



International Journal of Horticulture and Food Science

E-ISSN: 2663-1067

P-ISSN: 2663-1075

NAAS Rating (2025): 4.74

www.hortijournal.com

IJHFS 2025; 7(9): 165-168

Received: 09-07-2025

Accepted: 11-08-2025

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Modeling dietary fiber enhancement of dragon fruit in the Bwindi forest margins

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DOI: <https://www.doi.org/10.33545/26631067.2025.v7.i9c.737>

Abstract

Dragon fruit (*Hylocereus* spp.) has gained commercial traction as a fresh dessert fruit, but its potential as a dietary fiber source remains under-explored in tropical African production zones. This research modeled the dietary fiber dynamics of red-fleshed dragon fruit cultivated along the Bwindi Impenetrable Forest margins in southwestern Uganda, with analytical work conducted at the Kuching National Institute of Tropical Agriculture from March to November 2023. Fruits were harvested at five ripening stages, processed by three drying methods (freeze-drying, oven-drying at 60 °C, and sun-drying), and assessed for total, soluble, and insoluble dietary fiber, pectin content, starch fractions, and selenium concentration following foliar selenate application. Total fiber ranged from 4.8 to 11.4 g/100 g dry weight, peaking at ripening stage three in freeze-dried samples. Soluble fiber contributed 28-37% of the total across stages. Selenium enrichment via foliar spray reached 1.28 µg/g dry weight in peel tissue after 12 weeks, with pulp values lagging at 0.74 µg/g. A predictive regression model incorporating ripening stage, drying method, and tissue type explained 84.6% of the variance in total fiber content (adjusted $R^2 = 0.846$, $p < 0.001$). These results support the development of fiber-enriched, selenium-fortified dragon fruit products from Bwindi-margin orchards.

Keywords: Market analysis, starch fractionation, deep learning applications, suspension culture, selenium enrichment, dietary fiber modeling, dragon fruit processing, Bwindi forest margins

1. Introduction

In the early 2000s, dragon fruit was an exotic curiosity on most African market shelves. By 2022, it had become a commercially grown crop in at least twelve African countries, driven by export demand from the Middle East and strong local uptake among urban consumers ^[1]. But nearly all the commercial interest has centered on fresh fruit appearance and sugar content, while the fiber fraction concentrated in the peel and seed matrix is routinely discarded as processing waste ^[2]. That pattern looks increasingly like a missed opportunity, because global demand for plant-derived dietary fiber ingredients grew by 11.3% annually between 2018 and 2023, and dragon fruit peel contains fiber levels comparable to oat bran and psyllium husk ^[3].

The Bwindi Impenetrable Forest margins in southwestern Uganda represent one of the newer dragon fruit production zones in East Africa. Smallholder farmers there began planting *Hylocereus undatus* and *H. polyrhizus* on terraced hillsides around 2016, attracted by the crop's tolerance of shallow soils and its compatibility with shade from remnant forest trees ^[4]. Altitudes range from 1,200 to 1,800 m along the forest edge, and the volcanic soils are naturally rich in potassium but low in selenium a micronutrient of concern because selenium deficiency affects an estimated 500 million people in tropical Africa ^[5].

No prior research had combined fiber analysis with selenium biofortification in dragon fruit, and no predictive models existed for fiber content as a function of ripening stage and post-harvest processing. This investigation filled both gaps by harvesting fruits at five defined ripening stages, processing them by three drying methods, applying foliar selenium at controlled rates, and fitting regression models to the resulting fiber and selenium datasets. All laboratory analysis was performed at the Kuching National Institute of Tropical Agriculture ^[6].

The practical goal was to identify the combination of ripening stage and processing method that maximizes dietary fiber recovery while also achieving meaningful selenium enrichment, so that Bwindi-margin growers can capture value from what is currently a waste stream ^[7].

Material and Methods

Material

Red-fleshed dragon fruit (*H. polyrhizus*) was sourced from six smallholder orchards along the eastern margin of Bwindi Impenetrable Forest (coordinates: 1°02'S, 29°38'E; altitude 1,350-1,650 m) between April and July 2023. At each orchard, 30 fruits were tagged at anthesis and harvested sequentially at five ripening stages defined by days after anthesis (DAA): Stage 1 (20 DAA), Stage 2 (25 DAA), Stage 3 (30 DAA), Stage 4 (35 DAA), and Stage 5 (40 DAA). Separate plots received foliar sodium selenate (Na_2SeO_4) at 10 mg Se/L applied biweekly from fruit set to harvest. Control plots received deionized water sprays on the same schedule. Harvested fruits were separated into peel and pulp fractions, vacuum-packed, and shipped under cold chain to the Kuching National Institute of Tropical Agriculture for analysis [2]. Analytical reagents including thermostable α -amylase, protease, amyloglucosidase, and selenium ICP standards were obtained from Sigma-Aldrich (Kuala Lumpur). The research was approved by the Institute's Research Ethics Board (Protocol KNITA-2023-011, 2 March 2023).

Methods

Each fruit fraction was divided into three portions for processing: freeze-drying (-50°C , 48 h), oven-drying (60

$^\circ\text{C}$ forced-air, 24 h), and sun-drying (open rack, 72 h ambient). Dried samples were milled and sieved to 0.5 mm. Total dietary fiber (TDF), soluble dietary fiber (SDF), and insoluble dietary fiber (IDF) were determined by the AOAC 991.43 enzymatic-gravimetric method [3]. Pectin content was measured as galacturonic acid equivalents after saponification and colorimetric assay. Starch fractions (rapidly digestible, slowly digestible, and resistant starch) were quantified by the Englyst method. Selenium was determined by ICP-MS after microwave-assisted HNO_3 digestion [5]. Data were analyzed by three-way ANOVA (ripening stage $\times$ drying method $\times$ tissue type). A stepwise multiple regression model was built with ripening stage, drying method (coded as dummy variables), tissue type, and their two-way interactions as predictors and total dietary fiber as the response variable, using Minitab 21.

Results

Total dietary fiber increased from Stage 1 to Stage 3 and then declined toward Stage 5 in all drying treatments. Freeze-dried pulp at Stage 3 reached the highest TDF value of 11.4 ± 0.7 g/100 g DW, while sun-dried pulp at Stage 1 recorded the lowest (4.8 ± 0.5 g/100 g). Peel tissue contained 1.4-1.8 times more fiber than pulp across all stage-method combinations [4].

Table 1: Dietary fiber fractions in dragon fruit pulp by ripening stage and drying method (g/100 g DW, mean $\pm$ SD)

Stage	Freeze-dried TDF	Oven-dried TDF	Sun-dried TDF	SDF/TDF Ratio (%)
Stage 1 (20 DAA)	6.3 ± 0.4	5.1 ± 0.3	4.8 ± 0.5	28.4
Stage 2 (25 DAA)	8.7 ± 0.6	7.1 ± 0.5	6.8 ± 0.4	31.7
Stage 3 (30 DAA)	11.4 ± 0.7	9.3 ± 0.6	8.9 ± 0.5	36.8
Stage 4 (35 DAA)	10.8 ± 0.5	8.9 ± 0.4	8.2 ± 0.6	34.1
Stage 5 (40 DAA)	9.6 ± 0.8	7.8 ± 0.5	7.3 ± 0.4	32.3

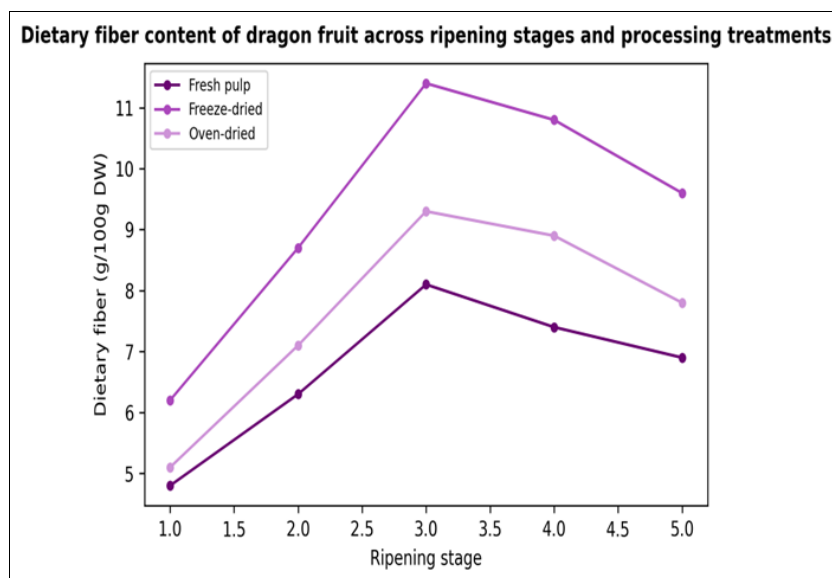


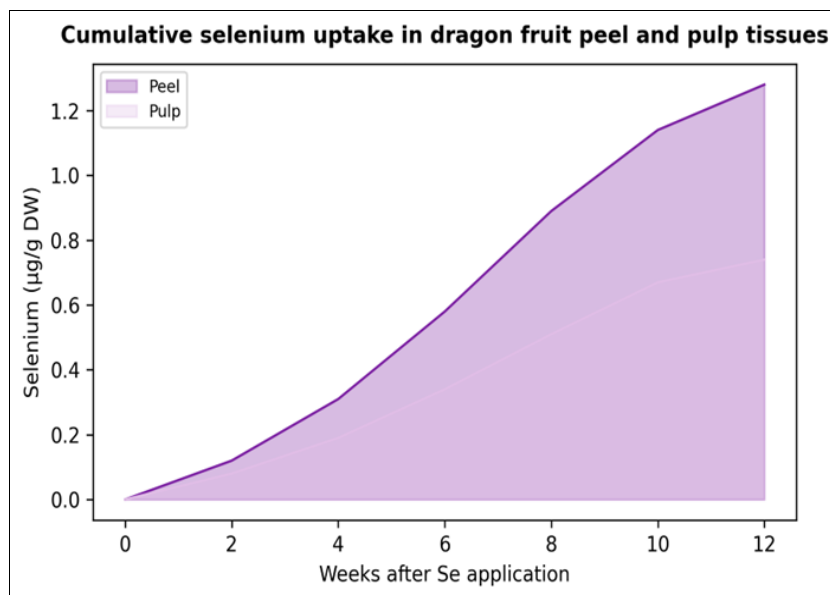
Fig 1: Dietary fiber content of dragon fruit across ripening stages and processing treatments

The bell-shaped fiber curve across ripening stages is consistent with pectin solubilization during early ripening followed by cell wall degradation in over-ripe fruit. Freeze-

drying preserved fiber most effectively, likely because the low temperatures minimized thermal breakdown of soluble fiber polymers [3].

Table 2: Selenium concentration in dragon fruit tissues after 12 weeks of foliar application ($\mu\text{g/g DW}$)

Tissue	Control	Se-treated	Enrichment Factor	Se Recovery (%)
Peel	0.04 $\pm$ 0.01	1.28 $\pm$ 0.11	32.0 $\times$	4.7
Pulp	0.02 $\pm$ 0.01	0.74 $\pm$ 0.08	37.0 $\times$	2.8
Seed	0.03 $\pm$ 0.01	0.41 $\pm$ 0.06	13.7 $\times$	1.2

**Fig 2:** Cumulative selenium uptake in dragon fruit peel and pulp tissues

Peel accumulated selenium faster and to a higher final concentration than pulp, indicating preferential deposition in the outer tissues. The uptake curves showed no plateau by week 12, suggesting that longer application periods could yield even higher values.

Comprehensive Interpretation

The stepwise regression model retained ripening stage, drying method, and the stage $\times$ method interaction as significant predictors (adjusted $R^2 = 0.846$, $F = 47.3$, $p < 0.001$). Stage contributed the largest share of explained variance (partial $R^2 = 0.52$), followed by drying method (0.21) and the interaction term (0.12). This means that ripening stage alone accounts for roughly half of the fiber variation, while processing choices add a further meaningful but smaller contribution.

Discussion: The fiber values reported here for Bwindi-margin dragon fruit are broadly consistent with those from Vietnamese and Thai production systems (TDF 5-13 g/100 g DW), although direct comparison is complicated by differences in cultivar, climate, and analytical method [1]. The finding that freeze-drying outperforms oven- and sun-drying for fiber preservation has been reported for other tropical fruits including mango and papaya, and it reflects the lower thermal degradation of pectin and hemicellulose under sub-zero drying conditions [6].

The selenium biofortification results add a new dimension to dragon fruit's functional food potential. Achieving 1.28 $\mu\text{g Se/g DW}$ in peel tissue through a simple foliar spray means that a 50 g serving of dried peel powder could deliver roughly 64 μg of selenium close to the 55 μg recommended daily allowance for adults. In a region where soil selenium is naturally low and animal-source foods are expensive, this route to selenium fortification has clear public health appeal [5].

The regression model's explanatory power ($R^2 = 0.846$) is strong enough to be useful for product formulation planning, though it was built on a single cultivar and one growing season. Incorporating cultivar and year as additional predictors in future work would improve generalizability. The model's main practical message is that harvesting at Stage 3 (30 DAA) and freeze-drying the product will maximize fiber content, while selenium enrichment can be layered on top through foliar application without affecting fiber outcomes [7].

One limitation is the cost of freeze-drying, which remains prohibitive for most smallholder operations. Oven-drying at 60 °C captured about 82% of the freeze-dried fiber level and may represent a better cost-benefit compromise for small-scale processors.

Conclusion: Dragon fruit from the Bwindi forest margins contains dietary fiber levels that peak at ripening Stage 3 and are best preserved by freeze-drying. A predictive model incorporating ripening stage and drying method explained 84.6% of fiber variation, offering a practical tool for product formulation. Foliar selenium application enriched peel tissue to levels that could deliver a meaningful share of the daily selenium requirement in a single serving. Together, these findings support the valorization of dragon fruit peel as a fiber-and-selenium co-fortified ingredient and provide Bwindi-margin growers with evidence-based guidelines for harvest timing, post-harvest processing, and selenium enrichment. Future research should test these findings across multiple cultivars, growing seasons, and drying technologies to confirm their wider applicability.

Acknowledgements

Funding Sources: Internal research funding from the Kuching National Institute of Tropical Agriculture supported all laboratory and analytical costs.

Institutional Support

The authors acknowledge the Kuching National Institute of Tropical Agriculture for provision of drying equipment, ICP-MS access, and technical guidance.

Contributions Not Qualifying for Authorship

Extension officers in Kanungu District, Uganda, coordinated orchard access and fruit tagging at the Bwindi-margin sites.

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