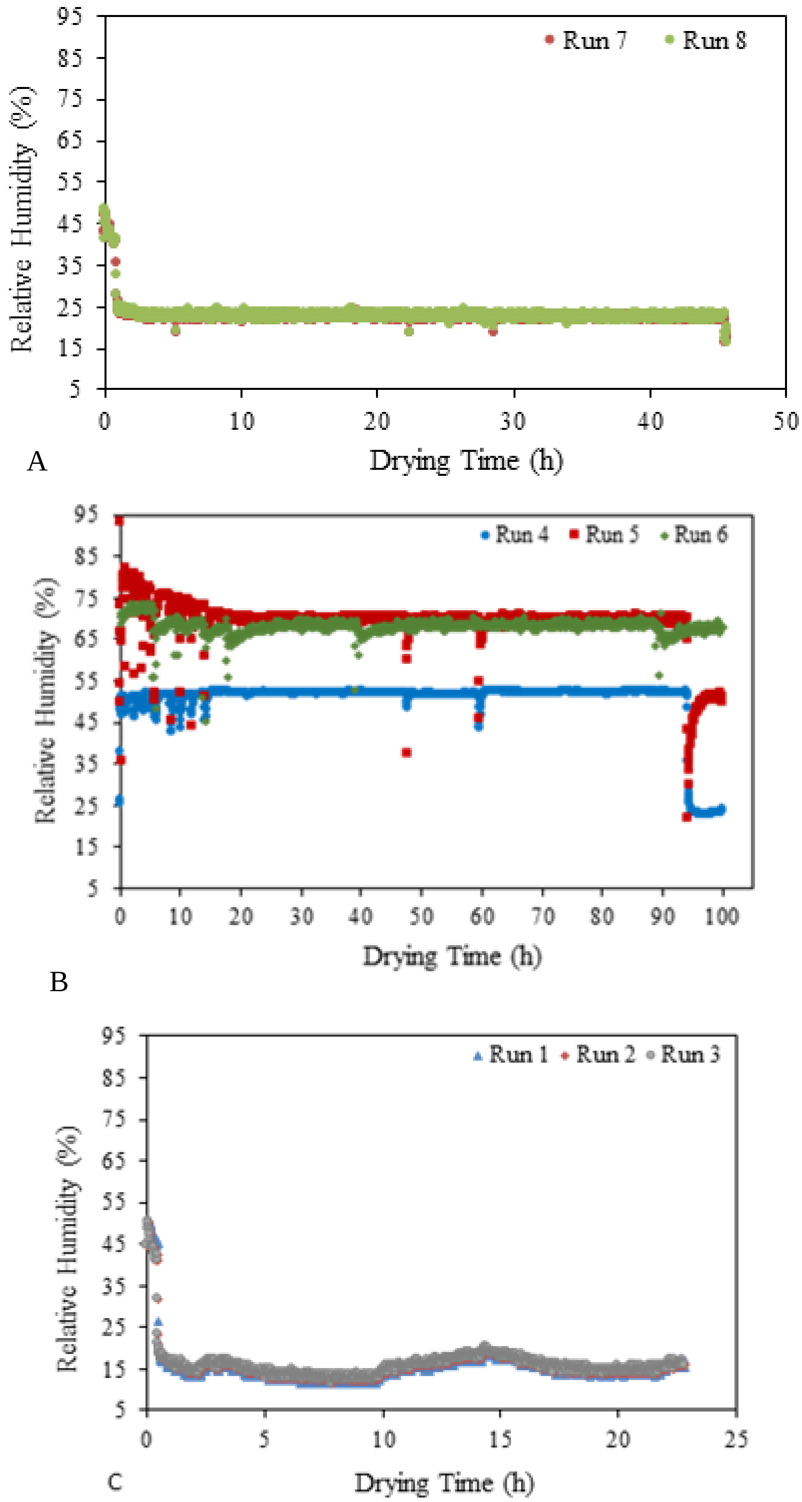


Figure 12. Relative humidity profile of air during drying *C. moschata* seeds at 45°C A. 75% RH for 96 h, B. 33% RH for 48 h and C. 11% RH for 24 h. Drying was terminated once a constant weight was reached.

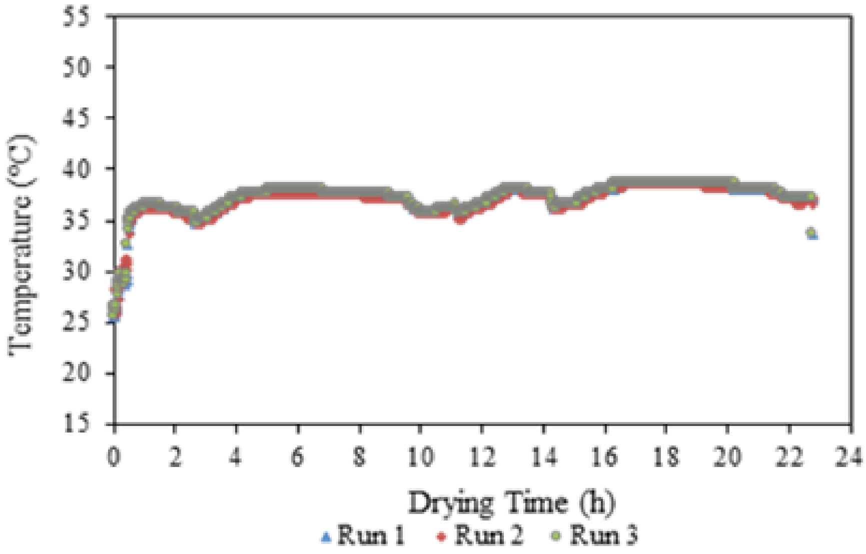


Figure 13. Temperature profile of air stream in humidity-controlled chambers with *C. moschata* seeds at 45 °C under 11% RH for 24 h.

Table 6. Statistical analyses for moisture content in *Cucurbita moschata* seeds during drying

Treatment conditions	Sampl e size	P-value	F value	F critica l	df	SS
30 °C	3	0	66	3	6363	16695
75%	3	0	260	3	6363	295433
33%	3	0	80	3	4772	26258
11%	3	0	25	3	6363	2570
55 °C	3	0	25	3	4772	11674
75%	3	0	294	3	4772	184653
33%	3	0	37	4	920	46796
11%	3	0	43	3	4772	5395

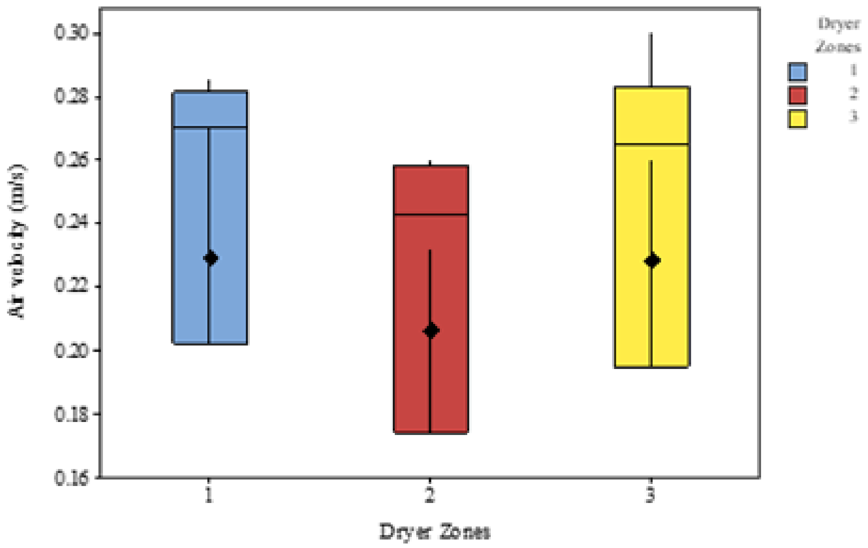


Figure 14. Composite air velocity measured through the drying chamber at 1. inlet, 2. centre and 3. outlet. The air flow was through the desiccant tube with four kg of silica gel.

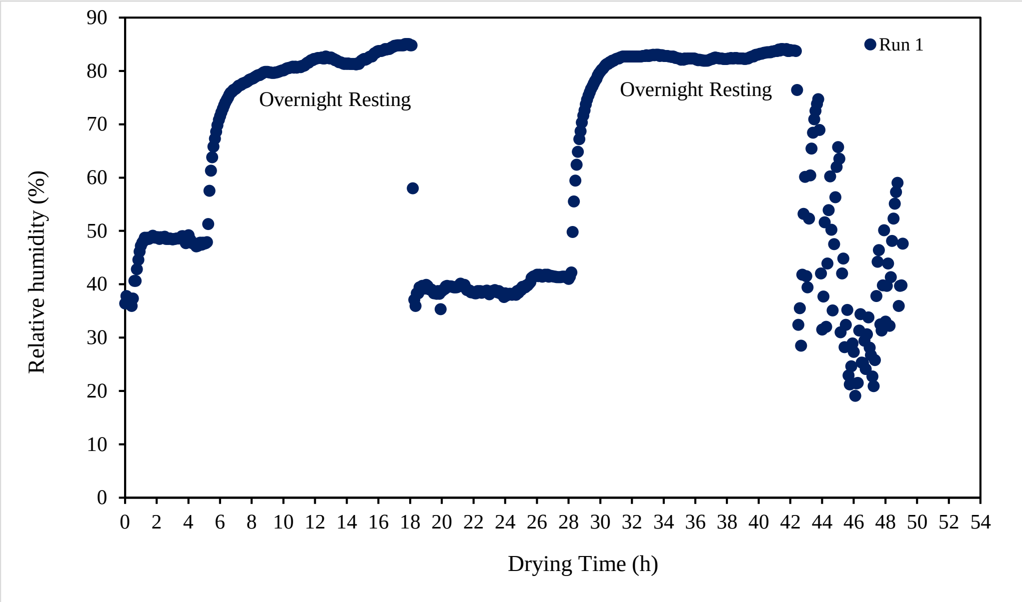


Figure 151. Relative humidity profile of drying chamber inlet during drying fermented *Theobroma cacao* beans at 55 °C (run 1) using silica gel as a dehumidifying agent. The first cycle was 12-hours of pre-drying at 44 °C under a constant RH of 30%, followed by 12 hours of drying at 55 °C under 10-15% RH.

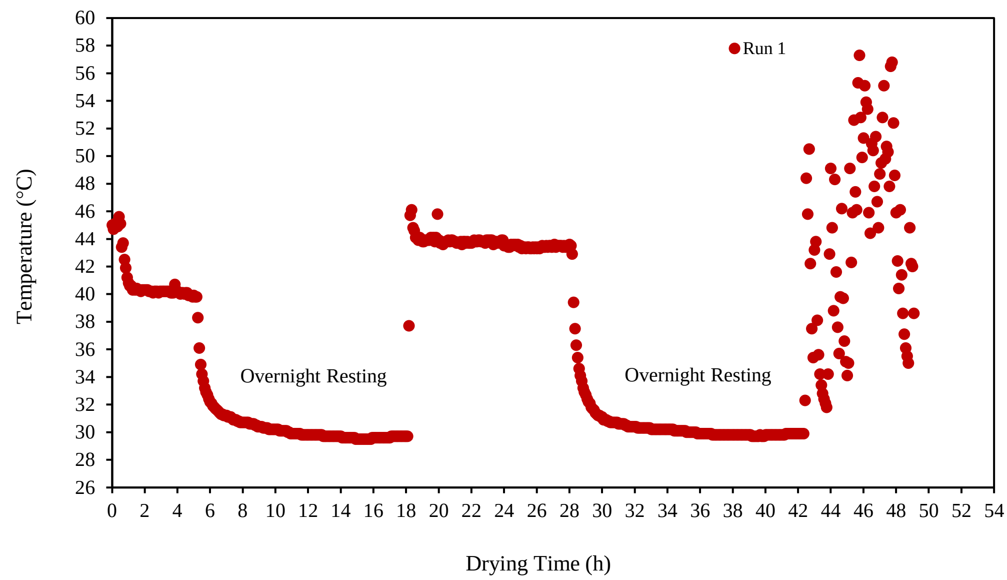


Figure 16. Temperature profile of air stream in the dryer during drying run 1 for fermented *Theobroma cacao* beans at 55 °C. The initial stages of drying were the preconditioning phase where the wet beans were pre-dried at 44 °C under 36-40% RH. Run 1 shows two overnight resting stages where drying was paused, and the conditions were equilibrated to ambient overnight temperature. Drying temperature for pre-dried cocoa beans were set at 55 °C. Variations in the moisture content may have been caused by product moisture.

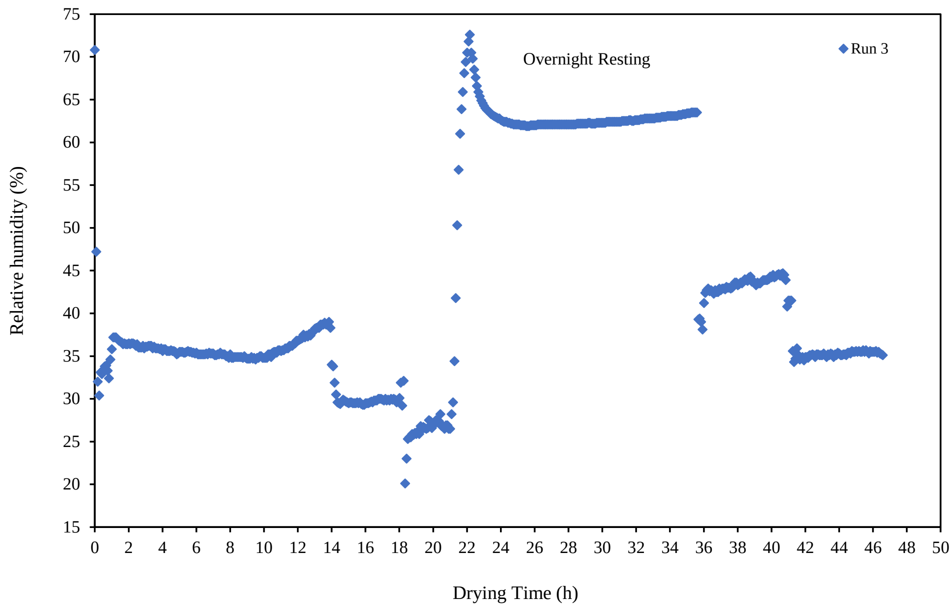


Figure 17. Relative humidity profile of dryer during drying fermented *Theobroma cacao* beans at 45 °C using silica gel as a sorbent. Batch 1 and 2 were treated to three drying cycles while batch 3 had two drying cycles. The first cycle was 12-hours of pre-drying at 44 °C under a constant RH of 30-42 %, followed by 12 hours of drying at 45 °C under 18-20 % RH.

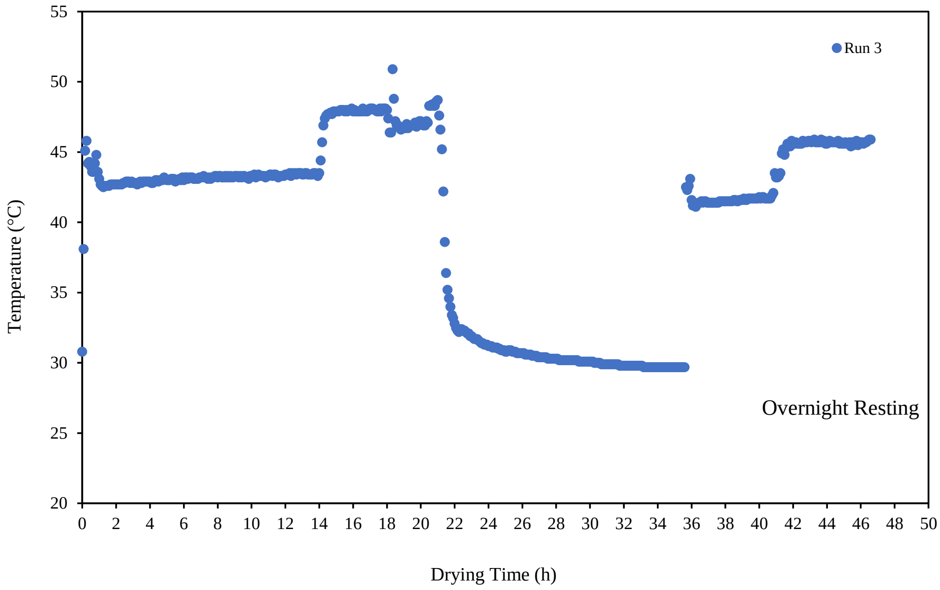


Figure 18. Temperature profile in the dryer during drying run 3 fermented *Theobroma cacao* beans at 45 °C. The initial stages of drying were the preconditioning phase where the wet beans were pre-dried at 44 °C under 36-40% RH. Run 1 shows two overnight resting stages where drying was paused, and the conditions were equilibrated to ambient overnight temperature. Drying temperature for pre-dried cocoa beans were set at 45 °C. Temperature profile during the second drying day was cooler than 45 °C. Variations in the moisture content may have been caused by product moisture.

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Drying behaviour of fermented Fijian *Theobroma cacao* using dehumidified air

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Abstract. Fermentation and drying are two important postharvest processing stages for *Theobroma cacao* beans. In the Fiji Islands, tropical weather conditions favour fermentation but the high relative humidity impedes drying. Slow or intermittent drying leads to product loss from mould growth and spoilage, which is costly for the cocoa industry. Conversely, direct solar drying can lead to unacceptably high temperatures (over 60 °C) and quality loss. Relative humidity can be controlled by applying low cost desiccant technology such as silica gel to dehumidify process air. The effect of dehumidified air on drying fermented *T. cacao* beans was evaluated at different drying temperatures of 56 °C and 46 °C. A rapid drying rate was achieved for fermented *T. cacao* beans dried at 56 °C under 10% relative humidity. Drying was slower at 46 °C under 18% relative humidity. Cocoa beans equilibrated to a moisture content <7% in 12 h and 34 h drying time respectively. Quality analyses are now under way to establish which of these drying profiles is preferable as a target for desiccant-assisted indirect solar drying.

INTRODUCTION

Theobroma cacao, are a highly valued commodity for the production of chocolate. The crop is widely cultivated in West Africa, South East Asia and South America. A tropical climate within 10-20° from the equator provides ideal conditions to cultivate *T. cacao*. Tropical conditions and volcanic soil in the Pacific Islands, such as Fiji provide a suitable environment for cocoa cultivation as well. In Fiji, the British introduced trinitario variety of cocoa during the colonial period from Sri Lanka. Farmers and local chocolate companies harvest the cocoa beans biannually and process raw beans into chocolates. Fermentation and drying are two important postharvest processing steps for Fijian *Theobroma cacao* beans.

Fermentation is spontaneous and lasts for 6 to 10 days [1]. Raw cacao beans with pulp are packed in wooden boxes (0.4m x 0.4m x 0.3m) with a perforated base. A microbial succession of yeast species, lactic acid bacteria and acetic acid bacteria metabolize pulp sugars and produce organic acids. A temperature rise in the fermentation mass (50 °C) and migration of organic acids, such as ethanol, lactic acid and acetic acid into the bean, devitalizes the embryo. This causes tissue breakdown, which releases endogenous enzymes that hydrolyse starch, protein, polyphenols and fats to develop flavour and aroma precursors. Degradation of bean tissue allows easier drying ideally to a moisture content of 7-10 % [2]. However, controlling drying conditions and consistent organoleptic quality during sun drying is challenging.

In the Fiji islands, fermented cocoa beans are sun dried in deep beds between 28 to 32 °C. However, the high relative humidity (>80%) and adverse weather conditions limits drying potential. Additionally, environmental contamination increases losses in sun-dried product. Contamination can be minimized using artificial dryers. However, these dryers operate at high temperatures (>60 °C), which deteriorates flavour quality [3]. Slow drying is recommended for 48 hours below 60 °C to encourage oxidation and volatilisation of excess organic acids [2]. Enhancement of organoleptic quality of dried Malaysian cocoa beans at lower relative humidity (RH) and mild temperature conditions highlights the importance of moderating drying parameters for improving quality [4].

Desiccant wheel technology can control RH during drying (Fig. 1). The honeycomb structure inside desiccant wheel contains silica gel that dehumidify process air. Silica can be regenerated using solar energy. Studies have demonstrated that dehumidifying process air has improved drying [4, 5, 6]. Desiccant Technology is also energy efficient and cost effective for continuous drying [7, 8]. Various studies recommend integrating desiccant system for drying thermally sensitive products [9, 10, 11]. This study tested the concept of drying with dehumidified air under mild temperature conditions on the drying behaviour of fermented *T. cacao* bean in Fiji. Silica gel was used to dehumidify air for drying fermented *T. cacao* beans at 46 °C and 56 °C with overnight resting (simulating operating conditions in a fully solar system).

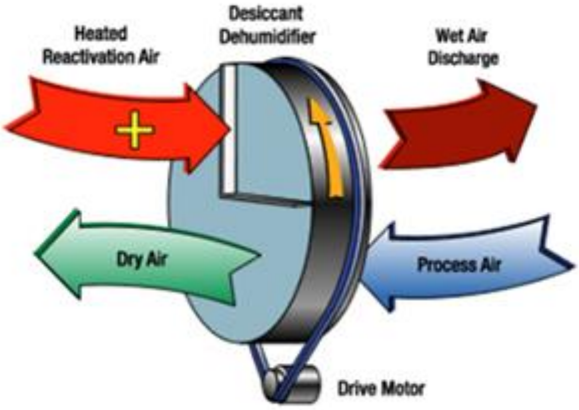

FIGURE 2. Illustration of a desiccant wheel demonstrating the airflow through various sections [12].

MATERIALS AND METHODS

Ripe *Theobroma cacao* pods (15 kg) of trinitario variety were sourced from Naduruloulou Agriculture Station, in Naitasiri, Fiji. Extracted *T. cacao* beans were fermented in perforated wooden boxes for 6 days with daily rotation. At the end of 6 days, the fermentation quality was assessed by a cut test on 100 beans [13, 14]. The cut test involves dissecting fermented beans longitudinally and assessing the colour of cotyledons before drying. The colour of fully fermented cocoa beans must change from purple to pale or brown. According to Malaysian Standard MS 293, a cut test score higher than 60% denotes a desirable flavour quality [14]. Fermented cocoa beans with a cut test score of 96 % per batch were dried under experimental conditions.

Drying was conducted in an experimental dryer with silica gel to control RH. Fermented beans (5 kg) were dried at 46 °C or 56 °C and between 10 to 15% RH (Table 1). Weight measurements were recorded at various time intervals using a hanging scale attached to the drying shelf. Temperature and humidity meter SE314 was used to measure air conditions during drying and overnight resting.

TABLE 1. Fermentation and Drying conditions for *Theobroma cacao* beans.

Process	Temperature (°C)	Relative humidity (%)	Time (h)
Fermentation	45 -50	85	144
Drying	46	18	34
	56	10	34

RESULTS AND DISCUSSION

Drying is essential for storage and flavour development in cocoa beans. Moderating drying conditions with desiccants has shown to be effective in improving drying [3, 15, 16]. Experimental results from this study demonstrate that dehumidifying process air improves drying time of *T. cacao* beans. Drying was conducted in two cycles of 12 hours per day with a 12 hour overnight resting period. RH was controlled by replenishing the silica gel every two hours of drying. In cocoa beans dried at 56 °C at 10% RH, there was a rapid moisture equilibration to 5% within one drying cycle (Fig. 2). Cocoa beans dried at 46 °C under 18% RH, equilibrated to a moisture content of 7% within two drying cycles (34 h) (Fig. 3).

There was a difference in the humidity profile of drying air between the two processing conditions. Humidity was slightly lower at 56 °C (0.010 kg/kg d.a.) when compared to humidity ratio at 46 °C (0.011 kg/kg d.a.). Temperature difference under the drying conditions may also have influenced heat and mass diffusion in the fermented *T. cacao* beans.

There was no noticeable weight change evident in the product after an overnight resting period (12 h) at room temperature between drying cycles. Overnight resting at room temperature encourages moisture redistribution and limits product breakage [17, 18]. High humidity during overnight resting can encourage mould growth, especially in areas with limited air velocity. Direct solar dryers with passive convection had condensation on cocoa beans after overnight resting delayed drying and encouraged mould growth [19]. This delayed drying and encouraged mold growth. Therefore, an airflow of 0.25 m/s was maintained overnight at 26 °C under 85% RH to avoid this problem.

The findings from this study are comparable to results reported in literature [15, 4]. The results strongly suggests that limiting RH at 56 °C may have a positive influence on drying potential and minimizing mould growth after overnight resting. Drying *T. cacao* beans to a lower moisture content was faster at 56 °C (12 h) when compared to drying at 46 °C (34 h). This suggests that under controlled RH, both temperature conditions are suitable for drying fermented *T. cacao* beans within two 12 h drying cycles. Further work is underway to assess chemical composition of dried beans, which would provide an insight on development of organoleptic quality. Drying conditions affect acidity and biochemical reactions that influence flavour, aroma and colour [20].

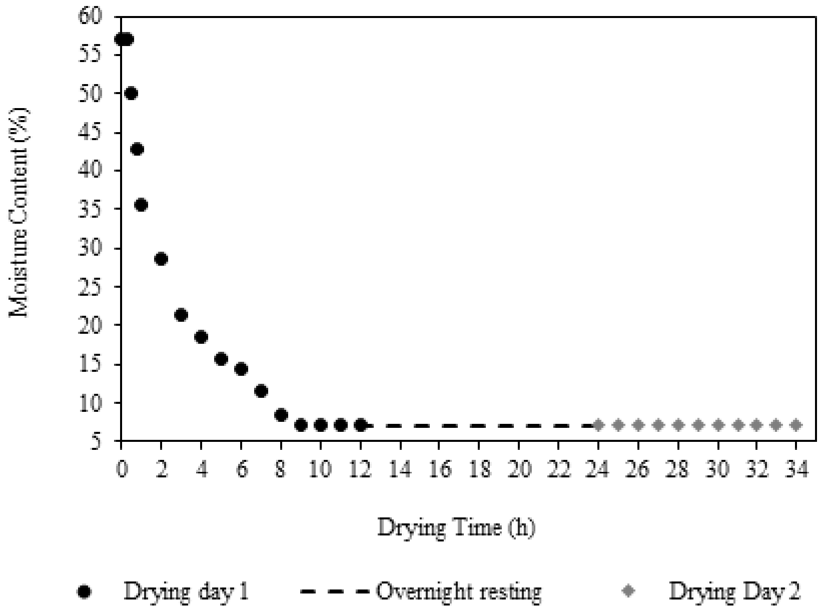

FIGURE 3. Drying curve for fermented *Theobroma cacao* beans at 56 °C under 10% relative humidity for two drying cycles (34 h). Each drying cycle was about 12 hours per day with an overnight resting period of 12 hours.

FIGURE 4. *Theobroma cacao* beans dried at 56 °C under 10% RH for 24 hours.

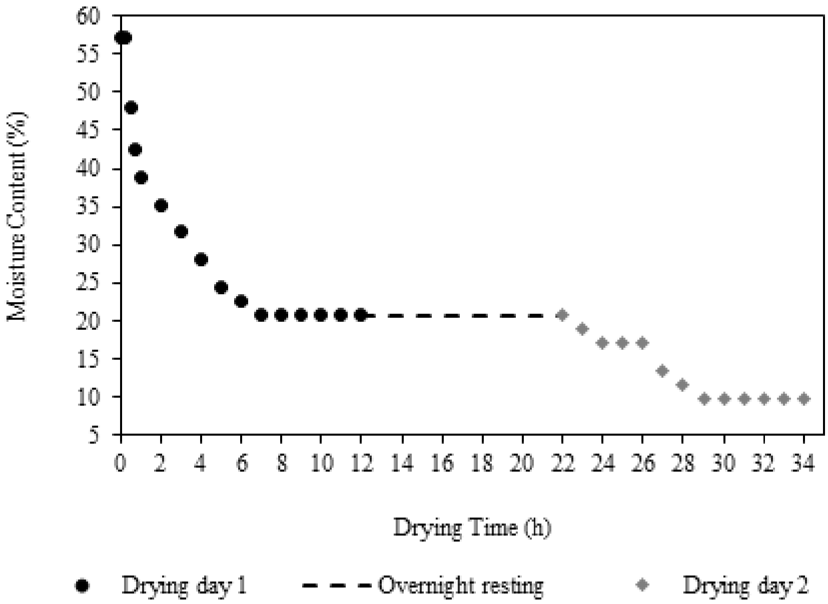

FIGURE 5. Drying curve for fermented *Theobroma cacao* at 46 °C under 18% relative humidity for two drying cycles. Each drying cycle was about 12 hours per day with an overnight resting period.

FIGURE 6. *Theobroma cacao* beans dried at 46 °C under 18% relative humidity for 24 hours.

CONCLUSIONS

There is some evidence that controlling RH improves drying. Cocoa beans dried under dehumidified conditions at 46 °C and 56 °C were found to have an acceptable moisture content (<10%). While rapid drying was evident at 56 °C (10% RH), implications on product quality are not yet known. Further analyses are underway to validate the effects of controlling RH on composition and quality of *T. cacao* beans. Integration of desiccants in dryers appears to be an effective technique to control RH.

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Chapter 5 Impact of drying conditions on polyphenol and methylxanthine content in Fijian Theobroma cacao beans

Quality control during the fermentation process involves mixing of the cocoa bean mass for aeration and to prevent clumping. During drying, clumping can cause irregular moisture loss. Figure 19 shows clumped cocoa beans removed from the dried bean mass.

Figure 19. Clumped dried *Theobroma cacao* beans at 45 °C. Clumping is a problem when cocoa beans are not mixed well during fermentation.

Another quality control measure to monitor and assess fermentation is a cut test. Cocoa beans are cut longitudinally, and the bean colour change is evaluated. Figure 20 shows the various colours in the cocoa beans after seven days of drying. A colour change from purple to brown or pale colour is desirable.

Figure 20. Cut test performed on fermented *Theobroma cacao* beans (*var*. Forastero) in Fiji

1. Analysis of bioactive components in cocoa beans

Theobromine and caffeine standards were used to analyse these compounds in fermented and dried cocoa beans. The absorbance spectra is given in Figure 21 and a four point calibration curve is presented in Figure 22.

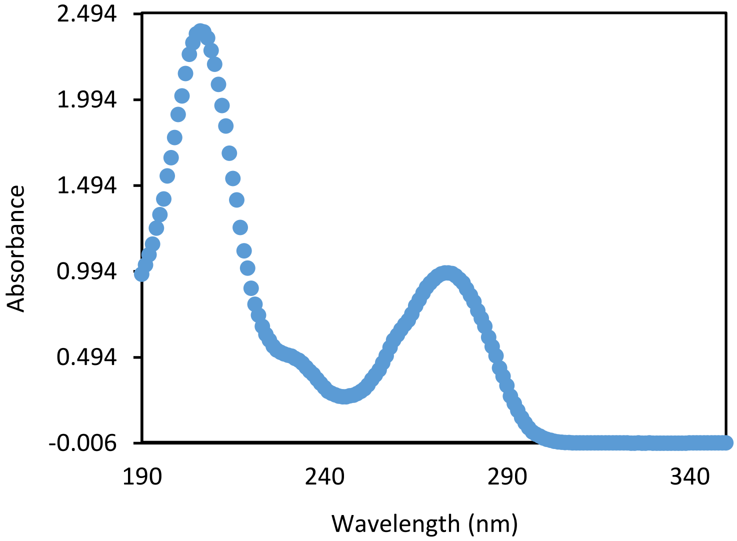

Figure 21. Absorbance spectra for Caffeine and Theobromine standards

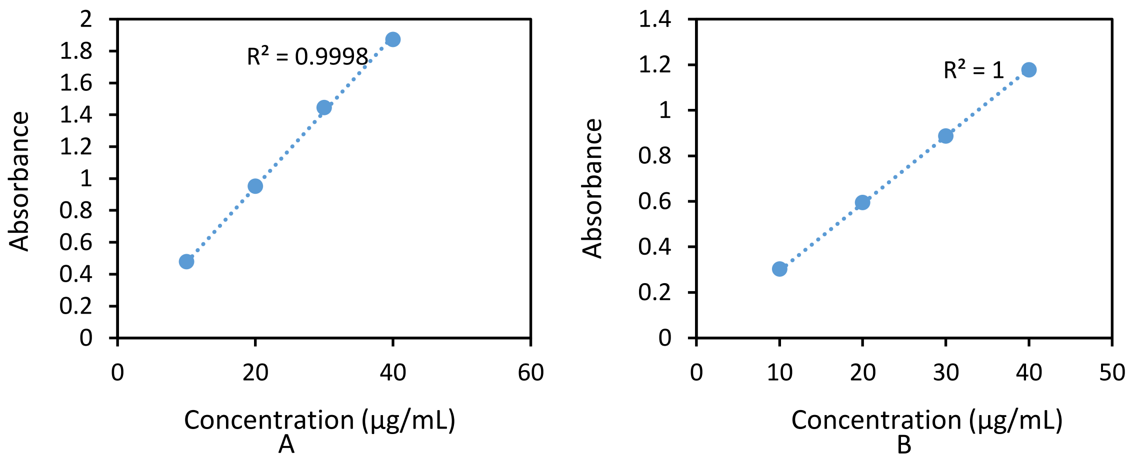

Figure 22. Calibration curve for caffeine (A) and theobromine (B) standards at 275 nm

Some of the thermodynamic properties of the solar collectors were calculated in this chapter. Convective heat transfer coefficient outside glass cover was calculated from thermal properties of air and gap between inner and outer glass covers (S2). The gap between glass covers 1 and 2 was set at 20 mm and between glass cover 2 and absorber plate was 10 mm. Air channel depth for air flow was set at 10 mm. Hydraulic diameter of air channel (Dh) was determined by:

Hydraulic diameter of air channel (Dh) was determined by:

$$Dh = a \times (1.0542 - 0.4660) \times \frac{a}{b} - 0.118 \times \left(\frac{a}{b}\right)^2 + 0.1794 \times (\frac{a}{b})^3 - 0.0436 \times (\frac{a}{b})^4) \quad (1)$$

Air flow outside of the glass cover can be described using Reynolds number. Reynolds number was calculated from characteristic collector size, ambient wind velocity and air viscosity using the following equation:

$$Re = \frac{u_{wind} \times Le}{v_a} \quad (2)$$

When airflow outside the glass cover 2, inside the dryer has a low Reynolds number <2100 then Nusselts number for air flow outside glass cover can be calculated by the following equation adapted from Earle (2004):

$$Nu = 0.86 \times Re^{0.5} \times Pr^{0.33} \quad (3)$$

Heat exchange coefficient is calculated from Nusselts number, thermal conductivity of air and depth of air channel (S_2) on collector plate.

$$h_c = Nu \times \lambda_a / (2 \times S_2) \quad (4)$$

Solar radiation absorbed by the collector is determined from the beam and diffuse radiation on the collector. Some the solar radiation will be lost to the environment as heat and some component is absorbed by the collector. The heat energy absorbed from solar radiation, and convective transfer from air by the double glazed FPC is calculated using the following equations given below.

Radiative heat transfer coefficient between glass and sky is:

$$h_r = 4 \times \sigma \times Tav^3 / (\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_p} - 1) \quad (5)$$

Convective heat transfer outside glass cover 1 is calculated by:

$$h_{w,gco} = Nu \times \lambda_a / Le \tag{6}$$

Radiative heat transfer coefficient outside of glass cover 1 was calculated using

$$h_{r,\ c-a} = \varepsilon_{gc} \times \sigma \times \left(T_{gc1}^2 + T_s^2\right) \times \left(T_s + T_{gc1}\right) \tag{7}$$

Convective heat transfer coefficient between glass covers (1 and 2) was calculated by:

$$h_{c1,p-c} = \frac{Nu\,\lambda_a}{S_2} \tag{8}$$

Convective heat transfer inside glass cover 2 was estimated by:

$$h_{w,gco} = Nu \times \lambda_a / S_1 \tag{9}$$

Radiation heat transfer coefficient between glass covers (1 and 2) is based on common local linearization of radiative flux:

$$h_{rpc} = \sigma \left[\frac{(T_{gc2}^2 + T_{gc1}^2) \times (T_{gc2} + T_{gc1})}{\frac{1}{\varepsilon_{gc}} + \frac{1}{\varepsilon_{gc}} - 1}\right] \tag{10}$$

σ is Stephan Boltzmann constant 5.67 x 10^{-8} W m^{-2} K^{-4}

ε_g is emissivity of glass

ε_p emissivity of plate

T_{cm} mean plate temperature

Radiative heat transfer inside the second glass cover (2) is:

$$h_{rpc2} = \sigma \left[\frac{(T_{cm}^2 + T_{gc2}^2) \times (T_{cm} + T_{gc2})}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_{gc}} - 1}\right] \tag{11}$$

Tp, Ts, Tg are temperature expressed in Kelvin. Heat transfer coefficient in airflow regimes with laminar flow is affected due to development of thermal and hydrodynamic boundary layer (Duffie and Beckman, 1974). Radiation heat loss to atmosphere through glass, convective heat transfer to air, conductive heat transfer to collector back and edge is deductedfrom amount of radiation received by absorber plate. Top loss coefficient is calculated from convective and radiative heat transfer inside glass cover using the following equation:

$$\frac{1}{Ut} = \frac{1}{(h_{r,pc-2} + h_{c,pc-2})} + \frac{1}{(h_{r,c-a} + h_{w,gco})} + \frac{1}{(h_{c1,p-c} + h_{r1,p-c})} \tag{12}$$

Back insulation loss coefficient is calculated from thermal conductivity of insulation material (λ_b) and back insulation thickness (t_b) by the following equation:

$$U_b = \frac{\lambda_b}{t_b} \tag{13}$$

Edge loss coefficient is derived from:

$$U_{bs} = \frac{\lambda_b}{t_e} \tag{14}$$

Total heat loss (U_L) coefficient is calculated by adding top, bottom and edge losses. The overall heat loss coefficient (U_L) is an important characteristic of solar air heater. Under the assumption that rate of heat storage in material of collector is small compared to other terms, the two heat gains should be equal which provides an operational definition of actual overall heat loss coefficient by:

$$U_L = U_t + U_b + U_{bs} \tag{15}$$

Heat absorbed by solar radiation is transferred to the dry air stream in the collector. Heat transfer to the air stream increases air temperature. Ambient air conditions were considered when calculating inlet and outlet air temperature and mean plate temperature. Mean plate temperature was determined by using average air temperature, useful heat gain, dryer dimensions, heat removal factor and overall heat transfer coefficient.

$$T_{pm} = T_a + Q_u/(W \times L) \times (1 - FR)/(FR \times U_L) \tag{16}$$

Temperature of dry air stream out of FPC (exit) after heating is calculated using useful heat gain in the equation given below:

$$T_{out} = \frac{Q_u}{(C_{pa} \times 1000)} + T_a \tag{17}$$

Based on the solar radiation and temperature conditions, useful heat gain (Q_u) through FPC is calculated from the difference between heat adsorbed and heat lost to the environment using Hottel-Whillier-Bliss equation:

$$Q_u = W \times L \times FR \times (It \times tae - U_L \times (T_m - T_a)) \tag{18}$$

The heat that is gained by the solar collector can be related to the maximum heat gain using the heat removal factor (FR), which determines collector efficiency. Collector efficiency can be estimated using collector efficiency factor (F') and collector flow factor (F"). The Collector efficiency factor (F') was calculated using the equation below:

$$F' = [1/(1 + U_L/h_c)] + [1/(1/h_c + 1/h_r)] \quad (19)$$

Collector flow factor (F") is calculated using dimensional collector capacitance rate (mC_p/A_cUL):

$$F" = ((mC_p/A_cULF \times (1 - \exp(-1/\mathrm{m}C_p/A_cULF) \quad (20)$$

Dimensional collector capacitance rate (mCp/AcUL) can be calculated by:

$$\frac{mC_p}{A_cUL} = Q_a \times C_{pa}/(W \times L \times U_L \times F') \times 1000 \quad (21)$$

Pessure drop across the collector is calculated using fanning factor (f):

$$f = 16/Re \quad (22)$$

$$P_a = 4 \times f \times \frac{L}{Dh} \times 1.2 \times va^2/2 \quad (23)$$

$$\frac{L}{Dh} = L/(2 \times S3) \quad (24)$$

Design features considered to calculate the size of the parabola were diameter of the tube, radius, aperture angle, and concentration ratio. The focal length was calculated using rim angle set at 80°.

$$s = \frac{\pi\varphi r}{180} \quad (25)$$

$$f = \frac{W_a}{4}/Tan(\frac{S}{2}) \quad (26)$$

Radius of the parabola is determined from the width of aperture set at 2.5 m:

$$r = \frac{W_a}{2/Sin(s)} \quad (27)$$

Theoretical diameter of receiver tube is determined by the radius in the equation below:

$$DR0 = 2 \times r \times \sin(\theta m) \quad (28)$$

The width of aperture (W_a) is used to calculate the height of parabola and arc length (60):

$$hp = \frac{Wa^2}{16} / f \tag{29}$$

Arc length

$$S = \frac{Wa}{2} \times \sqrt{1 + \frac{\frac{Wa^2}{16}}{f^2+2}} \times f \times LN(\frac{\frac{Wa}{4}}{f}) + \sqrt{(1 + \frac{\frac{Wa^2}{16}}{f^2})} \tag{30}$$

The surface area for heat transfer can be estimated using length and arc length (S).

$$Sa = L \times S \tag{31}$$

The theoretical diameter (58) and the ratio of real diameter to theoretical diameter (K) can be used to determine the real diameter (d_{ro}) outside receiver when calculating the diameter of the glass cover and distance between glass cover and receiver tube. These design aspects are critical for improving convective heat transfer for desiccant regeneration. These series of calculations finally determine the concentration ratio (CR) of the PTC demonstrates the thermal performance of the design.

Real diameter (d_{ro}) is calculated using:

$$d_{ro} = DR0 \ \times K \tag{32}$$

Diameter of glass cover

$$D_{gc} = dro + 40 \tag{33}$$

Distance between glass and tube

$$\delta gr = \frac{D_{gc}}{2} - \delta gc - dro/2 \tag{34}$$

Cross-sectional area

$$A = \ \pi \times D^2/4 \tag{35}$$

Area of receiver is calculated considering the real outside diameter of receiver (δro).

$$Ar = (\pi \times \delta ro/1000) \times L \tag{36}$$

Some parts of the collector would be exposed to solar radiation while other parts may experience shaded conditions. The area of unshading aperture (Aa) is the area exposed to sunlight.

$$Aa = (Wa - \frac{Dgc}{1000}) \times L \tag{37}$$

The concentration ratio (CR) is a significant part of the design parameter for PTC as it demonstrates the thermal efficiency.

$$CR = Aa\ /Ar \tag{38}$$

PTC design operates mainly heating air passing through the receiver tube. The cross-sectional area of the tube (Ari) determines the air velocity under operational conditions.

Inner cross-sectional area of the tube

$$Ari = \ \pi \times (\frac{\delta r}{1000} \times \frac{1}{2})^2 \tag{39}$$

Average air velocity in the tube

$$vra = Qa/Ari \tag{40}$$

Convective heat transfer equation inside receiver tube and glass cover around it is calculated using Reynolds number and Nusselts number.

$$hfi = Nu\ \times \lambda a/(\frac{dri}{1000}) \tag{41}$$

$$h_{gco} = Nu\ \times \lambda a/(\frac{D_{gc}}{1000}) \tag{42}$$

Nusselts number was calculated from Reynolds number (Re). Air flow in PTC is expected to be turbulent and is calculated using average air velocity and thickness ratio (δri).

$$Re = vra\ \times \delta ri\ /1000/va \tag{43}$$

Turbulent air flow (Re>10,000) estimated in PTC can be used to calculate the NU using various equations:

For internal flow: $$Nu = 0.023 \times Re^{0.8} \times Pr^{0.4} \tag{44}$$

For air flow inside glass cover $$Nu = 0.3 \times Re^{0.6} \tag{45}$$

Heat loss to the environment is calculated as thermal losses between glass cover to ambient air and from inside glass cover to air stream.

Thermal loss outside glass cover to ambient air is calculated using:

$$Ql_{gco} = \ \pi\ \times \frac{D_{gc}}{1000} \times L\ \times h_{gco} \times \left(T_{gco} - T_{amb}\right) + \varepsilon t\ \times \pi \times \frac{D_{gc}}{1000} \times L \times \sigma \times (T_{gco}^4 - T_{sky}^4) \tag{46}$$

Energy loss inside glass cover

$$Ql_{gci} = 2 \times \pi \times \lambda eff_{agci} \times L \times \frac{T_{ro} - T_{gci}}{LN\left(\frac{D_{gc} - \delta_{gc} \times 2}{dro}\right)} + \pi \times dro/1000 \times L \times \sigma \times \frac{Tro^4 - T_{gci}^4}{1} / (\frac{1}{\varepsilon t} + (1 - \lambda_{gc})/t_{gc} \times (dro/(D_{gc} - \delta_{gc} \times 2)$$

(47)

Heat energy that is absorbed by the collector improves the temperature of drying air. This heat energy absorbed can be determined from the increase in temperature of glass cover.

$$T_{gci} = T_{gco} + Ql_{gco} \times LN\left(\frac{D_{gc}}{D_{gc} - \delta_{gc} \times 2}\right)/(2 \times \pi \times \lambda gc \times L) \tag{48}$$

Thermal diffusivity of glass cover

$$\alpha a_{gci} = va_{gci}/Pr_{gci} \tag{49}$$

Effective thermal conductivity inside glass cover

$$\lambda eff_{agci} = 0.386 \times (Pr_{gci} \times \frac{Ra}{0.861 + Pr_{gci}^{0.25}} \times \lambda a_{gci}) \tag{50}$$

Thermal losses to the environment are calculated using heat loss coefficient (U_L), which is based on receiver area.

$$U_L = Ql_{gci}/(\pi \times \frac{dro}{1000} \times L \times (Tro - T_{amb})) \tag{51}$$

Heat energy absorbed and transferred to the drying air stream is estimated using useful heat gain (Qu).

$$Qu = Aa \times FR \times (It - \frac{Ar}{Aa} \times UL \times (T_m - T_{amb})) \tag{52}$$

An increase in the air temperature inside the receiver is calculated from useful heat gain and thermal properties of drying air stream.

$$\Delta Ta = Qu/(Qa \times C_{pa} \times 1000) \tag{53}$$

Finally, temperature of air out of PTC to the regeneration section of DW is calculated using the following equation:

$$Tout = Ta + \Delta Ta \tag{54}$$

Average temperature difference between receiver and air

$$\Delta Tra = Qu \times \left(\frac{1}{\pi} \times \left(\frac{\mathrm{dri}}{1000}\right) \times \mathrm{L} \times \mathrm{hfi}\right) + \mathrm{LN}\left(\frac{\mathrm{Dro}}{\mathrm{dri}}\right)/(2 \times \pi \times \lambda\mathrm{t} \times \mathrm{L})) \tag{55}$$

Temperature of receiver outside surface

$$T'ro = \frac{Tout+Ta}{2} + \Delta Tra \tag{56}$$

Pressure drops in PTC is a significant parameter that determines efficient operation of the design. Pressure-drop through collector

$$dp = 4 \times f \times L/(\frac{dri}{1000}) \times \rho_a \times v_{ra}^2/2 \tag{57}$$

The pressure-drop causes friction in the receiver, which causes heat losses. The heat lost from air flow in a pipe caused by friction is estimated using a fanning factor. The calculation from fanning factor is from D'Arcy Weisbach equation.

$$f = ((\frac{-1}{4 \times LOG\left(0.27 \times \frac{\lambda gc}{dri} + (\frac{7}{Re}^{0.9}\right)}))^2 \tag{58}$$

Air velocity

$$v = Qa/Ari \qquad 59)$$

Free convection of air flow inside the glass cover around the receiver tube is calculated using Rayleigh's number (Ra).

$$Ra_{gci} = 9.81 \times (T_{ro} - T_{gci}) \times (\frac{\delta_{gr}}{1000})^3/(Tm_{gcr} \times va_{gci} \times \alpha a_{gci}) \tag{60}$$

Rayleigh's number for free convection is determined from Ra_{gci} inside glass cover.

$$Ra = (LN \times ((D_{gc} - \delta_{gc} \times Dro)^4/(\delta_{gr} \times \frac{1}{1000)^3} \times \left(\frac{Dro}{1000}\right))^{-0.6} + ((\frac{D_{gc} - \delta_{gc} \times 2}{1000})^{0.6})^5 \times Ql_{gco} \tag{61}$$

Microbial Analysis during Fermentation

Yeast, moulds, and anaerobes dominate initial stages of fermentation, followed by aerobes, which break down organic acids and ethanol. Microbial analysis demonstrated a decline in yeast and mould and anaerobes as fermentation progresses. This appears to be in good agreement with trends reported in literature.

Table 7. Microbial analysis of *Theobroma cacao* during fermentation

Microbial analysis	Unit	Fermentation stage (days)	
		0	4
Yeast	cfu/g	2.8×10^3	<10
Moulds	cfu/g	6.0×10^3	4.3×10^5
Aerobic plate count	cfu/g	1.8×10^7	1.5×10^9
Anaerobic plate count	cfu/g	1.6×10^7	1.0×10^9

Table 8. Moisture content and sphericity of *Theobroma cacao* beans dried at different treatment conditions

Drying Runs	Drying conditions	Drying Time (h)	Moisture Content (%)	Sphericity	Flat beans (%)
	Sundried*	144	19 ± 1	0.55 ± 0.05	11
	Sundried*	144	15 ± 1	0.57 ± 0.06	18
3	45 °C	54	12 ± 3	0.59 ± 0.05	2
4		36	14 ± 3	0.61 ± 0.10	3
5		36	13 ± 3	0.60 ± 0.08	3
1	55 °C	54	11 ± 1	0.58 ± 0.04	3
2		54	12 ± 1	0.61 ± 0.08	1
6		36	13 ± 3	0.58 ± 0.04	1

*Sundried conditions are at 30°C between 75-80%

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STATEMENT OF CONTRIBUTION
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