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Research Article

SMART IOT-ENABLED IR-ASSISTED REFRACTANCE WINDOW DRYING KINETICS OF GUAVA PULP AND QUALITY ANALYSIS

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Abstract

This study evaluates the effect of Smart IoT-Enabled IR-Assisted Refractance Window Drying (IR-RWD) on drying kinetics as well as physicochemical and thermal characteristics of peeled and unpeeled guava pulp samples, with respect to other three drying techniques which are tray drying (TD), vacuum drying (VD), and refractance window drying (RWD). The drying experiments conducted at 60°C across four different drying techniques and revealed significant variations in drying time. The average drying times recorded for the peeled sample were 420, 420, 390, and 300 minutes for TD, VD, RWD, and IR-RWD, respectively, whereas the unpeeled guava sample exhibited drying times of 510, 450, 420, and 300 minutes. Moreover, this study highlighted that the RWD and IR-RWD dried sample displayed notably higher levels of total phenolic content (TPC) and total flavonoid content (TFC) as compared with TD and VD sample. Specifically, the TPC was observed 205.1 mg GAE/100g, and the TFC was 645.4 mg QE/100g in IR-RWU samples. An SEM analysis reveals that the peeled samples display smoother and more uniform textures than their unpeeled equivalents. Among the different drying techniques, the IR-RWD method was the most efficient, retaining the highest levels of nutrients while requiring the shortest drying time. This suggests that the IR-RWD technique could be a superior method for drying guava pulp, preserving its nutritional and antioxidant properties more effectively than the traditional TD and VD methods.

1. Introduction

RWD system is an innovative technique used to enhance the quality of liquid alimentary substances and various biomaterials through their conversion into powdered, flaked, or sheet forms. The RW drying technique has garnered significant attention within the food sector due to its ability to produce high-quality dried products and its cost-effectiveness (Abul-Fadl & Ghanem, 2011). Indirect contact drying is achieved by transferring heat from hot water to wet materials through a mylar membrane in the RW drier. The window facilitates the penetration of infrared energy into a wet sample through the mylar membrane (Dadhaneeya et al., 2023a).

Internet of Things (IoT) represents an emergent paradigm that fosters communication among electronic devices and sensors via the internet, thereby enhancing the quality of human life (Kumar, Tiwari, & Zymbler, 2019). The IoT engenders a novel landscape of opportunities for food enterprises that integrate IoT technology within the food sector to recognize and rectify supply chain challenges, uphold superior manufacturing standards, ameliorate inefficiencies, comply with and exceed food safety regulations, and provide their clientele with enhanced access (Dadhaneeya et al., 2023c). IoT integration in RW dryers offers precision, efficiency, and data-driven decision-making, contributing to higher-quality dried products, reduced energy consumption, and improved operational reliability. The IoT-enabled IR-assisted RW dryer combines RWD technologies with infrared techniques, which are further integrated with the intelligence of the IoT, bringing us one step closer to the fourth generation of the industrial revolution (Dadhaneeya et al., 2024).

Guava, scientifically referred to as *Psidium guajava*, belongs to the extensive Myrtle family (Jain, Jain, & Nema, 2011). Owing to its high nutritional value, ease of cultivation, and desirability in processed goods, guava plays a substantial role in the domestic economies of over 50 tropical nations and in international trade (Nagy S. and Shaw E. P., 1985). It is extensively grown in tropical and subtropical areas of the world. India is the world's largest producer of guava. The world's largest producer of guava is India. Guava is renowned for its exceptional nutritional value and is rich in vitamins C and A, fiber, potassium, and antioxidants. Guava is an excellent source of pectin, a crucial dietary fiber (Naseer, Hussain, Naeem, Pervaiz, & Rahman, 2018). Compared with oranges, guavas contains four times the amount of vitamin C (Flores, Wu, Negrin, & Kennelly, 2015). The high concentration of ascorbic acid found in guava renders it a potent agent for counteracting oxidation and free radicals, which are recognized as significant contributors to degenerative diseases. The antioxidant properties of guavas are believed to reduce the likelihood of developing pancreatic, stomach, esophageal, laryngeal, and oral cancer. Guava drying prolongs the longevity of the fruit, enabling it to be stored for prolonged periods without deterioration. Dried guava undergoes flavor concentration, leading to heightened sweetness and an intensified taste.

In this study guava pulp was dried using tray drying (TD), vacuum drying (VD), refractance window drying (RWD), and Infrared assisted refractance window drying (IR-RWD) techniques. This study also compared the effects of various selected drying techniques for peeled and unpeeled guava samples on their quality attributes. It is imperative to employ a drying procedure that not only yields a higher quality of the final product but also demonstrates commercial viability.

2. Materials and Methods

2.1. Sample Preparation

This study used completely ripened guava purchased from the marketplace near to NIFTEM-K. Firstly, fresh guava was cleaned with tap water and removed the top and bottom portions of the guava sample by using knife. Samples were evenly segregated into two categories, that is with and without peels. In the case of the peeled guavas, the outer layer was removed by employing a peeler. Both the samples were grinded and then the resulting mixture underwent the deseeding process through a sieve featuring a pore diameter of 2mm.

2.2. Experimental setup

There are several researchers (i.e Kheto et al., 2021) who have suggested that 60 °C is a suitable temperature for drying food-related materials, so the same was selected as drying temperature in this study. While spreading sample thickness was taken near to 5 mm. Which was selected based on preliminary trials. A laboratory scale of tray dryer (TC 303, Bajaj Process Pack Machinery Private Limited) was employed to produce tray-dried samples. The laboratory scale vacuum oven (Shel Lab) was employed to prepare vacuum-dried samples. An IoT-enabled IR-assisted RW dryer was used for preparing RW-dried and IR-assisted RW-dried samples. The IoT-enabled IR-assisted RW dryer installed in NIFTEM-K.

2.3. Physical Properties

2.3.1. Color Analysis

A portable colorimeter was employed to quantify the chromatic attributes of the specimen in terms of L* (lightness), a* (redness), and b* (yellowness) on Petri plate (Kardile, Nema, Kaur, & Thakre, 2020).The total color difference (ΔE), Chroma (C^*), hue (h) and browning index (BI) were derived through the application of Eq. (1), (2), (3) and (4) respectively.

$$\Delta E = \sqrt{(L^* - L)^2 + (a^* - a)^2 + (b^2 - b)^2} \quad (1)$$

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (2)$$

$$\mathrm{h} = \tan^{-1}\frac{b^*}{a^*} \quad (3)$$

$$\mathrm{BI} = \frac{[100(\mathrm{x} - 0.31)]}{0.172} \quad (4)$$

$$x = \frac{\mathrm{a}^* + 1.75\mathrm{L}^*}{5.645\mathrm{L}^* + \mathrm{a}^* - 3.012\mathrm{b}^*} \quad (5)$$

Where L, a and b are the color coordinates values of fresh pulp spreading at 5 mm thickness.

2.3.2. Texture Analysis

The texture analysis was performed by following the procedure as outline in Dadhaneeya, et al. (2023b).

2.3.3. Moisture Analysis

The moisture content of the samples was quantified utilizing a moisture analyzer (HE73, Mettler Toledo, Switzerland).

2.3.4. Water Activity

A water activity meter (Model-Aquala3 4TE, Decagen) was employed to measure the water activity of the samples (Kardile, Nema, Kaur, & Thakre, 2019).

2.3.5. Bulk Density

The bulk density was determined by calculating the ratio of mass of the powder to the volume of the occupied cylinder (Baeghbali et al., 2016).

2.3.6. Rehydration Ratio

The rehydration ratio was measured following the methodology outlined byZhou et al. (2022).

2.4. Chemical Properties

2.4.1. Ascorbic Acid Analysis

The ascorbic acid test was performed according to AOAC (1968) standard procedure. The process entails homogenizing about 0.25 g of samples with 25 ml of an HPO_3 - CH_3COOH solution. The resultant mixture is filtered using filter paper. Subsequently, resulting solution (2 ml) was incorporated into HPO3 - CH_3COOH solution (5 ml). Titration of the resultant solution was performed using 2,6-dichlorophenol indophenol (DCPIP) indicator solution (Dadhaneeya et al., 2025).

2.4.2. Total Phenolic Content (TPC)

The procedure for extracting bioactive compounds was performed in accordance with Carvalho Gualberto et al. (2021). The Folin-Ciocalteu spectroscopic method, as outlined by Sharanagat et al. (2019), was employed to determine the TPC.

2.4.3. Total flavonoid content (TFC)

Flavonoid levels of the sample extracts were assessed utilizing the aluminum chloride colorimetric approach as outlined by Dhua et al. (2021).

2.4.4. Antioxidant activity

The evaluation of antioxidant activity of the control and dried samples was conducted employing the DPPH (1,1-diphenyl-2-picrylhydrazyl) assay, as reported byDesai et al. (2023).

2.4.5. FTIR Analysis

A Bruker Alpha spectrometer was utilized to conduct Fourier Transform Infrared (FTIR) spectroscopy, enabling the identification of functional groups within the samples.

2.5. Thermal Analysis

Analysis of the dried guava powder samples was performed utilizing a differential scanning calorimeter (DSC 1, $STAR^e$ System) and $STAR^e$ Evaluation software.

2.6. SEM-EDS

A small quantity of guava powder samples was mounted on aluminum plates and subsequently coated with gold to enhance image quality. Structural analysis was performed utilizing a Thermo Scientific Axia Scanning

Electron Microscope, operating at an accelerating voltage of 5 kV and a magnification of 350. The mounted samples underwent Energy Dispersive X-ray Spectroscopy (EDS) analysis to ascertain their elemental composition.

2.7. Statistical analysis

The experimental procedures were replicated three times, with the outcomes reported as average value ± the standard deviation. Statistical analysis was conducted employing OriginPro 2021, software produced by OriginLab Corporation. To determine significant differences ($p < 0.05$) among mean values, a one-way ANOVA was employed, followed by Tukey's test for multiple comparisons. Additionally, Principal Component Analysis (PCA) was applied to the mean values.

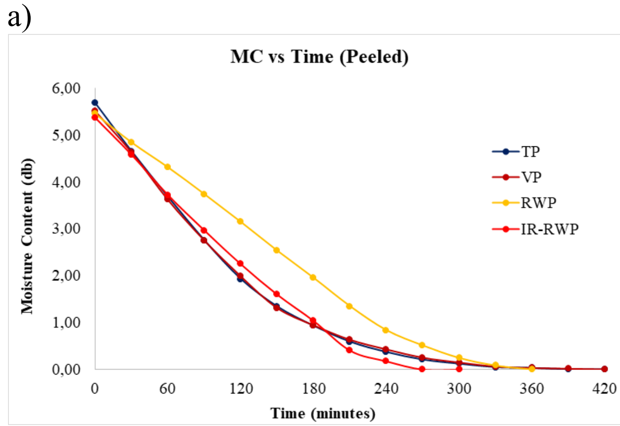
3. Results and discussions

3.1. Drying characteristics

The variation of moisture content over drying time is illustrated in Figure 1 (a & b). The moisture loss in the IR-RWD sample occurred rapidly due to the dual-sided heating mechanism intrinsic to this method. The upper surface of the sample was exposed to IR radiation, which facilitated direct heat transmission to the material via electromagnetic waves. The bottom surface of the sample was synchronously heated using RWD. The cumulative impact of these heating processes created a uniform temperature gradient throughout the sample, allowing rapid moisture evaporation from both sides. Figure 1 (a) illustrates the relationship between moisture content and drying time for peeled samples, subsequently Figure 1 (b) illustrates the unpeeled sample. The time taken for drying peeled samples was observed TP (420 min), VP (420 min), RWP (390 min) and IR-RWP (300 min). The drying times recorded for the unpeeled samples were TU (510 minutes), VU (450 minutes), RWU (420 minutes), and IR-RWU (300 minutes). Nevertheless, the TU sample had the longest drying duration, while presenting a steep gradient. Similar graph of moisture content over drying time was also observed by Dadhaneeya et al. (2023b).

Figure 1 (c & d) **(a)** depicts the correlation between the drying rate (DR) and time across various drying methods. Figure 1 (c & d) illustrates that the drying rate curve attains its peak value within 60 minutes for all samples. The drying rate curve at first exhibited an increase in drying rate until reaching a peak. This may be ascribed to the presence of free unbound water in the pore space of the samples, which might be rapidly eliminated. The drying rate escalated till it reached its peak point. Upon reaching the apex, all the unbound water had evaporated. Subsequent reaching the peak, the drying rate saw a decline owing to the need for more energy to vaporize the bound water present in the pore space Dadhaneeya et al. (2023b). For the peeled sample the highest peak values were observed for vacuum drying, while for the unpeeled sample highest peak values were observed for IR-RW drying. Similar graph of drying rate vs drying time was also reported by Mella et al. (2022).

a)



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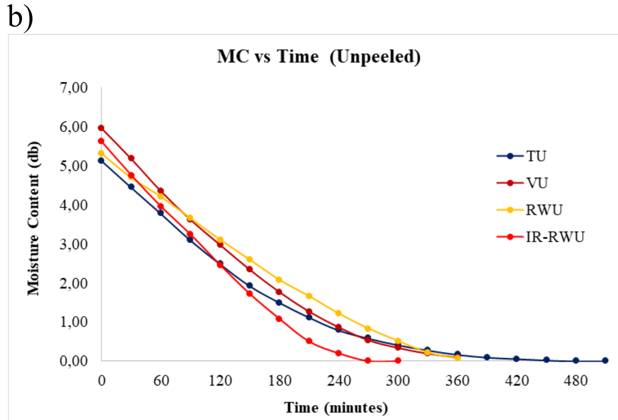


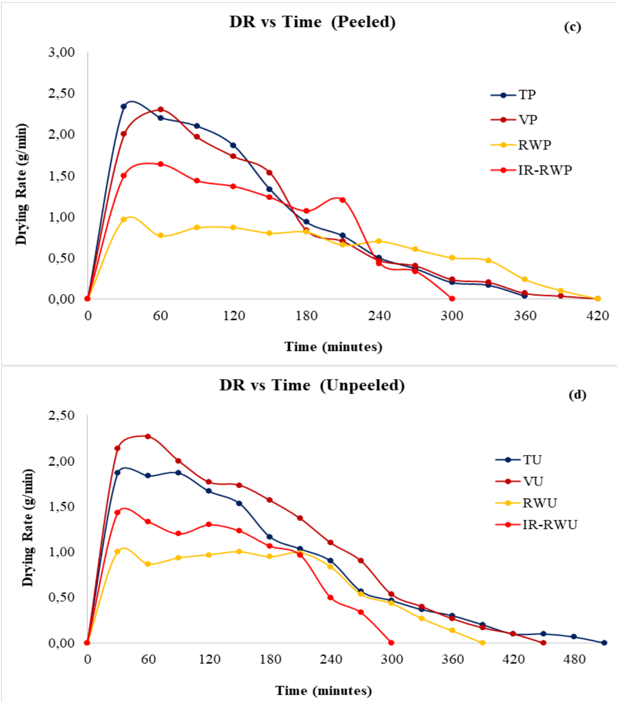


Figure 1. Drying kinetics of graphs of: **(a)**moisture content of peeled sample**(b)** moisture content of unpeeled sample **(c)** drying rate vs time of peeled sample**(d)** drying rate vs time unpeeled sample

3.2. Moisture Analysis and Water Activity

The moisture content of the dried guava powders is given in Table 1. The fresh peeled pulp had a moisture content of 85.1%. While fresh unpeeled pulp contained a moisture content of 86.13%. The dried powder samples exhibited moisture levels ranging from 3.67% (IR-RWU) to 7% (TP). The IR-RWU sample showed the lowest moisture content, whereas the TP sample had the highest. All powder samples were secured in zip-lock pouches and stored in a desiccator. However, some might have the chance to absorb atmospheric moisture.

Water activity was observed highest in the TP sample and lowest in the IR-RWU sample. While fresh guava pulp had a water activity of 0.98. RWP and RWU samples also had low water activity. A significant difference in water activity was noted between IR-RWP and TU samples, potentially due to more effective drying in the IR-RW dryer. As shown in Table 1, all water activity values fell within the range of 0.33-0.49, which is considered safe for storage (a_w< 0.6) (Dissa et al. 2008).

3.3. Color properties

Color differences, denoted by ΔE, of samples subjected to different drying techniques were analyzed to determine its effect on visual quality, which also serves as an essential indicator of product acceptance.Among the treatments, IR-RWU had the lowest ΔE value, indicating minimal color change and excellent preservation of the original appearance. There was no significant difference between RWP and IR-RWP color change values. Samples TU and VU exhibited intermediate color changes with values of 32.38 and 33.12, respectively. Analysis of the color change values of peeled and unpeeled samples indicates significant differences between both. Similar lower color differences in RW dried product was also reported by Baeghbali et al. (2016) and Nemzer et al. (2018). **Chroma values** of the dried samples have been evaluated to determine the intensity and vivacity of their color, which is essential in influencing customer attraction and product quality. The measured chroma values varied from 28.48 in the IR-RWU sample to 36.32 in the RWP sample. A higher chroma rating, shown by the RWP sample at 36.32, denotes a more vivid and intense color. **Hue** of the dried samples was observed within the range of 0.08 to 0.22, with RWP and RWU samples recording the lowest hue value of 0.08 and the IR-RWU sample exhibiting the highest value of 0.22. **Browning index** is a crucial metric that indicates the degree of non-enzymatic browning occurring throughout the drying process. The IR-RWP sample had the greatest browning index at 69.65, indicating considerable browning resulting from strong heat exposure during the IR-assisted RWD process. Numerous researchers have used anti-browning agents to minimize the browning effects that arise during the drying process, as noted byDadhaneeya et al. (2023b) in their study. In the current study, there was no anti-browning agent used to mitigate browning effects. This decision was motivated by the rising consumer appetite for natural food items free from chemical additives. The focus on preserving the quality of products without the use of chemical additives aligns with the overarching movement towards clean-label goods, which emphasize natural food.

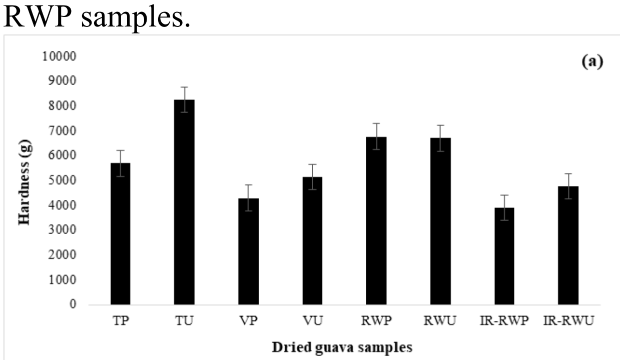
Table. 1 Physical properties of dried guava with different drying techniques
(TP: Tray dried peel guava sample; **TU:** Tray dried unpeeled guava sample; **VP:** Vacuum dried peel guava sample; **VU:** Vacuum driedunpeeled guava sample; **RWP**:

Physical Properties	**TP**	**TU**	**VP**	**VU**	**RWP**	**RWU**	**IR-RWP**	**IR-RWU**
Water Activity	0.48 ± 0.005^{a}	0.45 ± 0.005^{a}	0.41 ± 0.1^{b}	0.39 ± 0.02^{b}	0.38 ± 0.1^{bc}	0.35 ± 0.02^{cd}	0.35 ± 0.01^{cd}	0.33 ± 0.02^{d}
Bulk Density (g/cm^3)	640 ± 10^{a}	620 ± 5^{ab}	640 ± 10^{a}	610 ± 5^{b}	430 ± 5^{d}	430 ± 10^{d}	510 ± 5^{c}	510 ± 10^{c}
Moisture Content	7.01 ± 0.17^{a}	6.32 ± 0.57^{a}	5.18 ± 0.15^{b}	5.16 ± 0.1^{b}	5.11 ± 0.4^{b}	4.48 ± 0.33^{bc}	4.52 ± 0.15^{b}	3.67 ± 0.15^{c}
Rehydration Ratio (RR)	1.96 ± 0.05^{c}	1.97 ± 0.05^{c}	2.39 ± 0.11^{bc}	2.62 ± 0.18^{bc}	2.94 ± 0.58^{ab}	3.41 ± 0.38^{a}	2.7 ± 0.17^{abc}	2.89 ± 0.15^{ab}
Δ E	35.17 ± 0.51^{b}	32.38 ± 2.31^{c}	38.28 ± 0.76^{a}	33.12 ± 0.14^{bc}	39.19 ± 0.15^{a}	34.58 ± 0.32^{bc}	34.65 ± 0.25^{bc}	27.08 ± 0.87^{d}
Chroma	31.87 ± 0.59^{bc}	29.83 ± 1.31^{cd}	35.51 ± 0.64^{a}	30.97 ± 1.31^{bc}	36.32 ± 0.11^{a}	32.51 ± 0.25^{b}	34.99 ± 0.11^{a}	28.48 ± 0.31^{d}
Hue	0.09 ± 0.001^{c}	0.11 ± 0.006^{c}	0.11 ± 0.003^{c}	0.09 ± 0.01^{c}	0.08 ± 0.003^{c}	0.08 ± 0.004^{c}	0.16 ± 0.01^{b}	0.22 ± 0.02^{a}
Browning Index (BI)	53.63 ± 1.18^{cd}	51.44 ± 1.41^{d}	61.7 ± 1.18^{b}	54.05 ± 5.07^{cd}	61.26 ± 0.35^{b}	56.39 ± 0.38^{bcd}	69.65 ± 1.49^{a}	59.27 ± 1.85^{bc}
Chemical Properties								
TPC (mg GAE/100g)	147.59 ± 6.71^{e}	152.86 ± 4.75^{e}	162.2 ± 4.30^{de}	171.56 ± 2.12^{cd}	172.73 ± 4.5^{cd}	195.56 ± 5.09^{ab}	184.66 ± 7.63^{bc}	205.1 ± 12.26^{a}
TFC (mg QE/100g)	496.5 ± 5.76^{d}	501.4 ± 9.61^{d}	511.4 ± 5.12^{cd}	521.3 ± 7.51^{c}	620.6 ± 7.51^{b}	625.6 ± 6.65^{ab}	638.6 ± 4.16^{ab}	645.4 ± 8.33^{a}
DPPH (%)	89.58 ± 1.08^{e}	93.53 ± 0.85^{cd}	92.41 ± 0.38^{d}	93.31 ± 0.66^{cd}	95.12 ± 0.53^{bc}	96.37 ± 0.55^{ab}	96.05 ± 0.62^{b}	98.24 ± 0.41^{a}
Ascorbic Acid (mg/100g)	67.5 ± 0.5^{b}	72.5 ± 4.1^{b}	84.2 ± 4.95^{a}	85.43 ± 5.94^{a}	91.37 ± 3.16^{a}	92.37 ± 4.9^{a}	86.83 ± 3.01^{a}	92.17 ± 2.53^{a}

Refractance window dried peel guava sample; **RWU:** Refractance window dried unpeeled guava sample; **IR-RWP:** IR-assisted Refractance window dried peel guava sample; **IR-RWU:** IR-assisted Refractance window dried unpeeled guava sample

3.4. Texture Analysis

The textural characteristics of the dried samples were laid out in Figure 2, revealing significant differences in mechanical and structural characteristics across various drying techniques. **The hardness** values of the dried samples varied from 3906.81 g in the IR-RWP sample to 8246.41 g in the TU sample. The reduced hardness value in IR-RWP samples indicates a comparatively softer texture, possibly resulting from uniform heat distribution with controlled drying that maintains cellular structures. **The adhesiveness** of the dried samples, defined as the amount of force needed to counteract the attractive forces between the sample and its contact surface, exhibited considerable variation. The range encompassed -0.172 g·sec in RWU samples to -5.76 g·sec in TU samples. **Springiness** is a measure of the ability of a sample to return to its original shape after deformation. For this sample springiness ranges were observed from 0.044 in VP-dried samples to 0.145 in IR-RWP samples. **Cohesiveness,** representing the internal bonding strength of a material, varied from 0.03 in VP samples to 0.166 in IR-RWP samples. **Gumminess,** which combines cohesiveness and stickiness, was observed in the range of 161.10 g for VP samples to 527.44 g for RWP samples. **Chewiness,** a derived property combining hardness, cohesiveness, and flexibility, indicates the effort required to masticate the sample to a swallowable state. The values ranged from 10.28 g in VP samples to 46.41 g in RWP samples. Lastly, **resilience,** a measure of the sample's energy recovery capacity after compression, ranged from 0.014 in VP-dried samples to 0.05 in IR-RWP samples.



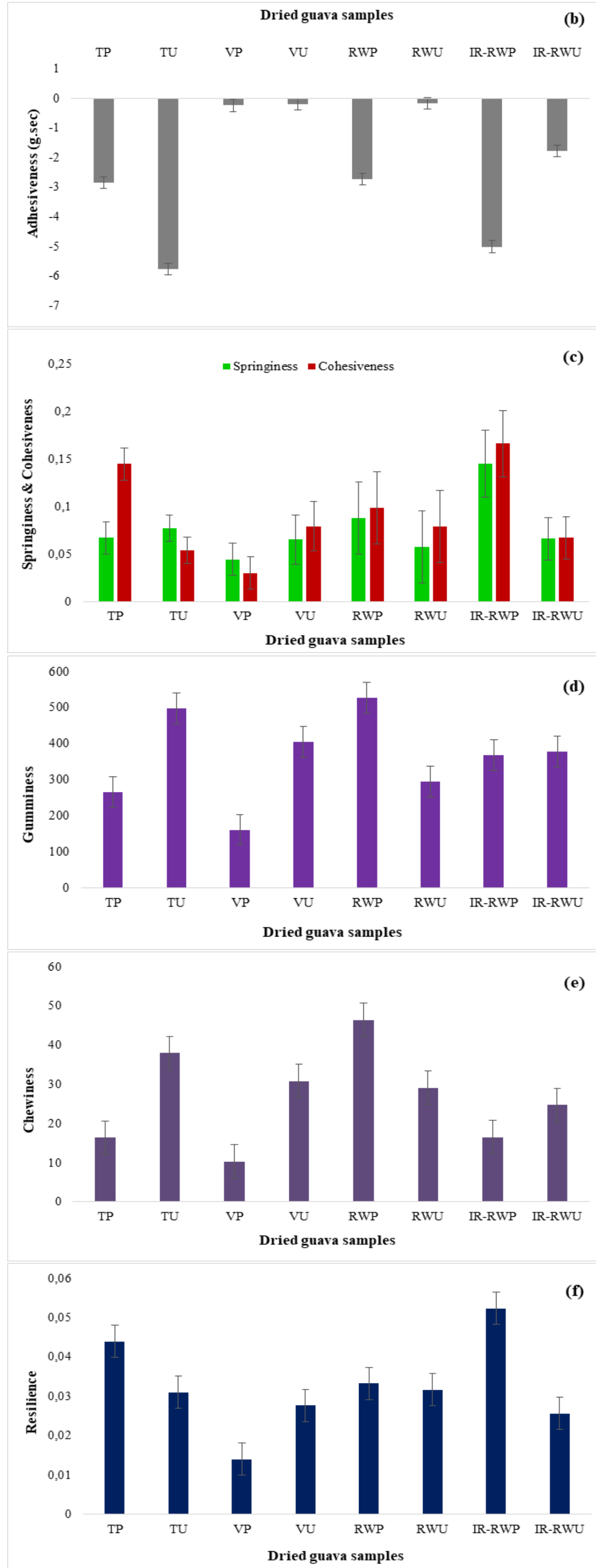


Figure 2. Textural parameter values of peeled and unpeeled dried guava obtained by various dehydration techniques **(a)** hardness **(b)**adhesiveness **(c)** Springiness&cohesiveness **(d)** gumminess **(e)** chewiness **(f)** resilience

3.5. Bulk density and Rehydration ratio (RR)

Table 1 provides detailed bulk density values for different samples. The bulk density of the dried samples indicated substantial differences across drying techniques and sample categories. TP and VP samples had the greatest bulk density values of 640 g/cm³, which were statistically comparable to the TU sample. TU samples had a somewhat reduced bulk density of 620 g/cm³ in comparison to TP and VP. The lowest bulk density values were recorded in the RWU and RWP samples, which was 430 g/cm³. The reduced bulk density in RWP, RWU, IR-RWU, and IR-RWP is primarily due to the gentle drying processes that maintain porosity and cellular integrity, hence decreasing the compactness of the final product.

The RR measures the capacity of dried samples to absorb water and recover their original structure, revealing the integrity and porosity of the dry matrix. The higher RR measured in RWU and RWP (3.41 and 2.94, respectively) indicate improved water absorption capacity, presumably due to better porosity and structural integrity throughout the drying process. In contrast, the lowest RR was observed in TP and TU, with values of 1.96 and 1.97, respectively. This is due to the denser structure and lower porosity of samples that undergo tray drying, which restricts access to water during rehydration.

3.6. Ascorbic Acid

Among the dried guava samples, the total ascorbic acid level varied between 67.5 mg/100g and 92.3 mg/100g as shown in Table 1. The RWU sample had the greatest ascorbic acid content. TP sample showed the lowest concentration of ascorbic acid of 67.5 mg/100g. It was also determined that the TU sample had 72.5 mg/100g of ascorbic acid. The ascorbic acid content is extremely responsive to light, oxygen, pH, heat, and other specific environmental factors (Horuz, Bozkurt, Karataş, & Maskan, 2017). The substantial decrease in ascorbic acid concentration in TP and TU samples can be attributed to the direct contact of heat medium and extended periods of drying. Analysis revealed that the VP and VU samples contained 84.2 mg/100g and 85.4 mg/100g of ascorbic acid, respectively. The RWP sample had 91.3 mg/100g of ascorbic acid. The concentrations of 86.8 mg/100g and 92.1 mg/100g were observed in the IR-RWP and IR-RWU samples, respectively. The slightly lower values of ascorbic acid in IR samples might be due the IR radiation. Analysis revealed that the unpeeled samples had a higher concentration of ascorbic acid in comparison to the peeled samples. The elevated levels of AA in the guava peel may account for this observation (Contreras-Calderón et al. 2011). Very closed values of ascorbic acid content in guava sample was also reported by Lim et al. (2007) and Leiton-Ramírez et al. (2020).

3.7. TPC

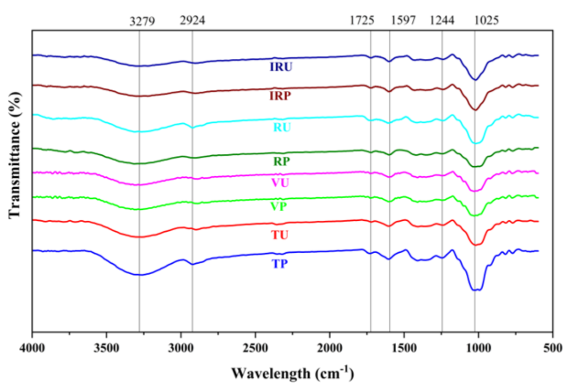
The IR-RWU dried guava was found to have the highest concentration of TPC of 205.1 mg GAE/100g as shown in Table 1. TPC was observed lowest in the TP sample, with 147.5 mg GAE/100g. While the TU sample had TPC values of 152.8 mg GAE/100g. In the IR-RWP sample, the GAE content was 184.6 mg/100g. The RWP and RWU samples had 172.7 mg of GAE per 100g and 195.5 mg of GAE per 100g, respectively. Higher retention of TPC in RW-dried guava than in tray and vacuum-dried samples could be attributed to the liberation of phenolics bound to the cellular structure of the dehydrated sample as a result of rapid heating and lower drying time (Rajoriya, Bhavya, & Hebbar, 2023). The presence of significant quantities of phenolic chemicals in guava peels may explain the elevated levels of TPC observed in unpeeled sample (Marina, Z; Noriham, 2014).

3.8. TFC

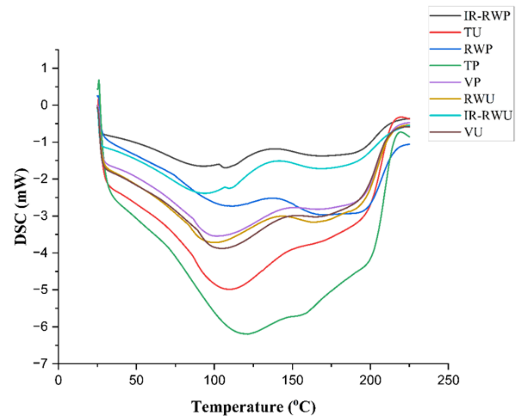
The range of values observed was 496.5 mg QE/100g (TP) to 645.4 mg QE/100g (IR-RWU), as depicted Table 1. The analysis showed that the TU and IR-RWP samples had 501.4 mg QE/100g and 638.6 mg QE/100g of TFC, respectively. The values of VP (511.4 mg QE/100g) and VU (521.3 mg QE/100g) were determined to be moderate, and no significant difference was observed. Zhang et al. (2024) observed similar trends for the jamun pulp. RW drying is a relatively gentle drying technique with less drying time thus retaining high TFC.Liu et al. (2018) observed that guava peel contained significant flavonoid content. Higher readings of TFC in unpeeled samples may be attributed to this reason.

3.9. Antioxidant activity

The antioxidant activity of the dehydrated samples was assessed through DPPH radical scavenging activity. The % inhibition was observed to vary between 89.58% (TP) to 98.24% (IR-RWU) shown in Table 1. The IR-RWU sample was found to have the highest antioxidant capacity due to it having high amounts of TPC and TFC. TP sample had the lowest antioxidant activity because of having low amounts of TPC and TFC. The elevated temperature of 60°C in a tray, vacuum, RW, and IR-RW dryers may have induced the degradation of cell components (Dadhaneeya et al., 2023b). In addition, the thermal inactivation of oxidative enzymes could have may have impeded the breakdown of antioxidant constituents, resulting in increased retention (Liang et al., 2018). Additionally, both enzymatic and non-enzymatic browning may have contributed to higher retention (Liang et al., 2018; Jogihalli et al., 2017).



a)



b)

Figure 3. (a) FTIR graph of dried guava samples **(b)** DSC curves of guava powders

3.10. FTIR

FTIR spectra of peeled and unpeeled guava powder obtained by varying drying methods are displayed in Figure 3(a). using Fourier transform infrared spectroscopy (FTIR). The powders exhibited six notable absorbance peaks. These peaks were observed at 3279 cm^{-1} (a strong peak) and within the range of 3280-3297 cm^{-1}, respectively. These peaks are indicative of OH bonds and are attributable to the presence of carbohydrates, proteins, alcohols, and phenolic chemicals. At this point deeper peak means stronger absorption was observed in TP and TU sample. Due to longer hot-air exposure can promote polymerization, crosslinking or condensation reactions (e.g., Maillard-type products, caramelization) that produce new hydroxyl-rich polymeric species with strong OH absorptions (Han et al. 2017). Elongated C-O bonds were detected at 1025 cm^{-1} in the 1025-1231 cm^{-1} range, which is a distinctive band associated with lignin, anhydride or alcohol, and phenols. A peak at 1725 cm^{-1} exhibited C = O stretches. The peak at 2924 cm^{-1} exhibited CH_2 asymmetrical stretching bands 2856-2928 cm^{-1}, indicating the presence of lipids, proteins, carbohydrates, and nucleic acids. The peak observed at 1244 cm^{-1} corresponds to the C = O stretching vibration within the bands 1237-1745 cm^{-1}. These bands are indicative of the presence of phospholipid, cholesterol ester, hemicellulose, pectin and lignin. The peak at 1597 cm^{-1} may be attributed to C = C and N-H bonds, indicating the existence of amide II structures, primarily in proteins.Athmaselvi et al. (2014) reported similar peaks in the FTIR study of freeze-dried guava.

3.1.1. Thermal Analysis

The DSC curves (Figure 3b) exhibit a broad endothermic peak for all the dried powders. The peaks were obtained at 121.04°C, 109.52°C, 101.50°C, 104.46°C, 111.40°C, 99.98°C, 92.85°C and 93.78°C for TP, TU, VP, VU, RWP, RWU, IR-RWP and IR-RWU samples respectively. Comparable findings were reported by Osorio et al. (2011) for hot air-dried and lyophilized guava powder. The complex endothermic peaks encompass the volatilization of water, the melting of pectin found in guava, and potential demethylation, dihydroxylation, and decarboxylation of pectin and other polysaccharides (Athmaselvi et al., 2014). The TP sample shows an intense peak, causing a larger heat flow leading to a lower thermal stability of the sample. By contrast, IR-RW sample showed the lowest peak temperatures, suggesting earlier onset of structural transitions. The intermediate peak values of the vacuum-dried and refractance window-dried samples indicate moderate thermal resistance. These findings align with earlier observations in fruit polysaccharide systems, where different drying techniques significantly shifted DSC peak temperatures, reflecting altered molecular interactions and stability (Zhang et al., 2024).

3.12. Microstructure and Energy Dispersive Spectroscopy

Figure 4 exhibits Scanning Electron Microscopy (SEM) pictures of dried guava samples subjected to various drying techniques and conditions, offering a comprehensive view of their microstructures. The SEM images of the TP sample exhibit relatively smooth and compact structures, which indicate less presence of irregularities. The TU sample exhibits greater irregularity than the TP sample, showing visible cracks and larger particle aggregation. The peel is likely to contribute to heterogeneity in the drying process. The VP sample structure exhibits a flaky texture characterized by low porosity. The VD conditions appear to maintain structural integrity while minimizing shrinkage effects. The VU sample displays more pronounced fibrous structures, suggesting the peel's impact on the drying process. The RWP surface exhibits a rough texture with few cracks present. The RWD technique produces a denser texture relative to tray drying, while maintaining surface smoothness. The microstructure of RWU exhibits improved fibrous networks characterized by greater irregularities in comparison to RWP. This indicates that the peel substantially influences the structural configuration during this drying process. The surface morphology of IR-RWP is predominantly smooth, exhibiting minimal porous regions. The incorporation of infrared heat in RWD enhances moisture removal while preserving surface integrity. Shende & Datta (Shende & Datta, 2019) reported similar results of microstructure of mango powder. Infrared-assisted drying improves moisture removal, resulting in more pronounced textural features in unpeeled samples. Peeled samples demonstrate smoother and more uniform textures relative to their unpeeled counterparts, as the presence of the peel results in heightened surface irregularities.

Table 2 displays the weight % of carbon (C), oxygen (O), aluminum (Al), and potassium (K) in several dried guava samples examined by Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS). The carbon content in all samples is mostly uniform, with minor increases seen in unpeeled samples (e.g., RWU and IR-RWU). The oxygen % increases in TD and RWD samples, with minor decreases seen in VD and IR- RWD samples. Aluminum concentration is negligible, with the maximum amount (0.5%) seen in VP and RWU. The potassium level exhibits fluctuation, with the greatest percentage recorded in IR-RWU (2.9%) and the lowest in TU and RWP (1.8%) sample. These data could influence the selection of drying techniques for maximum nutrient retention in guava processing.

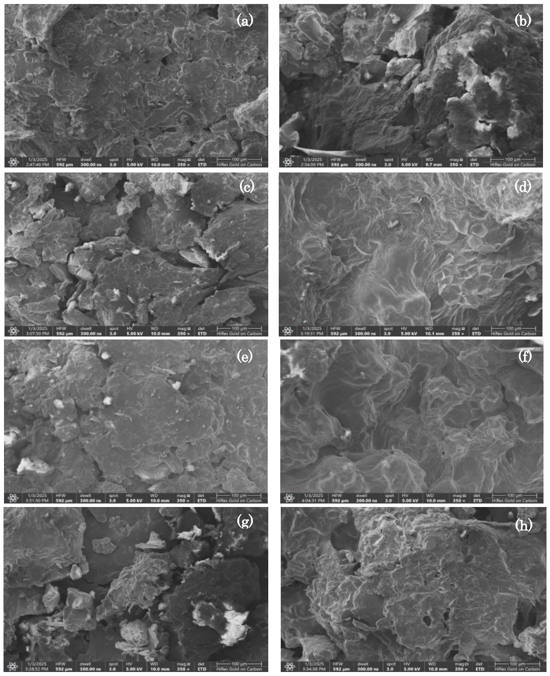


Figure 4 SEM images of Guava sample **(a)** TP **(b)** TU **(c)** VP **(d)** VU **(e)** RWP **(f)** RWU **(g)** IR-RWP **(h)** IR-RWU sample

Table 2. Elemental Composition of Dried Guava Samples through Energy Dispersive Spectroscopy

	Weight in percentage			
	C	**O**	**Al**	**K**
TP	33.7	63.6	0.3	2.1
TU	33	63.6	0.1	1.8
VP	33.3	58.4	0.5	2.4
VU	33.9	61.4	0.3	2.5
RWP	33.2	63.9	0.2	1.8
RWU	35.1	61.4	0.5	2.2
IR-RWP	33.5	63.1	0.3	2.6
IR-RWU	34.1	61.5	0.3	2.9

3.13. Analytic of quantitative data using multivariate analysis techniques

PCA is a statistical method that decreases the dimensionality of a dataset while retaining the most significant details (Subrahmanyam et al., 2024). The resulting biplot can be displayed in Figure 5. The PCA biplot presented separate groupings of samples in each of the four quadrants clearly and concisely, which indicates significant differences between entities. The biplot reveals that RWP, RWU, and IR-RWP are situated in the upper right quadrant of the plots, with chroma, BI, Ascorbic Acid, and TFC. This indicates that these attributes are more strongly preserved in those specified treatments. TP and TU were closely positioned alongside pH and bulk density on the contrary side, exhibiting higher values in the aforementioned samples. Although the VU sample was also located in the same quadrant. However, it is far from the pH and bulk density characteristics. The close proximity of the RWU samples to RR, Ascorbic Acid, and TFC indicates that these particular treatments have the highest retention of physicochemical attributes. The RWP sample exhibits a strong correlation with the chroma characteristic, indicating a substantial amount of this property in the RWP sample. IR-RWU is located in the bottom right quadrants alongside the TSS, AA, TPC, and Hue, which is the precise reason for the better preservation of these attributes in the IR-RWU sample. The results of the PCA analysis align with the theoretical analysis offered in the present article.

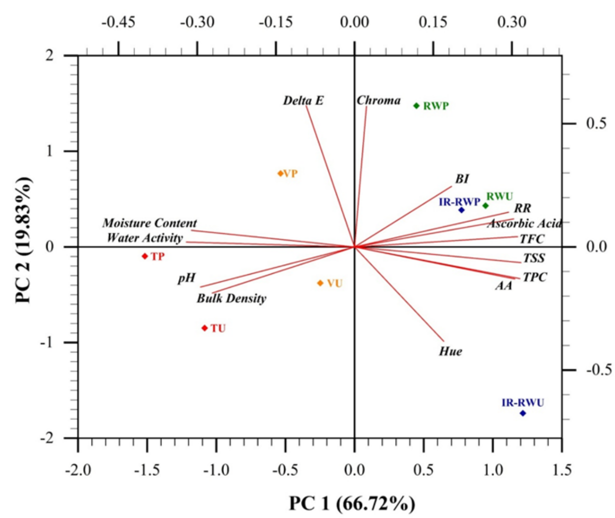


Figure 5. Biplot for multivariate analysis

4. Conclusions

Infrared refractance window drying is a novel and potentially advantageous technique for drying guava. In the current study we observed that among various drying techniques, the IR-

RW method has emerged as a superior method, offering a significantly reduced drying time of just 300 minutes. Experimental results demonstrated that the IR-RWD technique not only reduced the drying time but also excelled in preserving the physicochemical properties of guava. The TPC was observed 205.1 mg GAE/100g, TFC was observed 645.4 mg QE/100g, and ascorbic acid was 92.17 mg/100g in the IR-RW dried samples. The IR-RWD samples exhibited approximately 15% higher TPC, 20% higher TFC, 4% higher Antioxidant Activity, and 25% higher Ascorbic Acid content compared to the traditional drying techniques, such as tray drying and vacuum drying. An SEM analysis reveals the microstructural differences resulting from various drying techniques and peeling conditions, concluding that the peeled samples display smoother and more uniform textures than their unpeeled equivalents. The study concluded that IR-RWD technique ensures better retention of nutrients and antioxidants, better structural integrity, superior color, texture, and overall physical properties of the dried guava sample. This makes IR-RWD a highly effective method for making guava powder. These findings can act as a guide for selecting the best drying technology for guava powder.

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