Chapter 4

Chapter-IV

Results and Discussion

This chapter deals with the results obtained from the experiments conducted on design and development of a turmeric processor for simultaneous curing and drying of turmeric rhizomes using instant decompression. This includes preliminary studies on effect of instant controlled pressure drop on quality of turmeric rhizomes, optimization of the process parameters and quality evaluation of processed turmeric are discussed in this chapter. The results of quality analysis were compared with the existing methods and discussed. The results are tabulated, statistically analyzed and discussed with the following headings.

4.1 Preliminary Study

A preliminary study on processing of turmeric rhizomes using instant decompression assisted curing (IDASC) was carried out before developing the actual steam dryer. The method used for generation of instant controlled pressure drop for the preliminary study was explained in detail under the section 3.3. This study made it easier to plan and carry out the experiment while also providing fundamental knowledge on instant controlled pressure drop (ICPD) drying following Allaf & Allaf (2014). The next section presents and discusses the effects of ICPD on the quality of turmeric rhizomes at various combinations of temperature, duration, and curcumin level in order to improve the drying process parameters.

Size:

The turmeric rhizomes have branches of varying size. Hence, relatively smaller primary and secondary developments (fingers) were removed and all the measurements were made only for main reported by Prasath et al., (2024). Tri-axial linear dimensions viz., major (length), intermediate (width) and minor (thickness) of fresh, cured and dried turmeric rhizome in the natural rest position are presented in Table 4.1 from the table, it is observed that there was a considerable change in length, width and thickness of rhizomes after curing and drying. As compared to fresh ones, after cure the rhizomes, it shown 1.24 % increase in length, 3.83 % increase in width and 6.72 % increase in thickness. There was 29.41 % reduction in length, 48.30 % reduction in width and 53.82 % reduction in thickness were observed after drying. From the results, it is clear that the reduction is more in the radial direction as compared to longitudinal direction.

Table No 4.1 Dimensions of turmeric rhizome fresh cured and dried

Dimension(cm)	Fresh	Cured	Dried
Lenth	8.20	8.26	6.10
Width	2.61	2.68	1.41
Thickness	2.42	2.46	1.32

Shape:

The shape of turmeric rhizome (after removing primary fingers) and mother (after removing fibrous roots) rhizomes were measured at an average moisture content of 390.85, 504.14 and 9.55 % and 235.56, 259.20 and 12.14 % (db) for fresh, cured and dried rhizome and mother rhizomes. There was 1.43 and 1.97 % reduction in cylindricity of finger and mother rhizomes after drying over fresh rhizomes, respectively. As both finger and mother rhizomes cylindricity values were higher than roundness and sphericity values, the shape of the fresh and dried finger and mother rhizomes can be considered as cylinder for all practical purposes.

Experiments were conducted with the visual procedure depicted in Fig 3.3 (a) and (b) and is reproduced here for reference as Fig 4.1 and 4.2.

Fig 4.1 Turmeric Slice

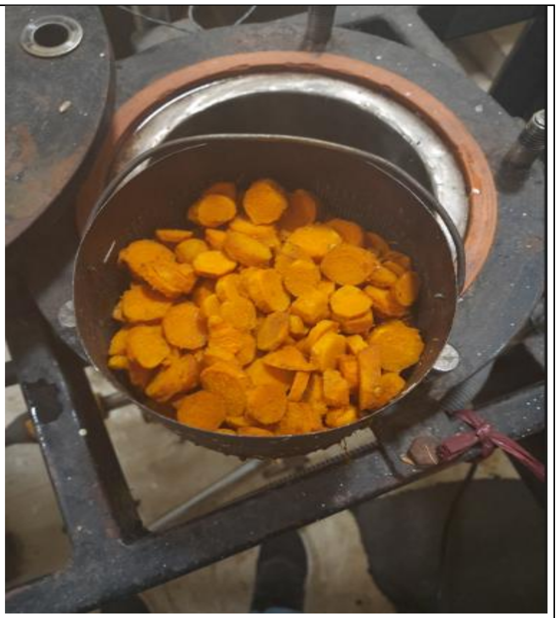


Fig 4.2 Turmeric Slice for treatment

4.2 Objective-I: To Enumerate the Effects of Instant Decompression Assisted Steam Curing (IDASC) in Inducing Swell Drying of Turmeric Slices

Objective-1 is discussed in the following sections.

4.2.1 Hot air Drying and Moisture Content Measurement

In the drying of turmeric slice at different temperatures 45°, 55° and 65 °C of hot air drying.

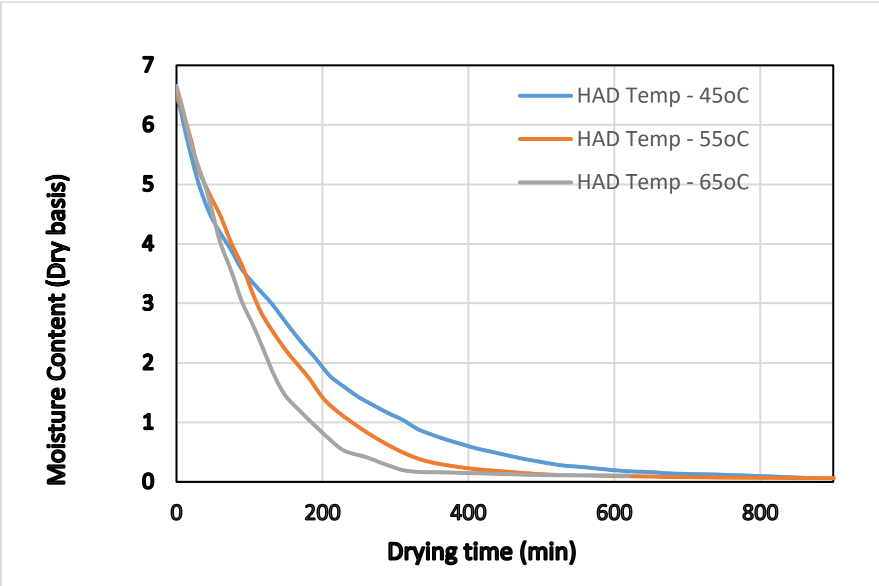


Fig. 4.3 Moisture content of turmeric slices using instant controlled pressure drop (ICPD) treatment parameters.

The graph (Fig 4.3) of the drying rate of turmeric slices processed with Instant Controlled Pressure Drop (ICPD) technology provides an insightful understanding of the drying kinetics. This analysis explores the rapid moisture removal facilitated by ICPD, emphasizing its efficiency and contribution to high-quality turmeric products (Trivedi et al., 2023).

Phase 1: Rapid Initial Drying

Early in the drying process, moisture is rapidly removed, as indicated by the high value of 0.9 g water/g dry matter/min at the beginning of the drying rate curve. The evaporation of surface water is reflected in this first phase, which usually occurs within the first 20 to 30 minutes. Because of its special mechanism of high-pressure steam treatment followed by immediate decompression, the ICPD technology performs exceptionally well throughout this phase.

Turmeric's cellular structure is upset by the abrupt pressure drop, forming micro channels that effectively move moisture from the inside to the surface.

This rapid drying phase is crucial as it reduces the bulk of moisture without exposing the turmeric slices to prolonged thermal stress. The high drying rate during this stage demonstrates the superiority of ICPD technology in minimizing processing time while maintaining energy efficiency.

Phase 2: Gradual Decline in Drying Rate

As the drying process progresses, the drying rate begins to decline, reaching approximately 0.35 g water/g dry matter/min by the midpoint of the 300-minute cycle. This phase is characterized by the transition from surface water evaporation to the removal of bound water within the turmeric's cellular matrix (Rezaei et al., 2023). The decrease in drying rate occurs because the moisture gradient between the slice's interior and its surface diminishes, reducing the driving force for water diffusion.

Despite the slower drying rate, ICPD technology remains advantageous during this phase. The micro-channels formed during decompression continue to facilitate the movement of moisture, albeit at a reduced rate. This ensures consistent drying without hotspots or uneven moisture distribution, critical for achieving a high-quality final product.

Phase 3: Equilibrium Approach

In the final stages of drying, the drying rate drops significantly, nearing zero as the moisture content approaches equilibrium. This phase reflects the extraction of tightly bound water, which requires substantially more energy and time to remove by this point, the turmeric slices have already achieved most of the desired moisture reduction, and the process shifts to fine-tuning the final moisture content.

The gentle and controlled drying environment provided by ICPD technology during this stage is instrumental in preserving the turmeric's bioactive compounds, including curcumin and essential oils. Unlike conventional methods that may degrade sensitive compounds due to excessive heat exposure, ICPD ensures product integrity and superior quality.

Rapid Moisture Removal

The turmeric slices have a very high moisture content at the beginning of the drying process roughly 80% on a wet basis. Fresh turmeric rhizomes, which have a significant amount of both bound and free water, typically have this level. The graph shows a sharp drop in moisture content over the first half hour, reaching almost 50% (Saha et al., 2022). The high-pressure steam treatment and fast decompression provided by the ICPD system enable the quick evaporation of surface moisture during this phase.

The instant decompression disrupts the cellular structure of the turmeric slices, creating micro-channels that enhance the diffusivity of moisture. This structural modification allows water to migrate more freely from the interior of the slices to the surface, where it evaporates quickly (Rane et al., 2022. Consequently, this phase is characterized by a high drying rate, showcasing the efficiency of ICPD technology in accelerating moisture removal.

Gradual Transition

Between 300 and 400 minutes, the graph exhibits a more gradual reduction in moisture content, decreasing from 50% to approximately 10%. During this intermediate phase, the drying process transitions from the evaporation of surface moisture to the diffusion of bound water from within the cellular structure. As the moisture gradient between the interior and surface diminishes, the drying rate slows down, reflected by the less steep slope of the curve.

This phase underscores the importance of ICPD's role in maintaining an optimal drying environment. By enhancing moisture diffusivity, the technology ensures a steady and controlled reduction in moisture content without exposing the turmeric to excessively high temperatures. This approach minimizes the risk of thermal degradation of curcumin and essential oils, preserving the product's nutritional and sensory qualities.

Final Phase

The final phase, spanning from 500 to 600 minutes, is marked by a significantly slower reduction in moisture content, eventually stabilizing at around 1%. This plateau indicates that the equilibrium moisture content has been reached, where the rate of moisture removal matches the ambient conditions of the drying environment. At this stage, only tightly bound water remains, requiring considerably more energy to extract.

The controlled nature of ICPD technology ensures that this phase is achieved efficiently without compromising the structural integrity of the turmeric slices. The end product retains its vibrant color, enhanced curcumin levels, and excellent rehydration properties, making it ideal for high-value markets.

4.2.2 Variation of Moisture Profile During HA Drying of ICPD treated slices

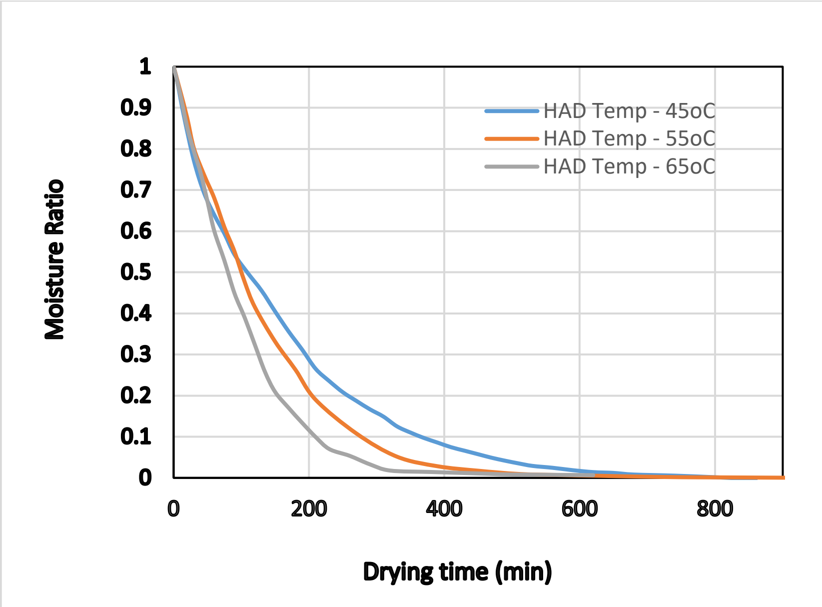


Fig. 4.4 Moisture ratio of turmeric slices using instant controlled pressure drop technology assisted with hot air drying

The graph (Fig 4.4) depicting the moisture ratio of turmeric slices processed with Instant Controlled Pressure Drop (ICPD) technology combined with Hot Air Drying (HAD) illustrates how the moisture content decreases over time during the drying process. This analysis helps in understanding the combined effect of ICPD pre-treatment and subsequent HAD on the drying kinetics of turmeric slices (An et al., 2016).

High Moisture Ratio and Rapid Reduction

Fresh turmeric naturally contains water; the slices of turmeric have a high moisture ratio at the start of the drying process. The graph indicates that the moisture removal rate is quick since it displays a sharp drop in the moisture ratio during the first phase (Saha et al., 2022). The ICPD pre-treatment, which uses high-pressure steam followed by immediate decompression, is principally responsible for this quick drop. The turmeric slices' cell walls are broken down during this process, forming tiny channels that effectively transfer moisture from the inside to the outside. This early, rapid moisture release is caused by the significant moisture gradient between the slices' exterior and interior.

As the drying process continues, the rate of moisture reduction slows down. The graph's curve begins to level out, indicating a decreasing drying rate. This behavior is typical in drying processes as the moisture content within the slices approaches the equilibrium moisture level. During this phase, the HAD further assists in moisture removal, but at a slower rate (Osae et al., 2020). The hot air provides continuous heat transfer, ensuring that moisture continues to evaporate from the surface of the turmeric slices, albeit at a reduced rate compared to the initial phase.

The combination of ICPD pre-treatment and HAD during this stage provides significant advantages. While ICPD ensures that the initial moisture removal is efficient and quick, HAD helps in maintaining a controlled drying environment that further facilitates moisture loss without causing thermal damage to the turmeric's bioactive compounds, such as curcumin.

Final Stage: Approach to Equilibrium

In the final stage of the drying process, the moisture ratio decreases at a much slower rate as the slices approach their equilibrium moisture content. At this point, the graph flattens out, indicating that only the bound water within the cellular structure remains (Surendhar et al., 2019). This stage typically requires a longer period and higher energy input to remove, which is why the drying rate becomes minimal.

The combined ICPD and HAD approach ensures that even in this stage, the turmeric slices are exposed to a gentle drying process that preserves their quality. The low temperature used in HAD, paired with the initial rapid moisture removal facilitated by ICPD, helps retain important bioactive components and prevents degradation.

4.2.3 Drying Kinetics Model

The drying kinetics of turmeric slices were examined using five drying models, and MATLAB R2018b was utilized for nonlinear regression analysis. The MR values of turmeric slices dried using different drying techniques were used to customize drying kinetics models. the comparison of experimental and anticipated MR using various drying models (Jha & Sit, 2020).

The drying kinetics model describes the behavior of moisture removal during the drying process, focusing on how moisture content changes over time. It's an essential part of understanding and optimizing drying systems, particularly in food, pharmaceuticals, and agricultural industries. The model provides a mathematical framework to describe the relationship between drying time and moisture content, which can help in: designing and scaling up drying systems, predicting energy consumption and maintaining product quality (Avhad & Marchetti 2016).

Table 4.2: Showing the performance of drying model

Model	Parameter(s)	Values at Different Drying Temps			Statistics at Different Drying Temps			
		45⁰	**55⁰**	**65⁰**		**45⁰**	**55⁰**	**65⁰**
Newton	k	0.00640	0.00728	0.00942	SSE	0.01165	0.00870	0.01442
					R^2	0.996	0.997	0.994
					RMSE	0.01432	0.01945	0.02504
Handerson Pabis	a	0.9679	1.023	1.05	SSE	0.00762	0.00711	0.01442
	k	0.00618	0.00750	0.00997	R^2	0.997	0.997	0.994
					RMSE	0.01476	0.01798	0.02504
Page	k	0.00922	0.00412	0.00366	SSE	0.00717	0.00247	0.00182
	n	0.9306	1.118	1.201	R^2	0.099	0.999	0.999
					RMSE	0.01476	0.0106	0.00889
Logarithmic	a	0.9709	1.033	1.065	SSE	0.00742	0.00566	0.01176
	k	0.00607	0.00725	0.00944	R^2	0.997	0.998	0.995
	c	-0.00538	-0.01421	-0.0221	RMSE	0.01477	0.01642	0.02312
Modified Page	a	0.9835	0.9837	0.9862	SSE	0.00762	0.00201	0.00150
	k	0.00803	0.00341	0.00315	R^2	0.997	0.999	0.999
	n	0.9535	1.152	1.23	RMSE	0.01476	0.00980	0.00826
Midilli	a	0.993	0.984	0.9849	SSE	0.00473	0.00201	0.00137
	b	-3.13×10^{-5}	-1.46×10^{-06}	1.01×10^{-05}	R^2	0.998	0.999	0.999
	k	0.01021	0.00344	0.00302	RMSE	0.01197	0.01002	0.00809
	n	0.9041	1.15	1.24				

Strong markers of a successful match include a lower χ^2 score and a higher R^2. According to the analysis, every model that was chosen fits the data satisfactorily within the acceptable range of goodness. Nevertheless, the Page, logarithmic, and Newton models are the most well-fitting and exhibit the greatest results for the dried turmeric slices (Table 4.2). This result demonstrates the models' ability to effectively depict the drying process and their potential for real-world use in drying operation optimization. The next subsections provide a discussion of the top three drying models.

4.2.4 Moisture Diffusivity

One of the most important parameters in drying technology is moisture diffusivity (D), which shows how quickly moisture passes through a substance. When using instant controlled pressure drop technology to process turmeric, knowing moisture diffusivity aids in assessing how well the drying process works (Rane et al., 2022). The commonly used method for characterizing the movement of moisture in materials, Fick's Second Law, can be used to compute the diffusivity.

Understanding moisture transport in food materials during drying, particularly during the declining rate periods, requires an understanding of effective moisture diffusivity (D_{eff}). D_{eff} for turmeric slices of varying thicknesses dried by different techniques is shown in Fig. 4.5. Values of D_{eff} lies in the range reported by Borah et al (2015). Differences are seen in IDASC-HAD and IDASC-RWD, which may be caused by differences in moisture vapor pressure and more mass transfer at higher airflow rates (0.016 kg/s) during drying (Kumari et al., 2023).

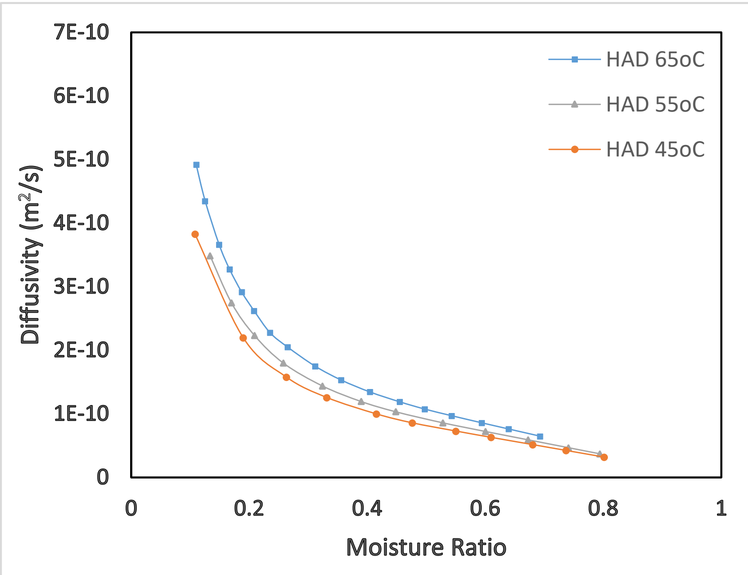


Fig. 4.5: Diffusivity with respect to moisture ratio

ICPD technology combines rapid steam heating and instant decompression to enhance moisture removal from materials. The sudden drop in pressure during ICPD results in the rapid expansion of water vapor within the plant cells, causing cellular disruption. This process greatly enhances moisture transport, leading to a higher moisture diffusivity than that seen in conventional drying methods (Saha et al., 2022).

4.2.5 Modelling of IDASC-HAD Process Parameters by using RSM

RSM was implemented for the mapping of factors and responses of the IDASC-HAD process of parameter drying of different models (Table 4.3)

Table 4.3: Represents significant effect for the predictive models of DT, CC and YV.

Sl. No.	Independent parameter	Dependent parameter
1.	Treatment pressure (0.1-0.4 MPa)	Drying time
2.	Treatment time (10-50s)	Curcumin content
3.	Temperature of drying (45-65 ºC)	Yellowness value

The responses were determined based on the experimental design. For determining the effect of independent variables (TP, TT and TD) on the responses (DT, CC and YV), ANOVA (analysis of variance) was performed. The predictive models, developed for various responses were evaluated based on the multiple regression analysis. Accuracy of developed model was determined on the basis of R^2 and LOF values. Table 4.4 shows the results of ANOVA for the developed quadratic models (Gautam et al., 2021).

Further, non-significant lack of fit values was observed for all the models. Furthermore, R^2 values for the DT, CC and YV models were 0.96, 0.98 and 0.97 respectively. On the basis of these results, accuracy of the developed models could be revealed (Gautam et al., 2021). To find out effects of different factors significant results were observed from the ANOVA table. In case of DT three factors namely TP, TT and TD were significant at 0.1% level, whereas for CC, these were significant at 0.1, 1.0 and 0.1% levels respectively. For YY, IDASC-HAD process factors, TP, TT and TD had significant effect at 0.1, 0.1 and 1% respectively in terms of coded factors, the final equations of DT, CC and YV were as follows.

$$DT=425.32-26.67A-46.67B-75.00C-13.71A^2-23.71B^2+131.29C^2+7.50AB+15.00AC+67.50BC \quad (8)$$

$$CC=4.35+0.85A+0.07B-0.14C-0.13A^2-0.03B^2-0.46C^2-0.01AB+0.01AC-0.02BC \quad (9)$$

$$YV=50.68+5.94A+1.78B-0.89C+0.54A^2+0.38B^2-2.29C^2-0.42AB+2.08AC-0.67BC \quad (10)$$

Where, *DT* is the drying time (mins), CC is the curcumin content (%), YV is the yellowness value, *A* is the TP (atm), *B* is TT (s) and *C* is TD (ºC).

Table 4.4: ANOVA results of the fitted models for the response variables

Variables	**DF**	**Estimated Coefficients**			***F* value**		
		DT	**CC**	**YV**	**DT**	**CC**	**YV**
Model	9	425.32	4.35	50.68	61.51[a]	210.99[a]	87.63[a]
x_1	1	-26.67	0.85	5.94	21.11[a]	1590.89[a]	623.71[a]
x_2	1	-46.67	0.07	1.78	64.64[a]	9.24[b]	55.78[a]
x_3	1	-75.00	-0.14	-0.89	166.95[a]	41.53[a]	13.95[b]
x_1^2	1	-13.71	-0.13	0.54	2.22	15.12[a]	2.07
x_2^2	1	-23.71	-0.03	0.38	6.63[c]	0.88	0.99
x_3^2	1	131.29	-0.46	-2.29	203.33[a]	184.14[a]	36.80[a]
x_1x_2	1	7.50	-0.01	-0.42	1.11	0.15	2.04
x_1x_3	1	15.00	0.01	2.08	4.45[c]	0.17	51.07[a]
x_2x_3	1	67.50	-0.02	-0.67	90.16[a]	0.37	5.23[c]
Lack of Fit	17				0.80[ns]	0.98[ns]	0.02[ns]
R^2		0.96	0.98	0.97			

[a]0.1% level of significance, [b]1% level of significance, [c]5% level of significance, [ns]non-significant

As observed from Table 4.4, all the three factors i.e.TP, TT and TD have significant impacts on DT at 0.1% level. These factors have negative impact on DT. From the Fig.4.6 3a, b and c, negative effect of TP, TT and TD on DT of turmeric samples can also be observed (Gautam et al., 2021). The decreasing trend in DT of the turmeric samples is due to the fact that IDASC treatment of the samples at higher steam pressure for certain treatment time followed by instant pressure drop tends to increase pore size of the material along with enlarged surface area. As a result, HAD of IDASC sample can be achieved with reduced DT, which is in line with earlier findings of Pilatowski et al (2010).

4.2.6 Curcumin Content

In case of CC, the treatment factors namely TP and TD have significant positive effect at 0.1% level. On the other hand, TT has significant negative effect on the CC at 1% level. Fig 4.6 d, e and f also show similar type of effects for various process factors. The increase in CC during IDASC-HAD method is due to the reason that treatment of samples at higher steam pressure for a certain duration followed by sudden pressure drop enhances instantaneous cooling effect on the surface of the samples. As a result, an increased amount of CC can be observed for the IDASC-HAD based turmeric powder. These results are inconsistent with the findings reported by Hmar et al., (2017)

4.2.7 Yellowness Value

At the 0.1% level, TP and TT exhibit a considerable beneficial effect on the turmeric powder's yellowness value (YV), while TD has a significant negative effect. Similar effects may also be shown in Fig 4.6 3g, h, and i. Immediate chilling during the hot air drying procedure helps to avoid significant deterioration of the turmeric samples during the IDASC treatment (Gautam et al., 2021) This makes it possible to obtain turmeric powder with a greater YV. Similar results on the preservation of color have also been reported by Xiao et al., (2019).

4.2.8 Particle Size Analysis

For the particle size analysis, different parameters namely fineness modulus (FM), average particle size (APS), volume mean diameter (VMD) and mass mean diameter (MMD) were calculated. FM was calculated by dividing the sum of weight fractions retained on each sieve by 100. MMD, APM and VPM were determined by using the following mathematical equations:

$$\mathrm{MMD} = \sum_{i=1}^{n} m_i D_{pi} \quad \text{……..………(11)}$$

$$\mathrm{VMD} = \left(\frac{1}{\sum_{i=1}^{n} \frac{m_i}{{D_{pi}}^3}}\right)^{\frac{1}{3}} \quad \text{………………(12)}$$

$$\mathrm{APS} = 0.135 \times 1.366^{FM} \quad \text{………………(13)}$$

Where, i refers to individual increment, n is number of increments, m refers to mass of particle and D_{pi} is the average particle diameter in each increment (Sahay & Singh,1996).

4.2.9 Optimizing by Using Hybrid RSM-PSO Approach

The best predictive models of the responses DT, CC, and YV—were then combined with the particle swarm optimization (PSO) technique to produce the optimal process parameters. Maximization for CC and YV and minimization for DT were the goals of the optimization method (Gautam et al., 2021). The PSO was carried out using the SPSO approach. Forty particles were the calculation's underlying populace size. The weight values varied between 0.4 and 0.6 with the generations, while the estimates of increasing speed constants, c1 and c2, were both 0.5. The SPSO algorithm was executed using a total of 2000 generations. After reaching the predetermined number of generations, the iterative process was terminated. According to hybrid RSM-PSO, the ideal process parameters were TP of 3 atm, TT of 50 s, and TD of 57°C. Under these circumstances, the maximum YV and CC were 60 and 5.05%, respectively, and the DT was 325 minutes (Gautam et al., 2021).

As reported in the previous section, Fig. 5(a) and 5(b) show the micro-structures of turmeric powder produced by CBWC-HAD and IDASC-HAD method. In case of IDASC-HAD based turmeric powder expanded granular structure can be observed. This is due to the reason that ICPD induced instant pressure release towards vacuum tank helps to swell and expand the ultimate granular structure of the dried turmeric powder (Gautam et al., 2021). The average size of the particles as analyzed from the SEM images, were observed to be 0.16 and 0.24 mm respectively for CBWC-HAD and IDASC-HAD based turmeric powder. The results, demonstrated in Fig. 4(f) also showed similar trends for the average particle size (APS) of the turmeric powder. Hence, IDASC treated turmeric slices face hot air drying conditions with higher specific surface area (Venkateshwari et al., 2024). As a result, for the IDASC-HAD based samples drying can be accomplished within a shorter period as compared to conventional hot air drying process. Therefore, minimization of drying time in case of IDASC-HAD based samples helps to retain higher quality properties in the final turmeric powder as compared to CBWC-HAD method. Ben Amor *et al.* (2008) reported comparative kind of findings related to modification of micro-structure during ICPD treatment.

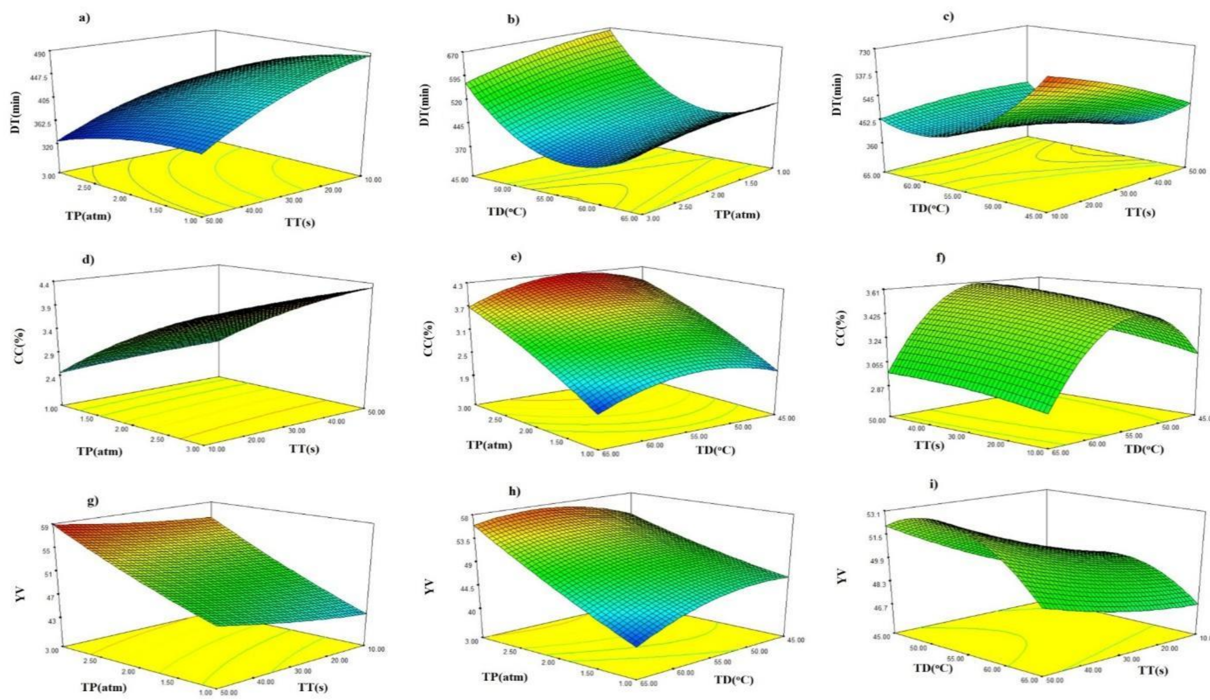


Fig. 4.6 Effect of IDASC-HAD treatment conditions on hot air drying time (DT) of slices and curcumin content (CC) and yellowness value (YV) of powder. [Plots (a), (d), and (g) shows the combined effects of TP and TT; (b), (e), and (h) depicts the effects of TP alone and (c), (f), and (h) depicts the effects of TT alone, on DT, CC and YV respectively.

In the pursuit of high-quality turmeric powder through advanced processing, the integration of Instant Controlled Pressure Drop (IDASC) technology with Hot Air Drying (HAD) offers a promising route to improve efficiency and product quality. However, optimizing such a process involves navigating a multi-objective landscape minimizing drying time while simultaneously maximizing yellowness (color intensity) and curcumin content (a key bioactive compound). To address this, the thesis introduces a hybrid optimization approach**,** combining Response Surface Methodology (RSM) with Particle Swarm Optimization (PSO)**.** This combination not only leverages the strengths of both techniques but also overcomes their individual limitations, offering a superior route to precise and reliable process optimization.

When RSM and PSO are used together in a hybrid form, the result is a synergistic optimization framework that combines the data-driven, statistically structured model of RSM with the adaptive, global-search capability of PSO. This integration offers several clear advantages:

RSM provides an empirical model of the system’s response, which is then used as **a** fitness function for PSO. This means PSO doesn’t blindly search the parameter space it searches intelligently, based on a model already built from real experiments. This leads to: Faster convergence, reduced computational time, Higher accuracy in locating the global optimum, especially in complex systems with non-linear or multi-peaked responses.

The hybrid model can balance trade-offs between drying time, yellowness, and curcumin content objectives that may conflict with one another. While RSM provides insights into how changes in parameters affect each output, PSO explores Pareto-optimal solutions, enabling: A broader view of all feasible trade-offs, Selection of the best compromise point for both quality and efficiency.

Instead of running a vast number of experiments, the hybrid approach allows for: Reduced number of trials, thanks to RSM's design of experiments (DoE), Targeted optimization, as PSO focuses its search based on the RSM-predicted response surface. This approach is highly resource-efficient, especially important when dealing with high-cost ingredients like turmeric and energy-intensive processes like pressure-drying.

RSM provides interpretable models such as contour and surface plots—that allow researchers to visualize how process parameters interact. PSO then works on top of this model to extract optimal conditions from these interactions, revealing non-obvious solutions that might be missed through statistical analysis alone. The hybrid use of PSO and RSM provides a powerful, efficient, and insightful optimization strategy for complex food processing systems like IDASC_HAD. For turmeric drying, it enabled a balanced, high-quality output by capturing both the statistical structure of the system and the non-linear dynamics of real-world processing. This combined approach not only improved the efficiency of determining optimal parameters but also established a methodological benchmark for future applications in multi-objective food and bio-product engineering.

4.2.10 Comparative Study of Turmeric Powder Produced by IDASC-HAD and HAD Method

Figure 4.7 shows the comparison of turmeric powder produced by IDASC-HAD and CBWC-HAD method (Pronyk et al., 2004).

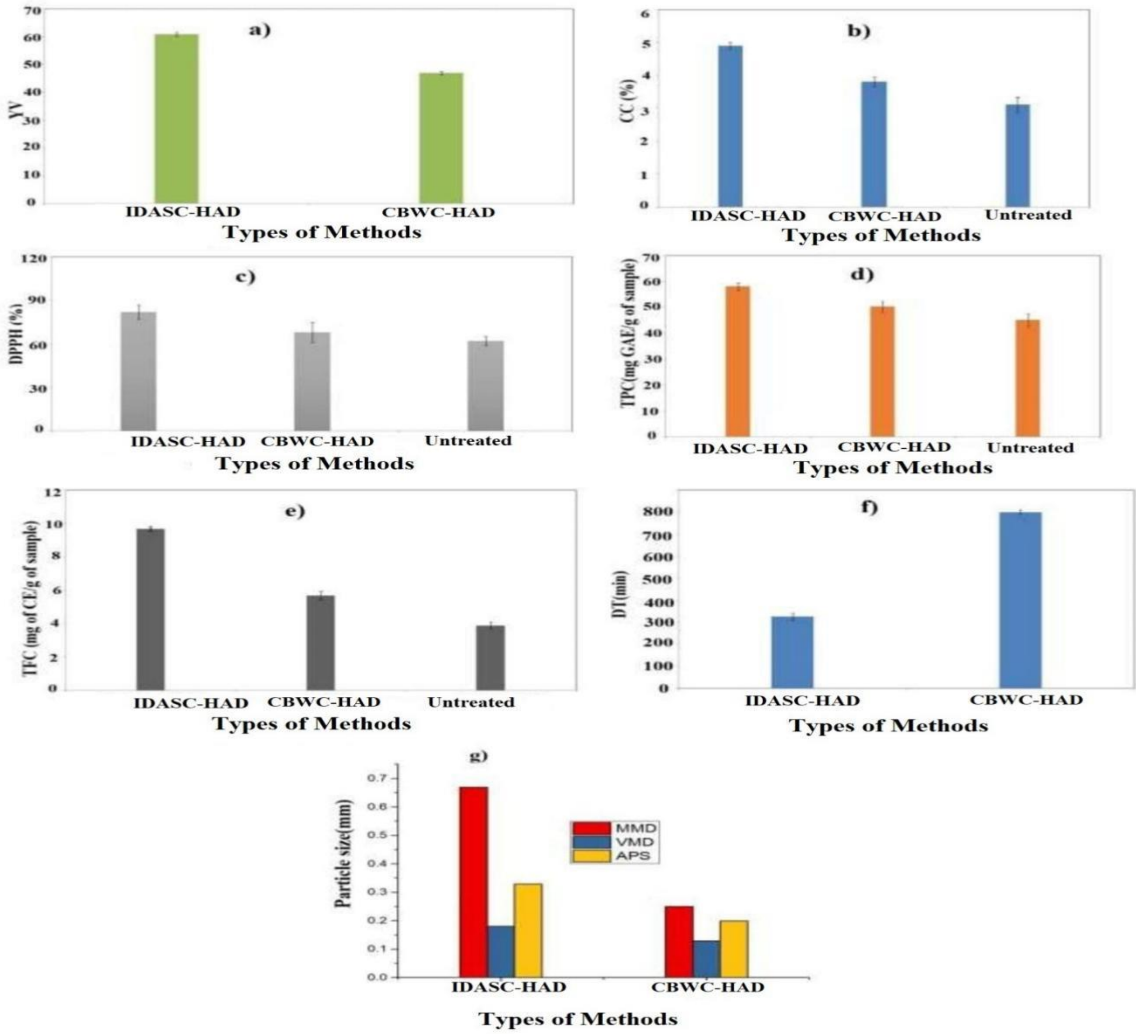


Fig. 4.7 Comparison of properties of turmeric powders produced by IDASC-HAD and CBWC-HAD methods [(a) yellowness value (YV), b) curcumin content (CC), c) DPPH activity, d) total phenolic content, e) flavonoids, f) drying time (DT) and g) particle size distribution].

Superiority of IDASC-HAD over CBWC-HAD method in term of YV, CC, DPPH, TPC and TFC of turmeric powder can be observed from Fig. 4(a-e). During IDASC treatment, allowance of treatment chamber for sudden pressure drop creates instantaneous cooling effect on the surface of the turmeric samples as was observed for apples by Xiao et al., (2019) As a result of which, degradation minimizes during post steaming drying process and higher retention of YV, CC, DPPH, TPC and TFC occurs in the turmeric powder. Similar types of findings are reported by Mounir et al (2011). Figure 4.7 shows the comparison between IDASC-HAD and CBWC-HAD method for the drying time (DT). Due to instant pressure release during IDASC treatment pore size and specific surface area of the turmeric slices increases, which results in higher diffusivity during post treatment drying process.

A comparison between the IDASC-HAD and CBWC-HAD method for the particle size of turmeric powder can be observed from Fig. 4f. The turmeric powder produced by IDASC-HAD has higher MMD, VMD and APS values as compared to CBWC-HAD method. The proof for the expansion of granular structure of IDASC-HAD based turmeric powder as compared to CBWC-HAD method can also be observed from Fig. 4.8(a) and 4.8(b). Similar types of findings are reported by Hmar et al., (2017).

The optimized parameters identified for the IDASC_HAD (Instant Controlled Pressure Drop coupled with Hot Air Drying) process 3 atm treatment pressure (TP), 50 seconds treatment time (TT), and 57°C drying temperature (TD) resulted in a drying time of 325 minutes, with a yellowness value of 60 and curcumin content of 5.05%**.** While these values signify a well-balanced enhancement in product quality and process efficiency, their true value lies in their industrial applicability, robustness, and reproducibility**,** which are critical factors for successful scale-up and commercialization of turmeric drying operations.

Curcumin is known for its thermal sensitivity and oxidative instability**.** In the study, even small deviations (±2°C in drying temperature or ±10s in treatment time) led to a noticeable decline in curcumin content: Increased drying temperature (above 60°C) accelerated curcumin degradation and color fading. Extended pressure time caused partial breakdown due to prolonged exposure to steam and pressure. Thus, the optimized curcumin content (5.05%) is highly sensitive to thermal and time-based variations**,** highlighting the need for precise process control systems in scale-up scenarios.

Other bioactive indicators such as DPPH radical scavenging activity**,** Total Phenolic Content (TPC)**,** and Total Flavonoid Content (TFC) were found to show moderate sensitivity**:** A ±5% change in temperature or treatment time affected these metrics by 5–10%. These compounds are relatively more chemically stable than curcumin, but still respond to oxidative stress and over-drying. While not as thermolabile as curcumin, these indicators still suggest that minor process deviations can lead to moderate declines in antioxidant quality**.**

The optimized IDASC_HAD parameters demonstrate strong potential for commercial turmeric drying**,** offering a compelling blend of reduced processing time**,** enhanced curcumin retention**,** and aesthetically superior powder color. However, their effectiveness is tied closely to the tight regulation of processing conditions, particularly due to the sensitivity of curcumin and antioxidant compounds. The process is reproducible under controlled settings and scalable with appropriate engineering modifications and quality assurance systems. Thus, the study not only proposes a high-performing method but also underscores the importance of precision, automation, and real-time monitoring in deploying this technique at the industrial level.

4.2.11 Scanning Electron Micrograph (SEM)

As reported in the previous section, Fig. 5(a) and 5(b) show the micro-structures of turmeric powder produced by CBWC-HAD and IDASC+HAD method.

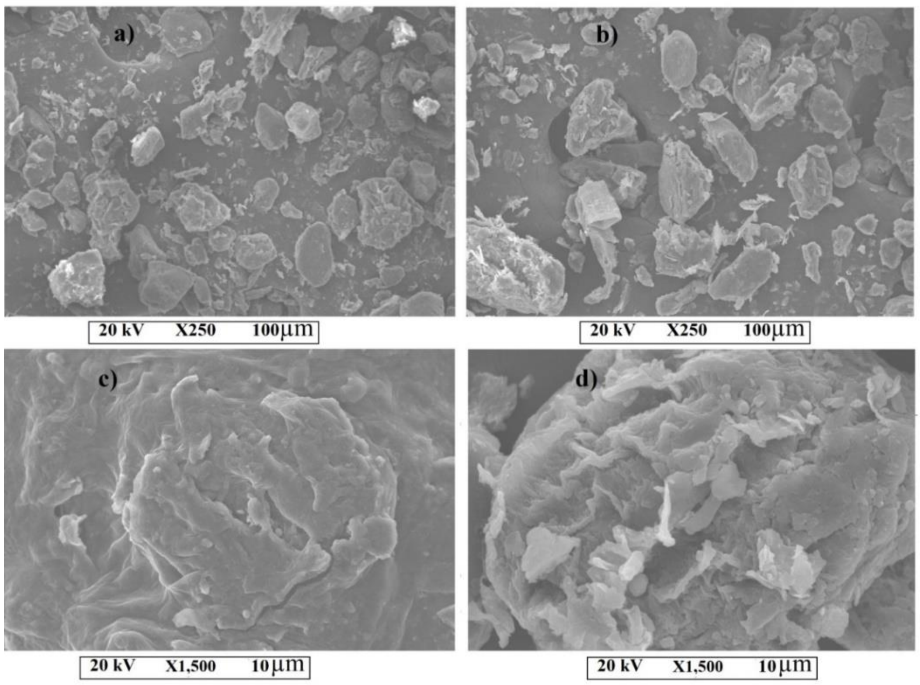


Fig 4.8 Micro-structures of i) turmeric powder, produced by (a) CBWC-HAD and (b) IDASC-HAD methods; and ii) turmeric slices, obtained after (c) CBWC-HAD treatment and (d). IDASC-HAD treatments.

In case of IDASC+HAD based turmeric powder expanded granular structure can be observed. This is due to the reason that ICPD induced instant pressure release towards vacuum tank helps to swell and expand the ultimate granular structure of the dried turmeric powder. The average size of the particles as analyzed from the SEM images, were observed to be 0.16 and 0.24 mm respectively for CBWC-HAD and IDASC+HAD based turmeric powder. The results, demonstrated in Fig. 4(f) also showed similar trends for the average particle size (APS) of the turmeric powder. From Fig. 5(c) and 5(d) similar expanded structure can be observed for the IDASC+HAD based turmeric slices as compared to CBWC-HAD. Hence, IDASC treated turmeric slices face hot air drying conditions with higher specific surface area. As a result, for the IDASC+HAD based samples drying can be accomplished within a shorter period as compared to conventional hot air drying process. Therefore, minimization of drying time in case of IDASC+HAD based samples helps to retain higher quality properties in the final turmeric powder as compared to CBWC-HAD method. Findings related to modification of micro-structure during ICPD treatment is reported in Gautam et al., (2021).

4.2.12 Curcumin Content of Turmeric in Respect to Time and Pressure

The turmeric content was estimated at laboratory scale and the integration of ICPD technology. In the observation of study researcher found that when pressure slowly increased curcumin content increase significantly. After pressure is 0.4 MPa showed the reduction of curcumin content. Furthermore, study with the respect to time slowly increased curcumin content up to 60 minutes (Mudge et al., 2016). After completion of time degradation stated with respect to time (Fig 4.9). The highest curcumin content found 4.8% at the pressure near to 0.4 MPa.(Fig 4.10).

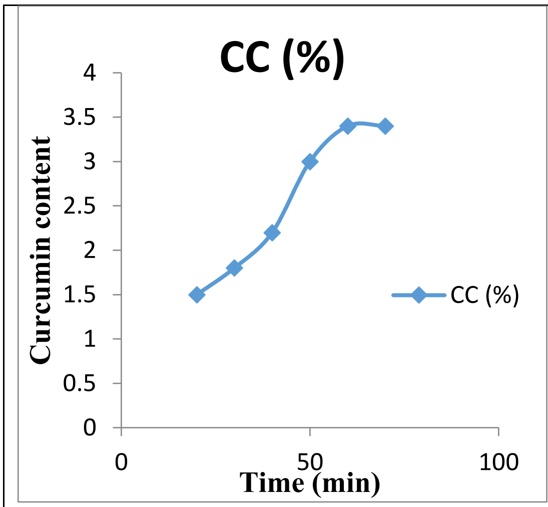


Fig 4.9 Curcumin content with respect to time

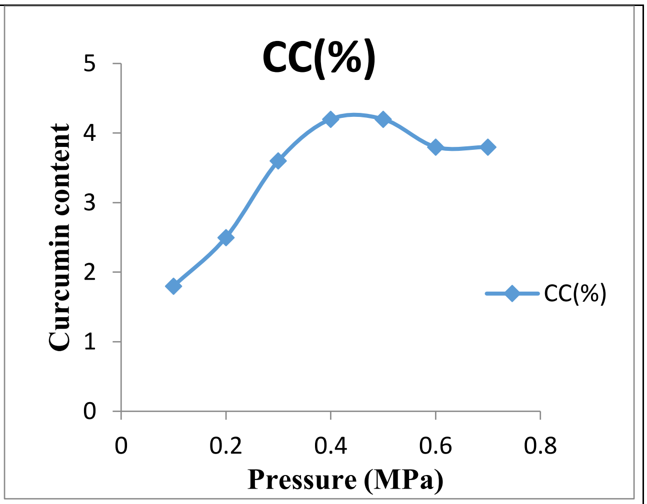


Fig. 4.10 Curcumin content with respect to pressure

After completion of time degradation stated with respect to time. The highest curcumin content is found as 4.8% at the pressure near to 0.4 MPa.

The graphs in Fig 4.9 and 4.10 illustrate the variation of curcumin content (CC%) with two different parameters: time and pressure. The left graph (Fig 4.9) shows how curcumin content changes over time, while the right graph (Fig 4.10) depicts the effect of pressure on curcumin content. In the first graph, curcumin content steadily increases with time, starting at a low value and gradually rising as the reaction progresses. This trend suggests that the curcumin extraction or synthesis process is time-dependent, reaching a plateau around 60 minutes. Beyond this point, the curcumin content stabilizes, indicating the completion of the process or the saturation of curcumin availability in the system. The second graph demonstrates the relationship between curcumin content and pressure. As pressure increases from 0 to 0.4 MPa, curcumin content rises significantly, peaking around 0.4 MPa. However, beyond this optimal pressure, the curcumin content begins to decline slightly, suggesting that excessively high pressures may hinder the process, possibly due to structural changes, equipment limitations.

The integration of instant controlled pressure drop technology into turmeric (*Curcuma longa*) processing represents a significant leap forward in overcoming the inherent limitations of traditional drying and extraction methods. While benefits such as reduced drying time, energy efficiency, and improved product quality are often highlighted, a deeper technical justification lies in understanding the biological and chemical nature of turmeric, particularly the poor bioavailability of curcumin, its principal active compound.

Curcumin, though pharmacologically potent, suffers from low water solubility, rapid metabolism, and degradation under high heat. Traditional drying methods such as sun-drying or hot air drying subject turmeric to prolonged exposure to elevated temperatures, leading to the degradation of curcuminoids and volatile compounds. Furthermore, these methods often result in a dense, compact structure that limits the release and absorption of curcumin during digestion or extraction.

IDASC offers a novel physical mechanism that directly addresses these challenges. The process involves subjecting turmeric to short bursts of high-pressure steam, followed by a sudden vacuum-induced pressure drop. This rapid expansion causes instant autovaporization of internal moisture, leading to the formation of a porous microstructure. This transformation significantly enhances the surface area and internal permeability of turmeric particles, making curcumin more accessible for both solvent extraction and gastrointestinal absorption.

Moreover, the brief thermal exposure in IDASC minimizes the degradation of heat-sensitive bioactive compounds, thus preserving the phytochemical integrity of turmeric. The resulting product retains higher levels of curcumin and essential oils, offering superior functional quality compared to conventionally processed turmeric.

From a scientific and technological standpoint, IDASC provides a multifaceted solution: it not only improves processing efficiency and product quality but also tackles the biochemical limitation of curcumin bioavailability through structural modification at the cellular level. This positions IDASC as a compelling, technically justified innovation in turmeric processing, with promising implications for the nutraceutical, pharmaceutical, and functional food industries.

4.3 Objective II: To Standardize the Processing Condition of IDASC Parameters for Improved Quality of Turmeric Powder

The present study evaluates the efficacy of Instant Decompression Assisted Steam Curing (IDASC) coupled with Refractance Window Drying (RWD) at three different temperatures 70°C, 80°C, and 90°C to optimize the drying process and retain the quality attributes of the treated materials. This dual approach is novel, combining the rapid heating and sterilization effects of IDASC with the low-temperature, efficient water removal capability of RWD. The discussion focuses on the effects of processing temperature on drying efficiency, quality retention, and potential industrial applicability.

The IDASC-RWD combination demonstrated significant drying efficiency, reducing the total processing time compared to conventional drying methods. However, it is critical to balance drying efficiency with quality retention, as elevated temperatures can compromise sensitive nutritional and structural attributes of the material.

4.3.1 Variation of Moisture Profile During RW Drying of ICPD treated slices

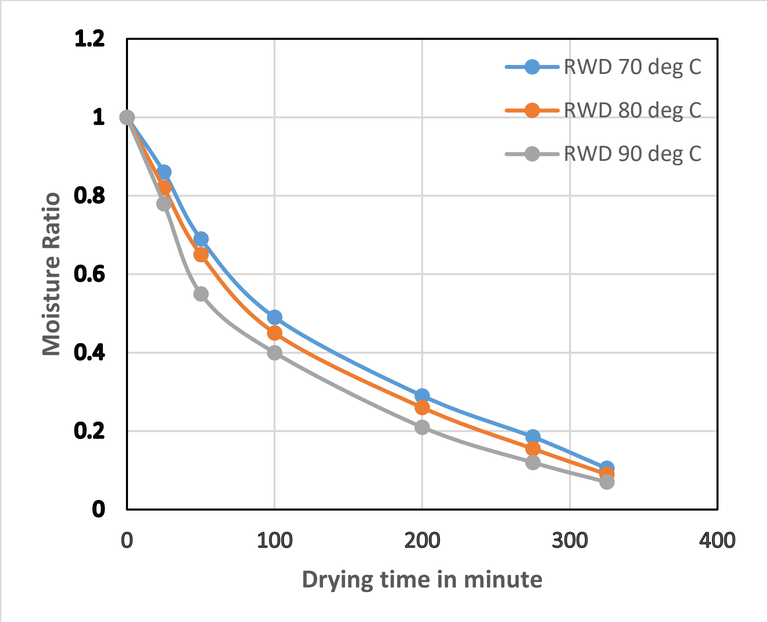


Fig. 4.11 Moisture ratio of turmeric slices using instant controlled pressure drop technology assisted with Reactance window drying

As the temperature increased from 70^0C to 90^0C, the temperature, drying rate improved due to enhanced moisture evaporation. At 90^0C, drying process achieved shortages time, owning to the increased heat transfer and vapour pressure differential (Fig 4.11)

In a small-scale turmeric processing facility where the goal is to produce high-quality turmeric slices, rich in color, flavor, and nutritional value. The facility adopts a novel approach using Instant Controlled Pressure Drop (ICPD) technology as the initial drying stage, followed by Refractance Window (RW) drying, to ensure the optimal balance of speed, energy efficiency, and quality retention.

Initial Drying: High Moisture Content and Rapid Reduction

The turmeric slices have a high moisture content at the beginning of the drying process, ranging from 75% to 80%. The graph representing the moisture ratio of these slices begins with a steep slope, indicating a rapid decrease in moisture. This sharp decline is due to the ICPD technology pre-treatment. When high-pressure steam is introduced to the turmeric slices, the steam quickly permeates and heats the cells. The instant decompression that follows causes the cell walls to break down and create micro-channels. This disruption facilitates an accelerated movement of water from inside the cells to the surface, where it can evaporate quickly. The moisture ratio plummets as the first significant amounts of water are removed in just a short span of time. Because it establishes the framework for the remainder of the drying process, this first step is essential. Rapid moisture removal keeps the turmeric from scorching, which could destroy its delicate curcumin content, which is highly prized for its health advantages, as well as its vivid yellow color.

The Middle Phase: Gradual Moisture Reduction with Refractance Window Drying

As the drying process progresses, the moisture ratio continues to decrease but at a slower pace. This is when the Refractance Window (RW) drying system steps in. The RW drying system uses a heated water film as its heat transfer medium, creating a window of radiant heat that gently dries the surface of the turmeric slices. The combination of ICPD pre-treatment and RW drying ensures that the drying process remains controlled and efficient.

In this phase, the moisture gradient between the turmeric interior and its surface starts to decrease, making it more challenging for moisture to move out. However, the RW system maintains a consistent, low-temperature environment that allows the remaining water to evaporate at a steady rate without compromising the integrity of the product. The gentle heat from the RW system minimizes the risk of thermal degradation, allowing curcumin and essential oils to be preserved effectively. The color of the turmeric slices stays bright, their aroma remains potent, and their texture remains desirable for culinary use.

The Final Phase: Approach to Equilibrium and Low Moisture Content

Eventually, the graph flattens out, showing that the moisture ratio of the turmeric slices is approaching equilibrium (Abdulkadir, 2012). This final stage is when the remaining water is bound tightly within the cellular structure, requiring more energy and time to remove. Table 4.5 of drying kinetics of turmeric slices of RW system is designed to handle this stage delicately, maintaining low, consistent heat to extract moisture while preserving the turmeric quality.

By now, the slices have reached a moisture level ideal for long-term storage and optimal shelf-life. The retained color, aroma, and nutritional content of the turmeric slices indicate the success of combining ICPD technology with RW drying.

Table 4.5: Drying kinetics of turmeric slices

Model	Parameter(s)	Values at Different Drying Temperatures			Statistic at Different Drying Temperatures			
		70⁰	**80⁰**	**90⁰**		**70⁰**	**80⁰**	**90⁰**
Newton	k	0.00664	0.00748	0.00919	SSE	0.00285	0.00411	0.01146
					R^2	0.996	0.994	0.984
					RMSE	0.02178	0.02618	0.0437
Handerson Pabis	a	0.9929	0.9793	0.9644	SSE	0.00965	0.00342	0.01117
	k	0.00657	0.00726	0.00887	R^2	0.986	0.995	0.985
					RMSE	0.04393	0.02613	0.04726
Page	k	0.00851	0.01214	0.02035	SSE	0.00223	0.00153	0.00363
	n	0.9503	0.9007	0.8298	R^2	0.997	0.998	0.995
					RMSE	0.02113	0.0175	0.02696
Logarithmic	a	0.9635	0.9387	0.9153	SSE	0.00241	0.00225	0.00547
	k	0.00721	0.00844	0.01103	R^2	0.997	0.997	0.993
	c	0.03706	0.05434	0.07412	RMSE	0.02453	0.02374	0.36990
Modified Page	a	1.007	1.004	1.005	SSE	0.00219	0.00152	0.00361
	k	0.00900	0.0125	0.02099	R^2	0.9969	0.9979	0.9951
	n	0.9407	0.8958	0.8246	RMSE	0.02337	0.01947	0.03002
Midilli	a	1.008	1.005	1.006	SSE	0.00214	0.00143	0.00358
	k	0.00986	0.01405	0.02226	R^2	0.997	0.998	0.995
	b	-5.57×10^{-05}	-6.95×10^{-05}	-3.37×10^{-05}	RMSE	0.02671	0.02186	0.03453
	n	0.9163	0.8642	0.8084				

The moisture diffusivity during the drying of turmeric slices by both the methods are compared in the table 4.6

Table 4.6 Moisture Diffusivity of turmeric slices of different technologies

Treatment	**Diffusivity Coefficient** (m^2/s)	
IDASC treatment	1.80×10^{-10}	
Refractance window dried	Temp	
	70°C	2.47×10^{-9}
	80°C	5.8×10^{-9}
	90°C	8.61×10^{-9}

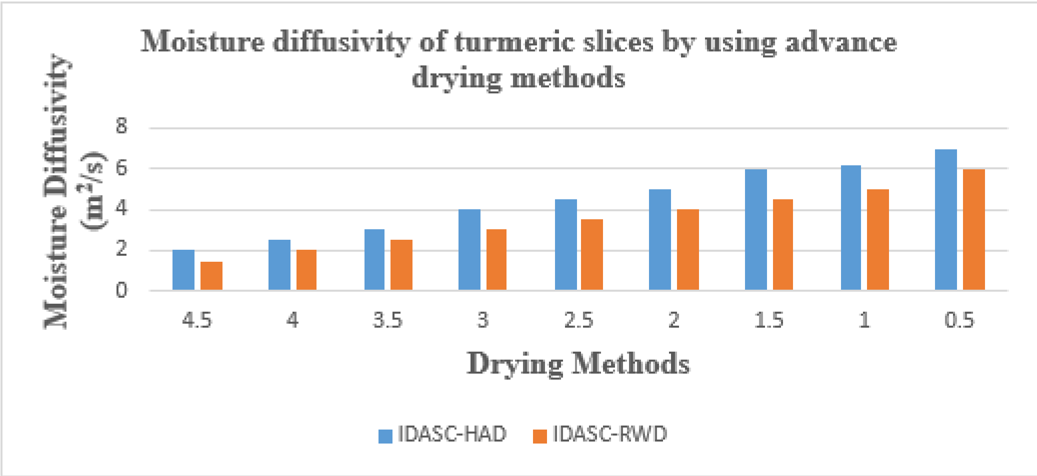


Fig. 4.12 Moisture diffusivity of turmeric slices by using advance drying methods

4.3.2 Rehydration Ratio

The dried turmeric product's RR is a crucial quality indicator; a higher value denotes higher quality. The rehydration values for dried turmeric are shown in (Fig. 4.13). At 4.5±0.29, the ICPD-RWD drying method showed the highest rehydration ratio. The ICPD-HAD, hot air dried, and commercial methods came in second and third, with respective values of 3.8±0.21, 3.6±0.19, 3.3±0.33, and 3.2±0.34. According to earlier research on turmeric by Saha et al., (2022), the sample with the highest rehydration ratio of 4.5 was discovered in the ICPD-RWD system because integrated ICPD drying technology creates a controlled environment with ideal temperature, humidity, and airflow, which raises the rehydration ratio (Bordoloi & Hazarika 2024).

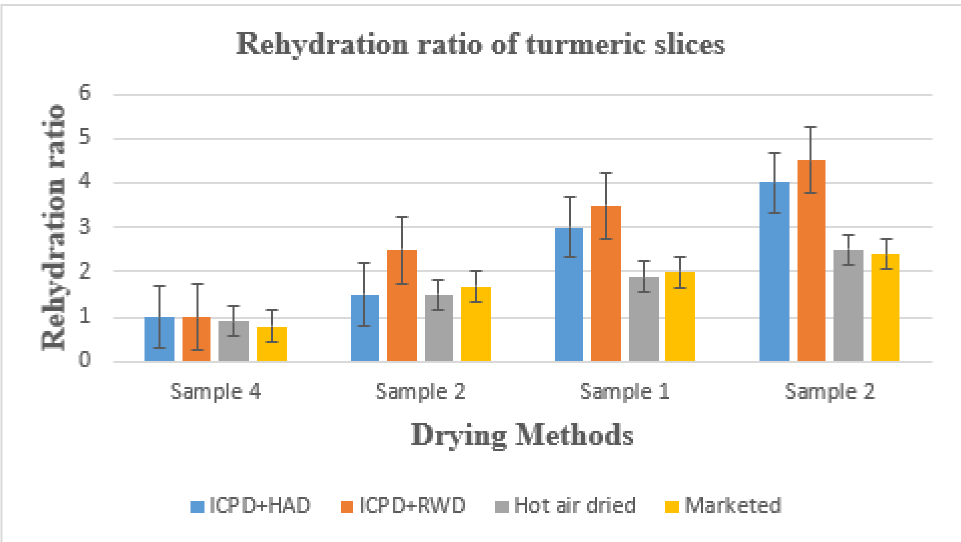


Fig. 4.13 Rehydration ratio of turmeric slices by using different methods

CPD + RWD:

- Typically has the highest rehydration ratio, particularly in Samples 2.
- Indicates this method preserves structural integrity, allowing turmeric slices to regain water more effectively.

ICPD + HAD:

- Shows good rehydration ratios, often sample 1 to ICPD + RWD.
- Combines the benefits of Instant Controlled Pressure-Drop (ICPD) with conventional hot air drying for better performance than hot air drying alone.

Hot Air Drying (HAD):

- Exhibits lower rehydration ratios than the ICPD-assisted methods, suggesting structural damage during the drying process reduces water absorption capacity.

Marketed Samples:

- Generally, show the lowest rehydration ratios, reflecting potentially harsher drying methods or longer storage durations affecting the product's rehydration potential.

Rehydration ratio as a quality indicator:

- The ability of turmeric slices to rehydrate is directly related to their structural preservation during drying. Higher ratios indicate minimal cellular damage, important for maintaining texture and quality.

Comparison of methods:

- ICPD-assisted methods (ICPD + HAD, ICPD + RWD) outperform traditional methods and marketed samples, demonstrating the efficacy of these advanced drying techniques in preserving product quality.
- The ICPD + RWD method is particularly noteworthy, possibly due to the gentle heating provided by refractance window drying.

Applications:

These findings can guide industrial drying practices for turmeric and other agricultural products, favoring methods that ensure high quality and consumer satisfaction.

4.3.3 Shrinkage Value

The ICPD-RWD drying method showed the highest shrinkage percentage of all the drying methods for sample 2, with the value of 60±3.2 percent (Fig 4.14). It was followed by ICPD-HAD at 40±2.5 percent, hot air drying at 30±2.8 percent, and commercialized at 29±2.0 percent. This demonstrates that ICPD-RWD has a better capacity to optimize shrinkage than the other techniques, which makes it a good option for maintaining the integrity of the dried product (Bordoloi & Hazarika, 2024). Furthermore, analysis of variance revealed significant differences ($p < 0.05$) between the variables of various drying techniques showed significant differences.

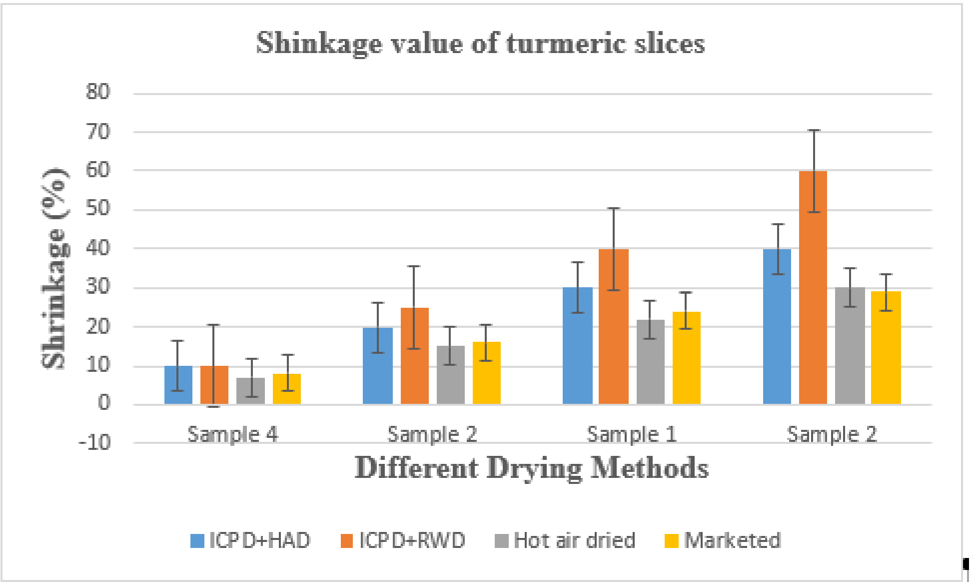


Fig. 4.14 Shrinkage ratio of ginger slices for different drying methods,

ICPD + HAD:

- Shrinkage ranges from approximately 20% to 70% across the samples.
- The highest shrinkage is observed in Sample 1 and Sample 2, suggesting that the ICPD process combined with hot air drying results in significant structural changes in these cases.

ICPD + RWD:

- Shrinkage values range from 15% to 60%.
- Lower shrinkage compared to ICPD + HAD, particularly in Sample 2, indicating that refractance window drying minimizes structural damage while drying turmeric slices.

Hot Air Drying (HAD):

- Shrinkage values are generally around 10% to 40%.
- Consistently lower shrinkage compared to ICPD-assisted methods, but possibly at the expense of rehydration capacity and quality.

Marketed Samples:

- Shrinkage values are relatively consistent at approximately 10% to 30%.
- This indicates moderate drying and processing conditions, but potentially reduced quality compared to ICPD-assisted methods.

Correlation with Quality:

- Higher shrinkage typically indicates greater structural damage during drying, potentially impacting texture and consumer acceptability.
- ICPD + RWD appears to offer a balance between efficient drying and lower shrinkage, preserving quality.

Comparison of Methods:

- ICPD + HAD results in the highest shrinkage values, suggesting intensive drying conditions that may compromise product structure.
- ICPD + RWD reduces shrinkage, indicating its suitability for retaining structural integrity.
- Hot air drying and marketed samples show lower shrinkage but might have other drawbacks (e.g., less effective drying or lower rehydration capacity).

4.3.4 Texture Evolution of the IDASC Processed Product

Figure 4.15 shows the crushing strength of dried turmeric using each drying method. differing drying techniques resulted in differing peak force values for the textural attribute of dried ginger, particularly its hardness. In line with earlier research, the ICPD-RW drying method yielded the lowest peak force at 20±2.4 g, followed by RWD at 28±3.3 g, HA at 30±1.7 g, ICPD-HAD at 10±2.7 g, and Marketed at 40.61±3.0 g. This method guarantees that turmeric slices are thoroughly dried, allowing fibrous bonds within the structure to break easily (Nair, 2019). As a result, less power is needed to smash the slices because they are more fragile. The observed decrease in crushing force demonstrates how well ICPD-RW produces turmeric slices with a superior texture that appeals to both food processors and consumers.

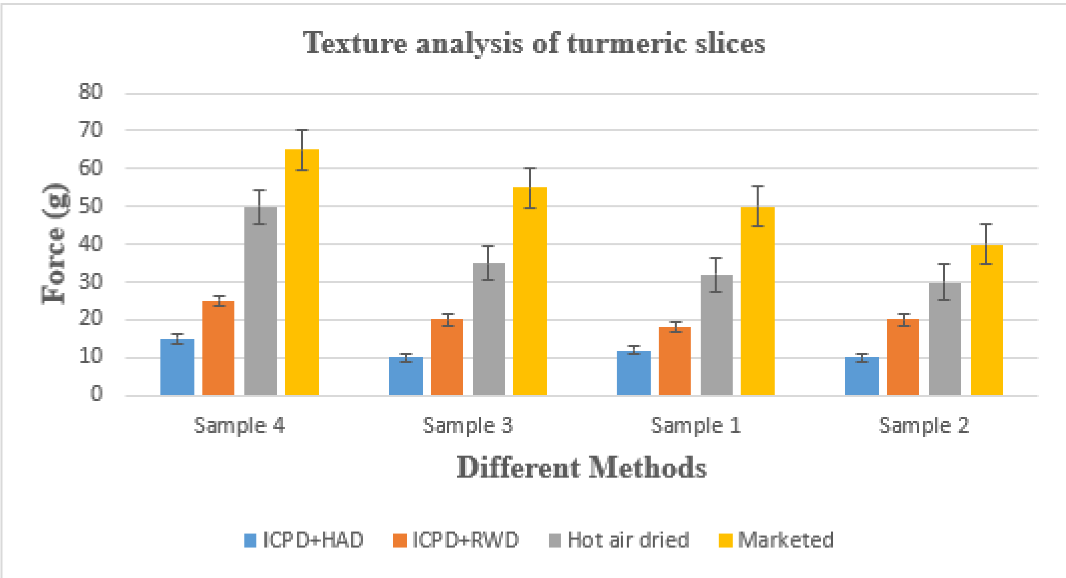


Fig. 4.15 Hardness of turmeric slices for different drying methods

ICPD + HAD:

- Force ranges from approximately 10 g to 30 g across all samples.
- Indicates a softer texture compared to other methods, possibly due to the structural effects of the drying process.

ICPD + RWD:

- Force ranges from 15 g to 35 g, slightly firmer than ICPD + HAD.
- Reflects better structural retention compared to hot air drying alone but not as firm as marketed samples.

Hot Air Drying (HAD):

- Force ranges from 20 g to 50 g, with moderate firmness.
- Indicates that traditional drying methods lead to moderately firm textures, likely due to higher moisture loss and structural changes.

Marketed Samples:

- Force values range from 50 g to 70 g, the highest among all methods.
- Demonstrates that marketed turmeric slices are the firmest, possibly due to additional processing or storage conditions.

Texture as a Quality Indicator:

- Texture, measured by force, reflects the structural integrity and consumer acceptability of dried turmeric slices.
- Firmer textures are preferred for certain culinary or processing applications.

Comparison of Methods:

- ICPD-assisted methods (ICPD + HAD, ICPD + RWD) produce softer textures, potentially making them suitable for applications where tenderness is desirable.
- Hot air drying achieves moderate firmness, but marketed samples show the firmest textures, possibly due to lower moisture content or additional drying processes.

Applications

- Include numerical values in the analysis:
- For instance, in Sample 4, marketed slices required the highest force (~65 g), while ICPD + HAD required the lowest (~15 g).

- Discuss the implications of softer versus firmer textures in terms of usability and consumer preferences

4.3.5 Total Tannin Content

Other significant water-soluble secondary metabolites of plants are tannins, which have been shown to possess antibacterial, antioxidant, and astringent properties (Anyaoku et al., 2023). According to a TTC investigation, the turmeric cultivars under study are excellent producers of tannins. In general, the TTC was higher in the chora variety from the Khulna and divisions than in the mura variety. The marketed sample had a lower TTC than the turmeric variant, whereas ICPD-RWD had a much greater TTC than the hot air dried of the four ethanolic extracts. The geographical differences between the Tezpur and Dolabari divisions were reflected in the notable differences in TTC across the turmeric types under study.

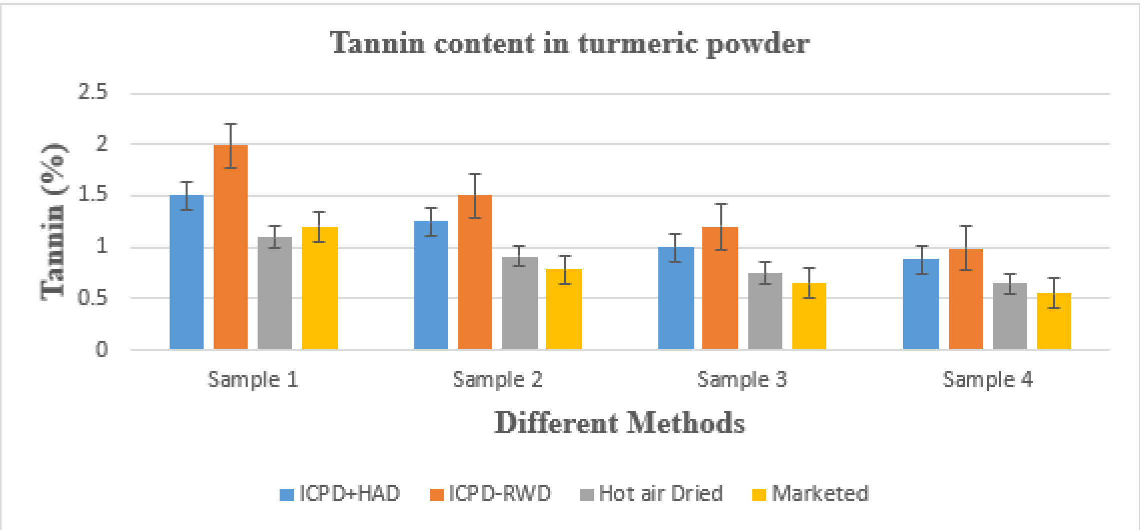


Fig. 4.16 Tannin content in turmeric powder prepared by different methods

Discuss any significant differences observed in tannin content between the samples, which might indicate the effect of different drying methods or storage conditions.

- Sample 1 (ICPD + HAD) might show a moderate level of tannins compared to hot air-dried turmeric, which may be expected if ICPD + HAD uses lower temperatures or faster drying methods that are gentler on the compounds.
- If Sample 3 (hot air drying, for example) shows lower tannin content, this could suggest that the rapid drying process may cause the decomposition of tannins more quickly than slower, traditional drying methods.
- For instance, ICPD + RWD might be the most effective method for preserving tannin content, while hot air drying could result in significant loss of tannins.

4.3.6 X-Ray Diffraction (XRD)

The XRD analysis identified distinct peak angles for various drying techniques: refractance window drying (RWD) combined with ICPD and integrated Instant Controlled Pressure Drop-Hot Air Drying (ICPD-HAD) revealed peaks at 55.68°, 58.65°, and 60.60°(Fig 4.17) indicating significant amorphous crystallinity, as similar findings were reported in Hmar et al., (2017). Conventional hot air drying, on the other hand, had smaller angles 18.57° and 37.57°, respectively. In contrast to the more conventional techniques of convention and hot air drying, the higher angles in ICPD and RWD imply a distinct structure that is probably the result of regulated drying circumstances. Changes in the protein structural composition can be reflected in the peak's intensity.

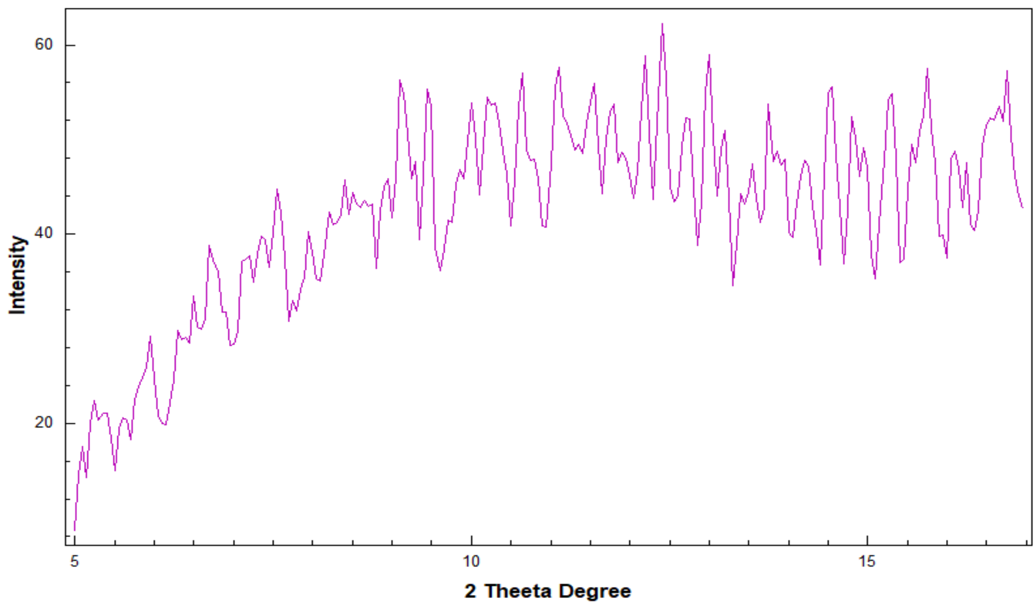


Fig. 4.17 The XRD pattern of turmeric IDASC-RWD Powder for different drying methods.

X-ray diffraction (XRD) analysis provides insight into the crystalline and amorphous nature of turmeric powder produced using various drying methods. The XRD pattern is influenced by the drying technique as it affects the physical structure, crystalline content, and phase stability of curcumin, the primary bioactive compound in turmeric. The relative crystallinity index (RCI) derived from the XRD pattern shows that freeze drying yields the highest crystallinity due to minimal thermal stress (Kumari et al., 2023). Oven and vacuum drying methods rank intermediate in preserving crystallinity, with sun drying resulting in the lowest RCI due to prolonged exposure to environmental factors. refractance window drying, while fast, may show variable results depending on drying settings.

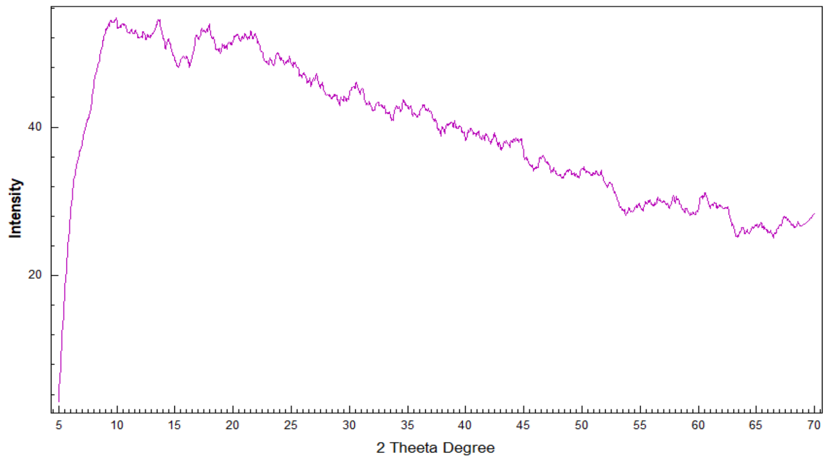


Fig. 4.18 The XRD pattern of turmeric IDASC-HAD Powder for different drying methods.

The X-ray diffraction (XRD) analysis of turmeric powder provides critical information about its crystalline structure, primarily focusing on the presence and stability of bioactive compounds like curcumin. The drying method significantly influences the structural and compositional properties of turmeric powder, including the crystallinity and amorphous phases.

The relative crystallinity index (RCI) calculated from the XRD patterns shows significant differences:

- Highest Crystallinity: Freeze drying (due to minimal structural damage).
- Intermediate Crystallinity: Vacuum drying and oven drying (controlled conditions).
- Lowest Crystallinity: Sun drying and some microwave drying (due to thermal and environmental stress).

Higher crystallinity correlates with better bioactive stability, while amorphization may enhance solubility in certain applications.

The XRD patterns of turmeric (IDASC-HAD) (Fig 4.19) powder highlight significant differences in crystalline structure and amorphous content across drying methods. Freeze drying preserves the structural integrity of curcumin most effectively, while sun and microwave drying result in partial or significant loss of crystallinity. These findings underscore the importance of selecting a drying method based on the intended application and desired balance between stability and functionality (McCall *et al* 2005).

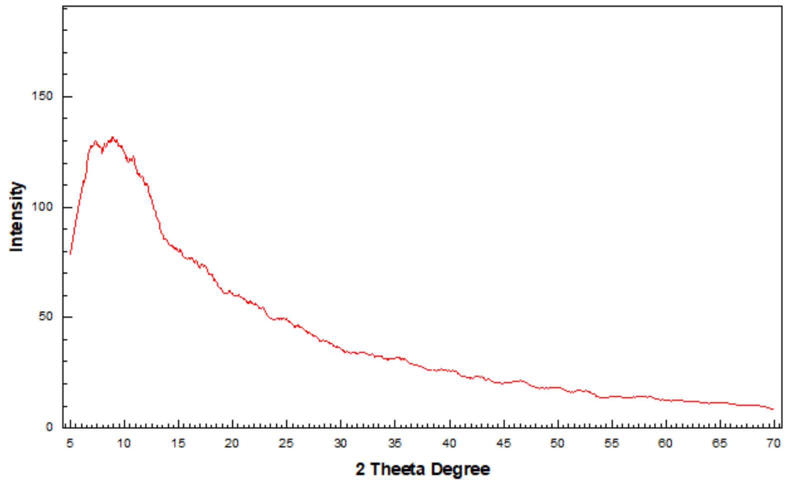


Fig. 4.19 The X-ray diffraction pattern of turmeric powder convention for different drying methods.

The X-ray diffraction (XRD) analysis of turmeric powder reveals critical insights into the structural and phase changes induced by various drying methods. The drying process significantly influences the crystalline and amorphous content of turmeric powder, primarily affecting the structural stability of curcumin (the primary bioactive compound) and associated matrix components like starch and polysaccharides. This discussion addresses the conventional and interpretation of XRD patterns for turmeric powder dried using different methods.

Peak Identification:

- Turmeric powder typically displays distinct peaks in its XRD pattern corresponding to the crystalline nature of curcumin, the dominant component.

- Minor peaks may represent contributions from other crystalline constituents like essential oils, polysaccharides, and starch granules.

Crystalline and Amorphous Features:

- Sharp, well-defined peaks indicate crystalline phases.
- Broad humps or diffuse features suggest the presence of amorphous materials.

The overall XRD pattern serves as a fingerprint for determining the structural integrity of turmeric powder, particularly in response to drying methods.

Peak Annotation:

Clearly label significant peaks with corresponding diffraction angles (2θ) and intensities. Identify peaks associated with curcumin and any secondary phases.

The XRD pattern of turmeric powder is a critical analytical tool for understanding the effects of drying methods on its crystalline and amorphous structures. Freeze drying preserves crystallinity most effectively, while sun drying results in the highest amorphization. Vacuum and oven drying provide intermediate results, balancing structural integrity with processing efficiency.

4.3.7. Antioxidant Activity Properties and Analyses by Design Experiment

Response surface methodology was studied on the effect of antioxidant activity due to factors, pressure, time and temperature. The ANNOVA analysis is presented in table 4.7, 4.7 and 4.8

Table 4.7: ANOVA for Response 1 (Anti-oxidant Activity)

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	886.8	12	73.9	**92.375**	0.0003	significant
A-Pressure	144	1	144	180	0.0002	
B-Time	140.3187	1	140.3187	175.3984	0.0002	
C-Temperature	0.175824	1	0.175824	0.21978	0.6636	
AB	81	1	81	101.25	0.0005	
AC	9	1	9	11.25	0.0285	
BC	0	1	0	0	1.0000	
A^2	62.06519	1	62.06519	77.58149	0.0009	
B^2	257.7779	1	257.7779	322.2224	< 0.0001	
C^2	4.385635	1	4.385635	5.482044	0.0793	
ABC	0	0				
A^2B	296.0526	1	296.0526	370.0658	< 0.0001	
A^2C	7.578947	1	7.578947	9.473684	0.0370	
AB^2	18	1	18	22.5	0.0090	
AC^2	0	0				
B^2C	0	0				
BC2	0	0				
A^3	0	0				
B^3	0	0				
C^3	0	0				
Pure Error	3.2	4	0.8			
Cor Total	890	16				

Std. Dev.	0.89	R-Squared	0.9964
Mean	82.00	Adj R-Squared	0.9856
C.V. %	1.09	Pred R-Squared	N/A

The significance of the model for anti-oxidant activity is indicated by its F-value of 92.38. The significance of the model is indicated by its F-value of 92.38. A "Model F-Value" this enormous could only be the result of noise in 0.03% of cases."Prob > F" values below 0.0500 signify the significance of the model terms.

Table 4.8: ANOVA for Response 2 (TPC)

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	24.17802	9	2.686447	24.6412	0.0002	significant
A-Pressure	4.5	1	4.5	41.27586	0.0004	
B-Time	3.031579	1	3.031579	27.8069	0.0012	
C-Temperature	2.105263	1	2.105263	19.31034	0.0032	
AB	2.131579	1	2.131579	19.55172	0.0031	
AC	0.105263	1	0.105263	0.965517	0.3585	
BC	2.25	1	2.25	20.63793	0.0027	
A^2	5.03453	1	5.03453	46.1788	0.0003	
B^2	5.328947	1	5.328947	48.87931	0.0002	
C^2	0.592105	1	0.592105	5.431034	0.0526	
Residual	0.763158	7	0.109023			
Lack of Fit	0.763158	3	0.254386			
Pure Error	0	4	0			
Cor Total	24.94118	16				

Std. Dev.	0.000	R-Squared	1.0000
Mean	12.76	Adj R-Squared	1.0000
C.V. %	0.000	Pred R-Squared	N/A

In the ANOVA for TPC, the p- value less then 0.05 suggests significance of the model and factors (Table 4.8). The other parameters. The significance of the model is indicated by its F-value of 24.64. A "Model F-Value" this enormous could only be the result of noise in 0.01% of cases."

Table 4.9: ANOVA for Response 3 (TFC)

		Sum of		**Mean**	**F**	**p-value**	
	Source	**Squares**	**df**	**Square**	**Value**	**Prob > F**	
	Model	24.18	9	2.69	24.64	0.0002	significant
	A-Pressure	*4.5*	*1*	*4.5*	*41.28*	*0.0004*	
	B-Time	*3.03*	*1*	*3.03*	*27.81*	*0.0012*	
	C-Temperature	*2.11*	*1*	*2.11*	*19.31*	*0.0032*	
	AB	*2.13*	*1*	*2.13*	*19.55*	*0.0031*	
	AC	*0.11*	*1*	*0.11*	*0.97*	*0.3585*	
	BC	*2.25*	*1*	*2.25*	*20.64*	*0.0027*	
	A^2	*5.03*	*1*	*5.03*	*46.18*	*0.0003*	
	B^2	*5.33*	*1*	*5.33*	*48.88*	*0.0002*	
	C^2	*0.59*	*1*	*0.59*	*5.43*	*0.0526*	
	Residual	0.76	7	0.11			
	Lack of Fit	*0.76*	*3*	*0.25*			
	Pure Error	*0*	*4*	*0*			
	Cor Total	24.94	16				

Std. Dev.0.33	0.33	R-Squared	0.9694
Mean	8.06	Adj R-Squared	0.9301
C.V. %	4.10	Pred R-Squared	0.5251
PRESS	11.84	Adeq Precision	20.575

The significance of the model is indicated by its p value (Table 4.9) model reduction may improve your model. The significance of the model is indicated by its F-value of 24.64. A "Model F-Value" this large could only be the result of noise in 0.02% of cases."Prob > F" values below 0.0500 signify the significance of the model terms.

The "Adj R-Squared" of 0.9301 and the "Pred R-Squared" of 0.5251 are not as near as one may often anticipate. This could point to a significant block effect or a potential issue with your data and/or model. Outliers, response transformation, model reduction, and other factors should be taken into account.

$$DPPH = 83.53 + 6.00A - 7.06B - 0.25C + 4.50AB - 1.50AC + 0.000BC + 4.22A^2 -8.25 B^2 - 1.25C^2 + 14.06A^2B + 2.25A^2C -3AB^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

$$TPC = 12.89+0.25A+1.75B +0.37C-0.25AB+0.25AC -0.50BC+0.28A^2 -0.42B^2-0.42C^2-1.50 A^2B+0.38A^2C+AB^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(15)$$

$$TFC= 7.61+0.75A+0.63B+0.53C+0.71AB-0.16AC-0.75BC+1.27A^2-1.13B^2+0.37C^2 \quad \ldots..(16)$$

Plots at Fig. 4.20 show the response surface of antioxidant activity in terms of DPPH for IDASC-RWD samples. Following inferences are of importance.

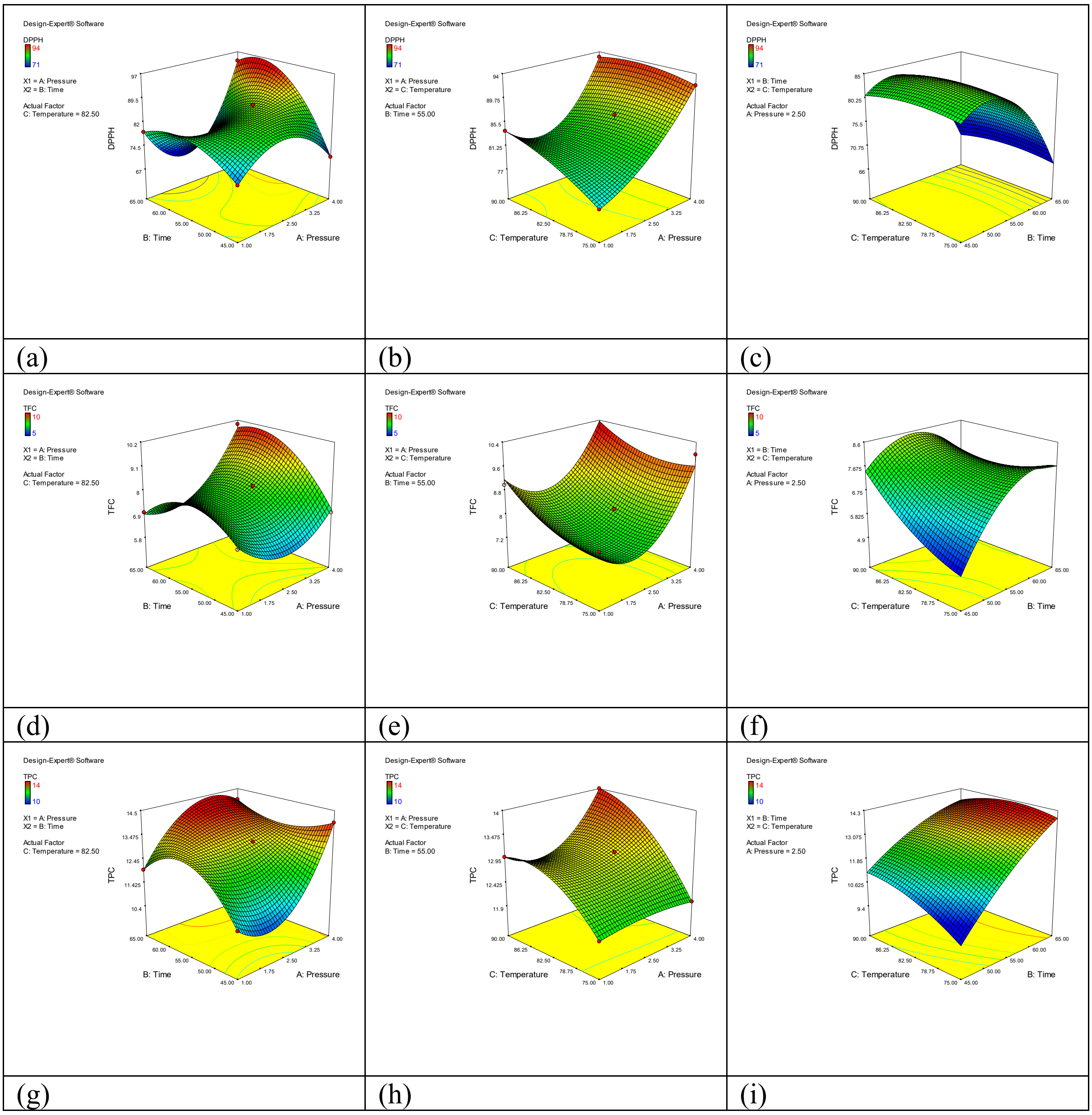


Fig. 4.20 Response surface of IDASC-RWD of Antioxidant activity of parameters.

a. Change of DPPH with respect to Time and Pressure: The color gradient from blue to red indicates increasing DPPH activity: Blue Regions: Lower DPPH activity (around 72-77%).
b. Green Regions: Moderate DPPH activity (around 77-82%). Yellow to Red Regions: Higher DPPH activity (above 86%, with a peak around 91%). The red region in the top right corner indicates the conditions under which the DPPH activity is highest (around 91.8146%). This occurs at higher pressure (close to 4 atm) and higher treatment times (around 65 seconds).
c. Change of DPPH with respect to Temperature and Pressure Similarly, as pressure reaches to 4 atm and temperature around 82 ℃, the maximum DPPH Activity is observed.
d. Change of DPPH with respect to Time and Temperature Time and Temperature interaction shows a lower to moderate DPPH activity. At higher time and intermediate temperature, the DPPH activity is moderate.

e. Change of TPC with respect to Time and Pressure as pressure approaches 3 atm and time above 60 seconds TPC values are highest.
f. Change of TPC with respect to Temperature and Pressure Temperature above 82 ℃ and pressure at 4 atm shows highest TPC.
g. Change of TPC with respect to Time and Temperature Temperature close to 82 ℃ and time above 60 seconds shows a TPC peak at 13.4 %
h. Change of TFC with respect to Time and Pressure Increasing pressure above 3.5 atm and time 60 seconds showed a peak value of 9.33%
i. Change of TFC with respect to Temperature and Pressure The red region is observed at 1 atm pressure and highest temperature of 90 ℃ and also at lower temperature for higher pressure above 3.5 atm.
j. Change of TFC with respect to Time and Temperature Time and Temperature shows lower to moderate TFC increase.

Table 4.10: Optimized Solution

Solution	Pressure	Time	Temperature	DPPH	TPC	TFC	Desirability
1	3.98	63.2	89.46	94.40	14	10	1
2	3.99	63.12	88.85	95.04	14	10	1
3	4.0	62.97	88.06	95.36	14	10	1
4	3.99	63.57	90.0	94.38	14	10	1
5	3.99	63.12	89.24	94.83	14	10	1
6	3.99	63.06	88.48	95.19	14	10	1
7	4.0	63.58	89.87	94.70	14	10	1
8	4.0	63.43	89.25	94.86	14	10	1
9	4.0	63.12	89.17	95.11	14	10	1
10	4.0	63.20	89.16	95.10	14	10	1
11	4.0	55.97	90.0	94.00	13.95	10	0.99
12	4.0	55.9	89.68	94.00	13.95	10	0.99
13	3.99	56.06	90.0	94.00	13.94	10	0.99
14	4.0	63.71	84.97	95.23	14	9.88	0.99
15	4.0	60.45	89.29	96.12	13.90	10.29	0.99
16	4.0	59.46	89.66	95.99	13.89	10.37	0.99
17	4.0	64.28	83.80	94.75	14	9.85	0.99
18	4.0	64.71	83.02	94.32	14	9.84	0.99
19	4.0	64.83	82.80	94.19	14	9.84	0.98
20	3.99	64.85	82.69	94.02	14	9.83	0.98
21	1.0	54.98	90	83.99	13	9.18	0.70
22	1.0	55.28	90	84.06	12.99	9.16	0.70
23	1.0	54.56	90	83.88	12.99	9.21	0.707
24	1.0	55.13	89.62	83.95	13.03	9.10	0.704

The optimal value for pressure, time and temperature are 4.98 MPa, 63.2 s and 89.46^0 for maximum DPPH activity,TPC and TFC content (Table 4.10)

4.3.8 DPPH Activity of cured IDASC Powder

Figure 4.1 shows the DHHP activity of turmeric rhizomes for various combinations of the process parameters. Turmeric's DPPH activity peaked (94.65%) at 80°C, 60 seconds of drying time, and 4 atm, then it decreased (70.64%) at 60°C, 20 seconds of drying time, and 1 atm volume (Long et al., 2022). The DPPH activity was considerably ($p<0.01$) decreased by the increase in drying time and temperature. Although it had little effect, an increase in pressure raised the DPPH activity. Turmeric's substituent group and two benzene rings may decompress at high temperatures and over time, which could lower the rhizome's DPPH activity.

This was in line with the findings of the investigation into the thermal degradation behavior of DPPH activity, which revealed that DPPH activity dramatically decreased as temperature and time increased (C. Chen et al., 2014). The following is the second-order quadratic equation that best fits the DPPH activity of turmeric rhizomes as a function of time, pressure, and DPPH activity (R^2 value = 0.992):

$$DPPH = 83.53+6.00A -7.06B -0.25C +4.50AB-1.50AC+4.22A^2 -8.25B^2- 1.25C^2 +14.06A^2B +2.25A^2C-3.00AB^2 \quad \ldots\ldots\ldots\ldots\ldots(17)$$

Where A is the DPPH activity; B is the time in second and C is the pressure in atm

This is the baseline DPPH activity when all factors A, B, and C are at their reference levels (usually zero if the variables are centered).

This term indicates the effect of factor A on DPPH activity. A positive coefficient means that as A increases, the DPPH activity increases linearly.

This term indicates the effect of factor B on DPPH activity. A negative coefficient means that as BBB increases, the DPPH activity decreases linearly.

This term indicates the effect of factor C on DPPH activity. A negative coefficient means that as C increases, the DPPH activity decreases linearly.

Interaction term

This phrase describes how factors A and B interact. When A and B have a positive coefficient, their combined impact on DPPH activity is larger than the sum of their separate impacts. This phrase describes how factors A and C interact. When A and C have a negative coefficient, their combined impact on DPPH activity is less than the total of their separate impacts. In this model, this term indicates that B and C do not interact to affect DPPH activity. There is no discernible interaction between these two elements, as the coefficient is 0 (Fig 4.20).

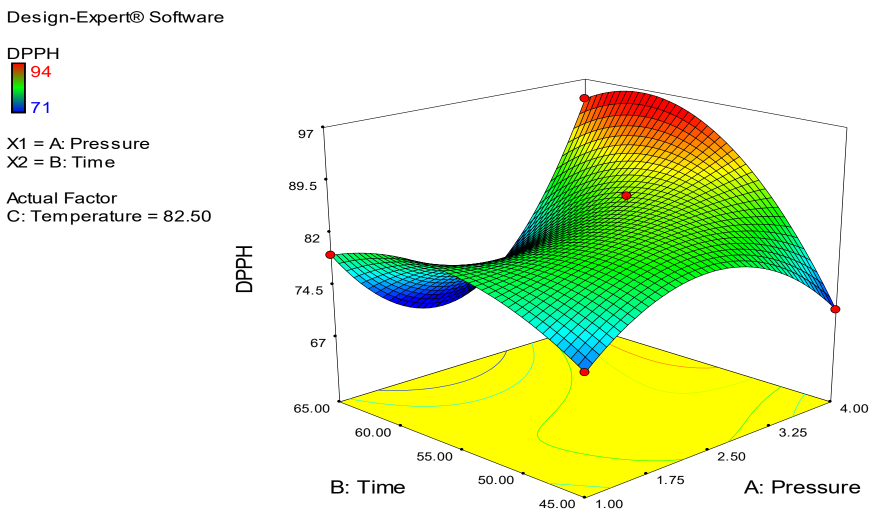


Fig. 4.21 Response surface for the effect of DPPH activity and pressure on the time of treatment.

4.3.9 Total Phenolic Content of IDASC Cured Powder

Figure 4.21 shows the total phenolic content of turmeric rhizomes at various combinations of temperature, time, and pressure. The rates of total phenolic content increased significantly ($p<0.01$) with an increase in pressure, as shown in Figure 4.21. The negative effects of A and B and the beneficial effects of C on moisture content are confirmed by Cubic equation 4.2. Figure 4.2b demonstrated that when temperature and time increased, the TPC content dramatically ($p<0.01$) declined. The moisture content may have decreased as a result of the greater TPC rates brought on by the longer drying time and higher temperatures. This was consistent with the results obtained in a study of IDASC drying of cashew kernels in According to reports, a greater steam temperature increased the sample's heat transfer rate, which in turn dramatically lowered its moisture content. Similar outcomes were noted when pork slices were dried with IDASC steam; the drying time increased with slice thickness due to the thicker slices' higher moisture content (Gautam et al., 2021).

Total phenolic content (TPC) of turmeric rhizomes was empirically correlated (R2 value = 1.00) for the trial conditions as:

$$TPC=12.89+0.25\,A+1.75\,B+0.37\,C-0.25\,A\,B+0.25AC-0.50BC+0.28A^2-0.42B^2-0.42C^2-1.50\,A^2\,B+0.38\,A^2\,C+AB^2 \quad \ldots\ldots\ldots\ldots(18)$$

Where A is pressure in atm, B is the Time and C is the temperature.

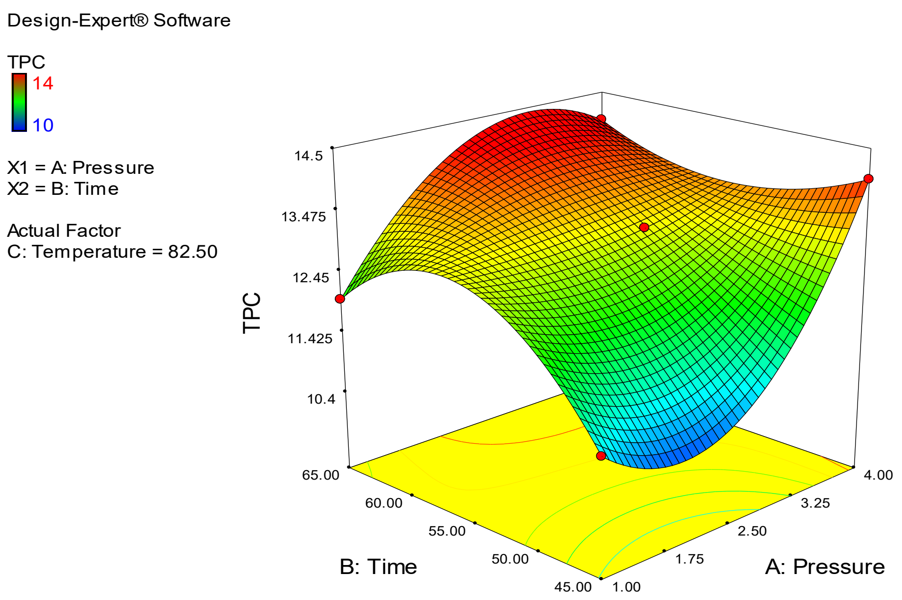


Fig 4.22 Response surface for the effect of Time and total phenolic content at the 4 atm.

4.3.10 Total Flavonoid Content of IDASC Cured powder

Figure 4.22 shows the total flavonoid concentration of turmeric rhizomes for various combinations of process parameters. Turmeric's total flavonoid concentration peaked at 10.2 for 60 seconds and was at least 1 atm at 10 seconds. The content of total flavonoids dropped considerably ($p<0.05$) as time and pressure increased, but not significantly as pressure volume increased. The negative impact of A, B, and C on the total flavonoid content is confirmed by the quadratic equation 19. As the amount of time and pressure increases, flavonoids, which make up the majority of the composition, degrade. This may have reduced the amount of flavonoids in the rhizomes of turmeric. The findings aligned with a microwave-powered drying research of turmeric rhizomes, which found that the essential oil content decreased with increasing power (Hmar et al., 2017).

The best fit second order quadratic equation (R2 = 0.9605) for Total flavonoid content of turmeric rhizomes is as follows:

$$TFC=7.61+0.75A+0.63B+0.53C+0.71AB-0.16AC-0.75BC+1.27A^2-1.13B^2+0.37C^2 \quad .....(19)$$

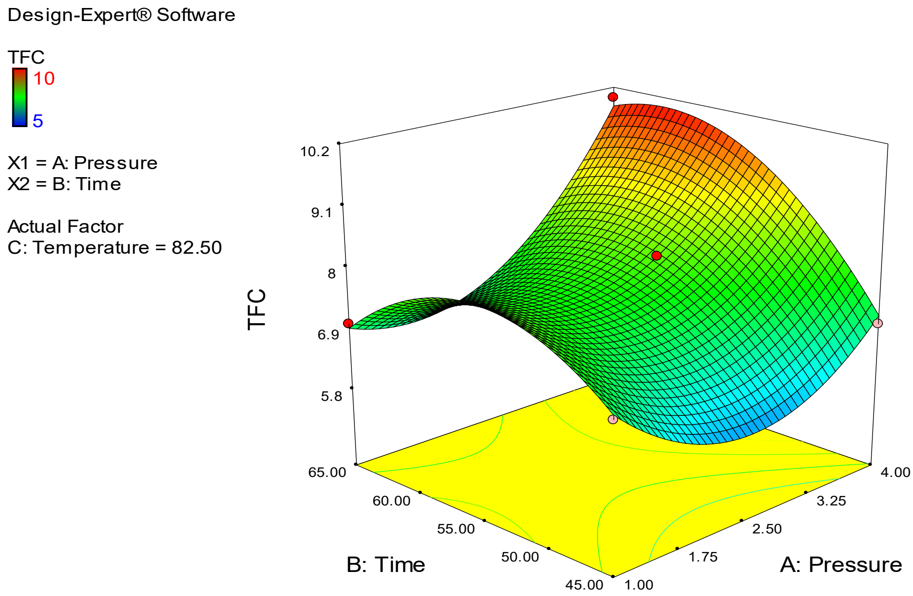


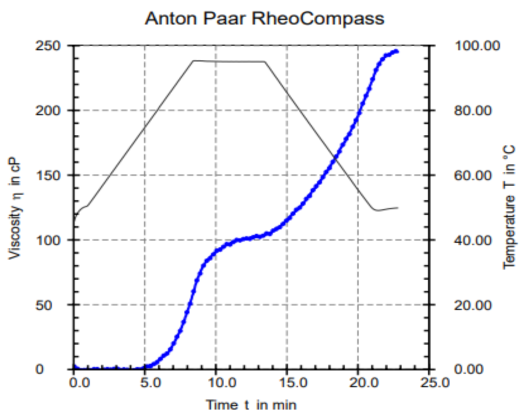
Fig 4.23 Response surface for the effect of pressure and time on total flavonoid content of IDASC treated powder.

A group of statistical and mathematical methods known as Response Surface Methodology (RSM) are used to model and analyze situations in which multiple variables affect a response of interest. It is frequently employed in experimental settings to enhance reactions and optimize procedures. Although this precise acronym is less frequently used in RSM contexts, the IDASC principle frequently refers to an organized approach to experimental design and analysis. Usually, it includes elements like analysis, design, identification, and so forth.

4.3.11. Rheological properties of turmeric powder

As the amount of turmeric powder increased, so did the values in the parameters. As the amount of turmeric powder grew from the pasting temperature - the first deviation of temperature in

RVA where the curve starts to rise rose from 80.3^0 C to 98.2^0 C. The addition of turmeric powder may have raised the pasting temperature because it prevented the crystallites from breaking down, requiring more energy for gelatinization to take place.



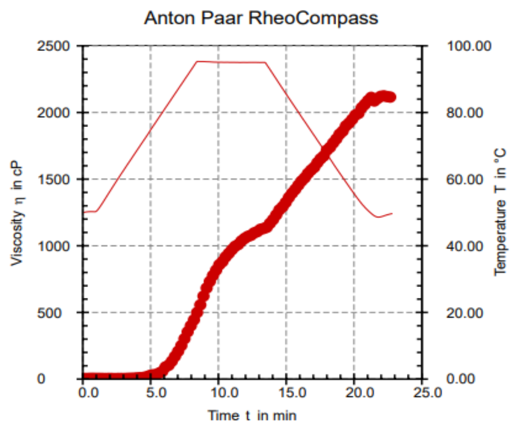


Fig 4.24 IDASC-RWD turmeric powder **Fig 4.25** IDASC-HAD turmeric powder

Fig 4.23 and Fig 4.24 show that the setback value for RWD treated sample were higher compared to HAD powder suggesting more retrogradation.

Reason for the increase in peak viscosity could be that the antioxidant properties of turmeric powder inhibit the oxidative polymerization of cake flour slurry, which results in a lack of polymer cross-links and increased viscosity. The material slurries are exposed to high temperatures and mechanical shear stress throughout the viscosity test holding time, which further breaks up the starch granules in the grains and causes amylase to leach out and align. A breakdown in viscosity is frequently linked to this time frame (Kumari et al., 2023). The degree of swelling of the starch granules during heating is correlated with high peak viscosities, which are linked to high breakdown values.

4.3.12 HPLC Analysis of Chemical Profile

Figure 4.26 shows the chromatograms of curcumin standard and Fig 4.27 shows the chromatograms of turmeric extract of IDASC/RWD. The we calculated concentration found to be slightly less than standard.

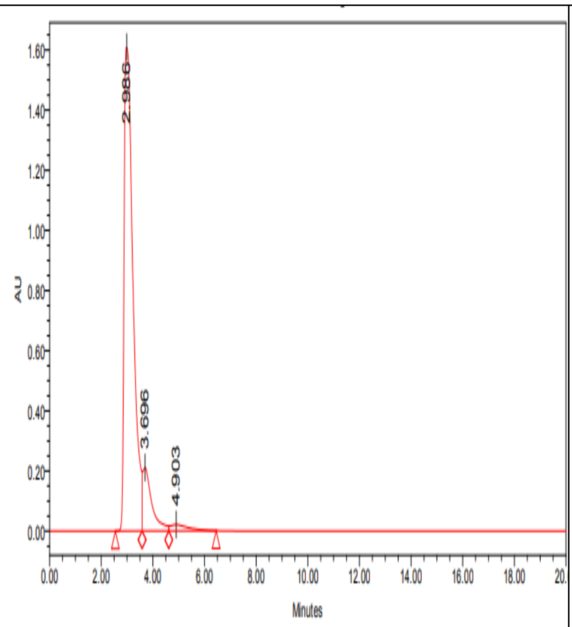


Fig 4.26 Chromatograms of curcumin standard (20 μg mL^{-1})

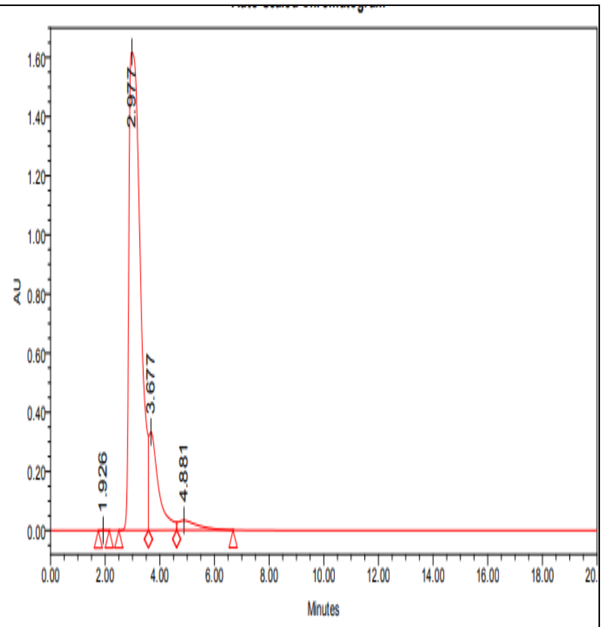


Fig 4.27 Chromatograms of Turmeric extract of IDASC-RWD (20 μg mL^{-1})

4.3.13 Scanning Electron Microscopy (SEM)

The SEM micrographs of the samples (a) IDASC-HAD and (b) IDASC-RWD are shown in Figure [Fig 4.28 and Fig 4.29]. Microstructural properties have influence on the quality both chemically by facilitating the contact of substrates and the accessibilities of air required for chemical conversion and physically by changing the capabilities of turmeric slices. IDASC-HAD observation was more rigid and compact the cell wall and IDASC-RWD have more soften and open up cell wall and have showed starch granules in high Crystallinity. The images, taken at 500X magnification, reveal notable differences in the surface morphology and structure of the two materials:

HAD

The surface shows a relatively smooth and porous structure with interconnected pores. The pore walls appear to be uniform, indicating a homogenous material structure.

IDASC

The surface morphology is more complex and features irregular textures with additional particulate formations. The particles attached to the surface suggest possible modifications due to a different treatment or process, which may have enhanced surface roughness and heterogeneity.

The observed differences between HAD and IDASC can influence their properties, such as mechanical strength, adsorption capacity, or other performance metrics, depending on the application.

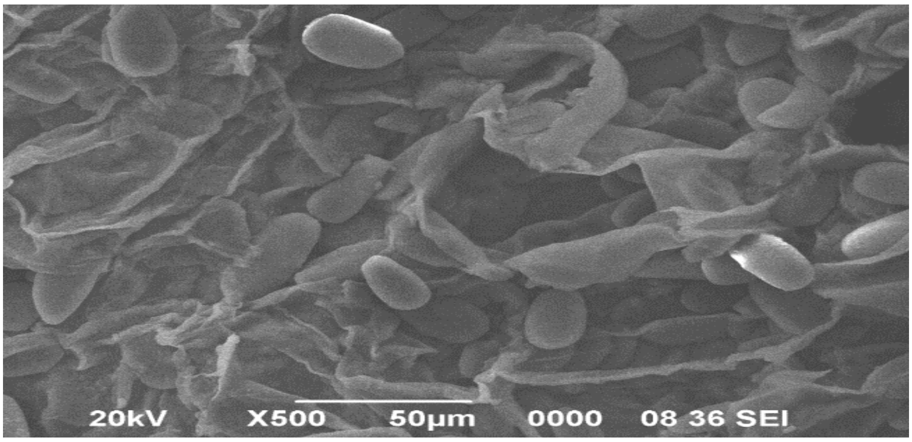


Fig 4.28 IDASC-RW dried microstructure of turmeric

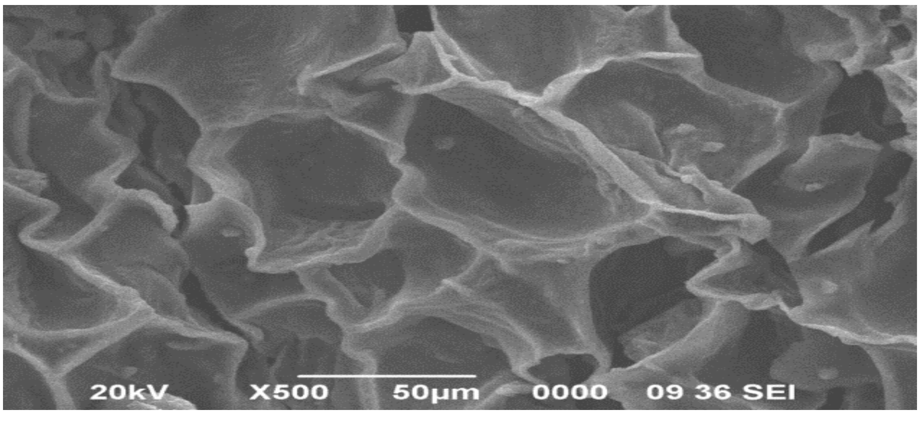


Fig 4.29 HA dried microstructure of turmeric

4.4 Objective-III: To Evaluate a Curcumin Enriched Infusion Drink Based on Turmeric Powder Obtained by Incorporation of IDASC Treatment

Fig. 4.30 Turmeric infusion drink prepared by different combination ICPD-HAD (S1), ICPD-RWD (S2), HAD (S3), Marketed (S4) samples added odd flavor masking as lemon, honey, vanilla and palm candy

4.4.1 Color Properties

Different color characteristics, such as L*, a*, and b*, are used as shown in Table 4.11 to evaluate the efficacy of different drying techniques on fresh turmeric, including, ICPD-HAD drying, tray drying (TD), ICPD-RWD dryer, hot air drying, and fresh turmeric (FG) (Fig 4.30).

The calculated overall color differences (ΔE) were 10.77±0.33 for ICPD-HAD, 0.24±0.45 for ICPD-RWD, 1.02±0.35 for HAD, and 2.92±0.18 for Marketed. The b* values for ICPD-HAD were 33.16±01.52, ICPD-RWD 23.52±1.11, HAD 23.46±1.21, and Marketed sample 24.0±.25. showed the lowest ΔE, indicating fewer browning reactions or inhibition during the drying process, perhaps as a result of regulated drying conditions and less oxygen exposure. This trend was similar to that observed for turmeric when compared to other methods, as described for turmeric (Rodgers et al., 2008).

1. *Lightness (L*) Trends*:

- The lightness values (**L***) increase from **S1 (56.2)** to **S4 (71.74)**, indicating that **S4 is the brightest** and **S1 is the darkest**.

- The increase in lightness might be attributed to the drying method, processing conditions, or turmeric variety. For instance:
  - **Darker samples** (S1) might indicate higher retention of curcuminoids, which are associated with deeper orange hues.
  - **Lighter samples** (S4) could result from thermal degradation of pigments or different drying conditions leading to reduced color intensity.

Table 4.11: Color properties of turmeric drink

Sample	**L* Lightness**	**a* Red-green**	**b* Yellow blue**	**Interpretation**
ICPD+HAD(S1)	56.2 ± 1.23	2.89 ± 0.023	33.16 ± 1.52	S1 is relative dark (low L*) with a sight red tinge (+a*) and high yellowness (b*)
ICPD+RWD(S2)	65.43 ± 1.56	0.52 ± 0.011	23.52 ± 1.11	S2 is brighter than S1 (higher L*) with minimal redness (a* close to 0) and reduced yellowness
Hot air drying(S3)	68.17 ± 1.74	0.15 ± 0.045	23.46 ± 1.21	S3 is brighter than S2 with almost no red-green tint (a*close to 0) and similar yellowness as S2
Marketed(S4)	71.74 ± 1.51	1.26 ± 0.049	24.28 ± 0.89	S4 is the brighter sample (higher L*) with mid red tint (+a*) and moderate yellowness

***Red-Green Component (a*) Trends*:**

- The **a*** values are **positive** for all samples, meaning there is a slight red tint.
- S1 (**2.89**) has the **highest redness**, while S3 (**0.15**) has almost no red tint, suggesting possible pigment changes due to processing.
- Low redness in S2 and S3 could indicate **less thermal impact** or **oxidative degradation** of red pigments.

3. ***Yellow-Blue Component (b*) Trends*:**

- The **b*** values are **positive** for all samples, indicating yellowness, which is characteristic of turmeric due to the presence of **curcuminoids**.
- S1 has the **highest yellowness (33.16)**, while the other samples (S2-S4) show lower values (~23–24), suggesting:
  - **Higher yellowness** (S1) might correlate with greater curcuminoid retention.
  - **Lower yellowness** (S2-S4) could indicate pigment degradation during processing

Drying and Processing Impact:

Heat exposure during drying may reduce L* (darkening the sample) while degrading pigments, leading to lower b* values (less yellow). Samples with lower a* values (less red) could have undergone oxidative changes.

Pigment Retention:

Higher b* and lower L* values (as in S1) suggest better pigment retention, possibly due to less thermal damage.

Quality Assessment:

Samples with higher b* values (yellowness) and moderate a* values (redness) might be perceived as better-quality turmeric due to their vibrant color.

4.4.2 Antioxidant Properties

The Ferric Reducing Antioxidant Power (FRAP) assay (Fig 4.31), which gauges the capacity of turmeric's bioactive components to convert ferric (Fe^{3+}) ions to ferrous (Fe^{2+}) ions, is the main technique used to assess the antioxidant activity of turmeric. Since gallic acid is a well-known phenolic molecule with a high reducing potential, it is employed as a reference compound to measure antioxidant activity.

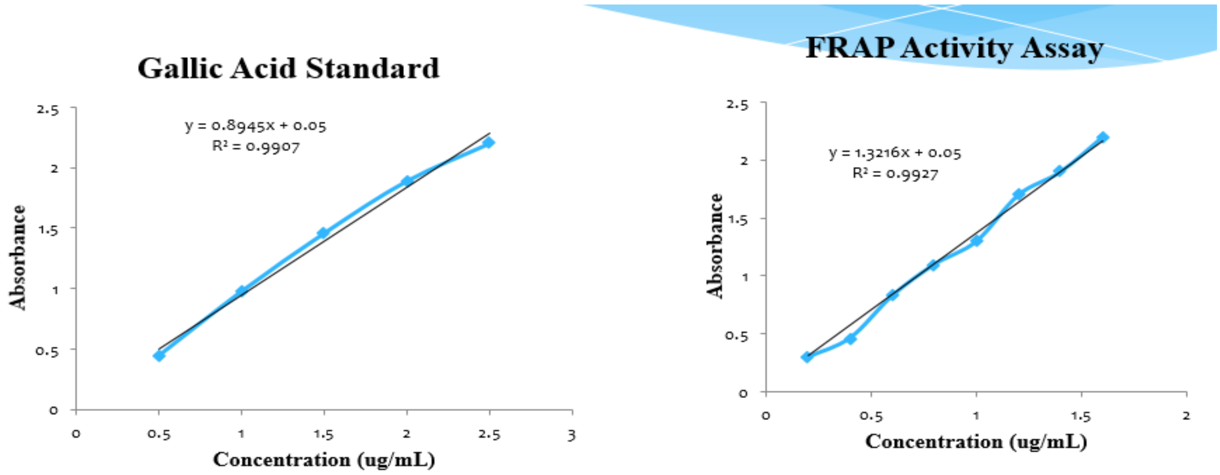


Fig no 4.31 Ferric reducing antioxidant power assay of turmeric drinks FRAP Activity an gallic acid standard

By assessing the antioxidants' capacity to convert ferric ions (Fe^{3+}) to ferrous ions (Fe^{2+}) in an acidic media, the FRAP assay assesses the sample's reducing power. The color intensity of the resulting ferrous-tripyridyltriazine (Fe^{2+}-TPTZ) complex, measured at 593 nm, is directly proportional to the sample's antioxidant capacity. Turmeric contains various bioactive compounds like curcuminoids (curcumin, demethoxycurcumin, bisdemethoxycurcumin) and phenolics, which contribute to its antioxidant properties.

FRAP Values of Different Samples:

Comparing the FRAP values across the turmeric samples (e.g., S1, S2, S3, and S4) helped to indicate stronger antioxidant activity based on a higher FRAP value.

- S1 (hot air-dried): Lower FRAP value due to thermal degradation.
- S2 (ICPD + RWD): Higher FRAP value due to better preservation of antioxidants.
- Marketed turmeric: FRAP value might be lower due to processing and storage degradation.

Correlation with Bioactive Compounds:

FRAP values correlate with the concentration of curcuminoids and total phenolics in your samples. Samples with higher levels of these compounds typically exhibit higher FRAP values (Fig 4.31).

4.4.3 ABTS Activity

The ABTS radical scavenging assay is a widely used method to measure the antioxidant activity of samples (Gauvin, 1981). In the context of turmeric powder, this assay evaluates the ability of bioactive compounds (such as curcuminoids and phenolics) to neutralize the ABTS+ radical cation, providing insight into the effectiveness of different drying methods -IDASC-HAD (Instant Controlled Pressure Drop Assisted Hot Air Drying) and IDASC-RWD (Refractance Window Drying Assisted by Instant Controlled Pressure Drop) as shown in Fig 4.32**.**

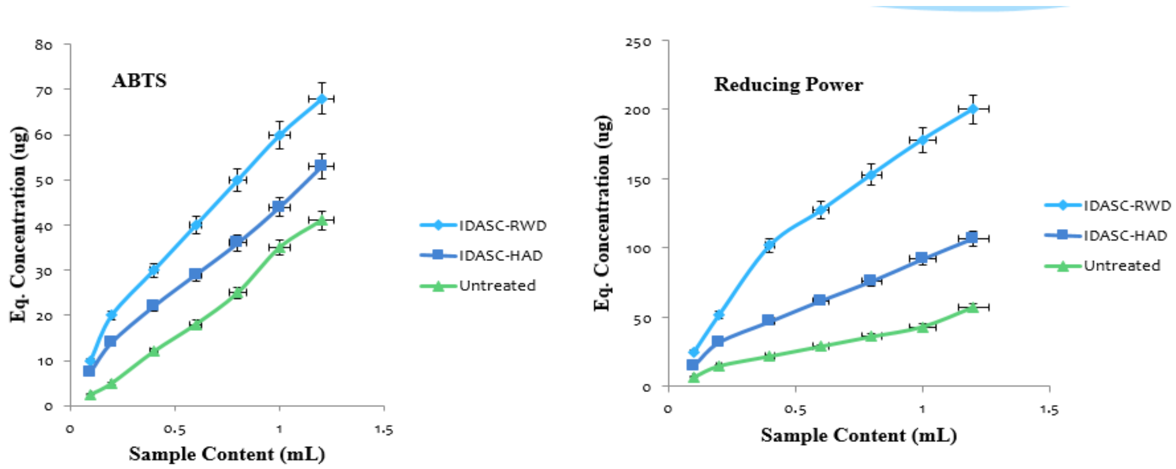


Fig 4.32 ABTS and reducing power activity of turmeric

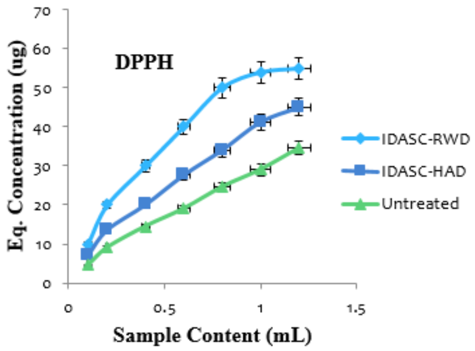
IDASC-HAD shows m**o**derate antioxidant retention; thermal degradation of some bioactive compounds. IDASC-RWD High antioxidant retention due to minimal thermal degradation (Fig 4.32).

4.4.4 DPPH activity of turmeric

DPPH activity of turmeric samples process by various methods are given in Table 4.12 and shown Fig 4.33.

Table 4.12: Antioxidant activity of turmeric infusion drink

Drying Methods	DPPH activity	TEAC (mg/g)	Observation
IDASC-HAD	72. ± 1.2	18.4 ±0.8	Moderate activity due to partial degradation of antioxidant
IDASC-RWD	86.3±1.4	22.7 ±0.6	High activity due to better preservation of curcumins and phenolics



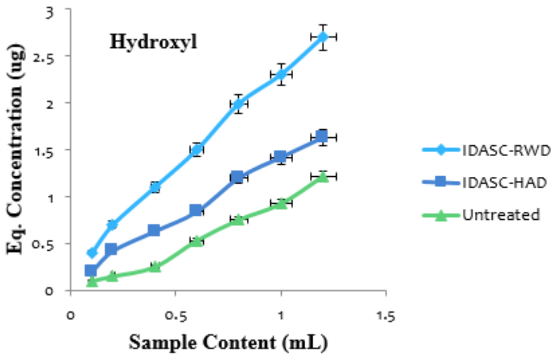


Fig 4.33 DPPH activity of turmeric drinks at different methods

IDASC-HAD

- **Drying Method**:
  - Combines controlled pressure drop with hot air drying at moderate temperatures.
  - While effective in moisture removal, it may cause partial degradation of curcuminoids and phenolic compounds due to heat exposure.
- **Antioxidant Retention**:
  - Moderate DPPH radical scavenging activity due to the degradation of heat-sensitive antioxidants during drying.

IDASC-RWD

- **Drying Method**:

- Utilizes refractance window drying coupled with controlled pressure drop. This method involves low temperatures and rapid drying, preserving bioactive compounds.

- **Antioxidant Retention**:
  - Higher DPPH radical scavenging activity compared to IDASC-HAD, as it better preserves phenolic compounds and curcuminoids.

4.4.4 Sensory Evaluation

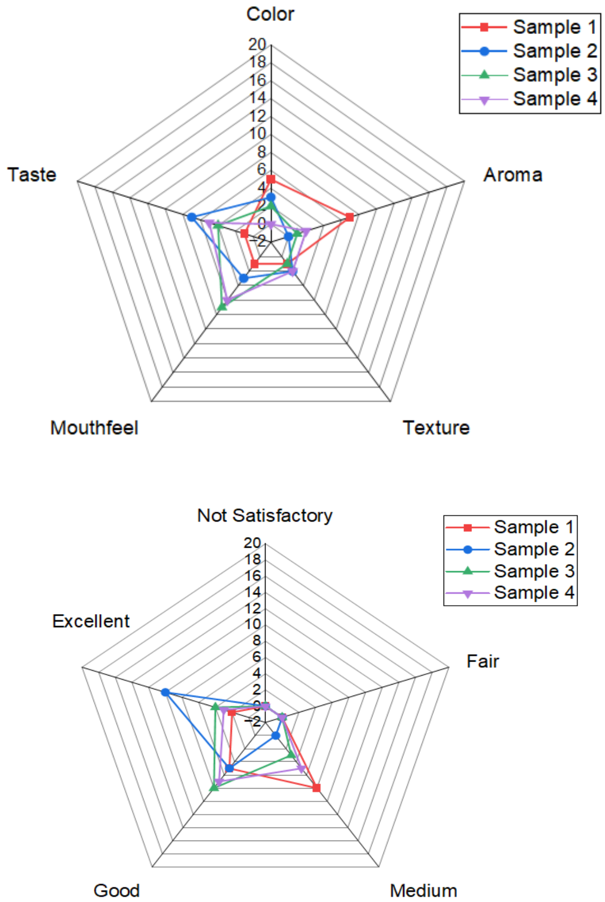


Fig 4.34 Radar chart for the sensory scores of the quality attributes of turmeric drinks

Visual Comparison: Displays multiple sensory attributes simultaneously to identify strengths and weaknesses of a product.

Attribute Analysis: Helps assess specific qualities such as taste, aroma, texture, appearance, and overall acceptability.

Product Benchmarking: Allows comparison of sensory profiles between products or variations of the same product (e.g., formulations, storage conditions).

Radar chart for sensory evaluation

A radar chart (Fig 4.34) is a graphical method used to display multivariate data in a two-dimensional plot. In food and beverage studies, radar charts are commonly used to visualize sensory evaluation data, where multiple quality attributes are assessed and compared.

A radar chart showing the sensory evaluations of two drinks evaluations (A and B) for quality qualities. Sweetness, sourness, scent, texture, and general acceptance are among the qualities assessed. Evaluation B performs exceptionally well in terms of sourness and scent, but Evaluation A shows superior marks for sweetness and general appeal.

4.4.5 Fuzzy logic model

The sensory evaluation of turmeric drinks was evaluated utilizing fuzzy modeling and similarity analysis (Das et al., 2022). Calculating the overall sensory scores of the turmeric beverage samples as triplets, figuring out membership functions on a standard fuzzy scale, computing overall membership functions, and estimating similarity values and ranking the turmeric beverage samples were the primary steps in this analysis. These procedures were carried out with MATLAB2018b.

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(a) Overall Sensory Scores of Turmeric Drinks Samples as Triplets

On a 5-point scale, each sensory score is represented by a triplet. The membership function's peak (value 1) is represented by the first number in the triplet, and the range on either side of the peak where the membership value falls to zero is represented by the second and third numbers. Based on the judges' evaluations (n1 through n5), the sensory scores for characteristics including Color, Flavor, Homogeneity, and Taste were determined using Eqn. 20. For every sample, these triplets were produced.

$$.S_{ia} = \frac{n_1(0\ 0\ 25)+n_2(25\ 25\ 25)+n_3(50\ 25\ 25)+n_4(75\ 25\ 25)+n_5(100\ 25\ 0)}{n_1+n_2+n_3+n_4+n_5} \quad \text{.........(20)}$$

(b) Determining Membership Functions on a Standard Fuzzy Scale

Each sensory attribute's relative relevance was then determined. After calculating the overall sum (Qsum) by adding the scores of each triplet, Eqn. 21 was used to identify the triplet for the relative weightage of each quality characteristic. This gave each attribute's weighted contribution to the total sensory score.

$$Q_{arel} = \frac{Q_a}{Q_{sum}} \quad \text{.........(21)}$$

(c) Computing Overall Membership Functions

The overall sensory score for each sample was calculated by multiplying the triplets of sensory scores by their respective weightage triplets (Eqn. 22). Triplet multiplication was performed using the multiplication rule in Eqn. 23. The fuzzy sensory scales (F1 to F6) were modeled using a triangular distribution pattern, with values ranging from 0 to 100 points as described in Eqn. 24.

$$\mathrm{SO_i} = \mathrm{S_iC} \times \mathrm{QC_{rel}} + \mathrm{S_iA} \times \mathrm{QA_{rel}} + \mathrm{S_iT} \times \mathrm{QT_{rel}} + \mathrm{S_it} \times \mathrm{Qt_{rel}} \quad \text{........ ...... (22)}$$

$$(a\ b\ a) * (d\ e\ f) = (a \times d \quad a \times e + d \times b \quad a \times f + d \times c) \quad \text{. ....(23)}$$

F1= (1, 0.5, 0, 0, 0, 0, 0, 0, 0, 0)

F2= (0.5, 1, 1, 0.5, 0, 0, 0, 0, 0, 0)

F3= (0, 0, 0.5, 1, 1, 0.5, 0, 0, 0, 0) ....(24)

F4= (0, 0, 0, 0, 0.5, 1, 1, 0.5, 0, 0)

F5= (0, 0, 0, 0, 0, 0, 0.5, 1, 1, 0.5)

F6= (0, 0, 0, 0, 0, 0, 0, 0, 0.5, 1)

(d) Estimating Similarity Values and Ranking the Turmeric Drinks Samples

Each sample's overall membership functions (Bx) were calculated using Equation 25 and compared to the typical fuzzy scale membership functions (F1 to F6). Using Equation 26, the similarity values were determined. Matrix multiplication was used to determine the similarity values Sm (F1, Bx), Sm (F2, Bx), Sm (F3, Bx), Sm (F4, Bx), Sm (F5, Bx), and Sm (F6, Bx) for each sample separately. The category with the highest similarity value was determined after these values were computed, and the samples were then rated according to their general quality. The largest value between F×F/ and B×B/ was utilized in the denominator and F×B/ was used in the numerator to calculate the similarity. The samples were then ranked based on the maximum similarity value, which helped determine the overall quality of each turmeric beverage sample. This analysis was performed using MATLAB R2015a.

$$B_x = \frac{x-(a-b)}{b}, \quad \text{for (a-b) < x < a}$$

$$= \frac{(a+)-x}{c}, \quad \text{for a < x < (a+c)} \quad \text{...........(25)}$$

$$S_m(F,B) = \frac{F*B'}{Max\ (F*F' and\ B*B')} \quad \text{........(26)}$$

The sensory evaluation data of the turmeric beverages were analyzed using fuzzy logic modeling. Sensory scores for attributes (Color, Flavor, Homogeneity, Taste) for the turmeric beverages were represented as triplets, and membership functions on a fuzzy scale were computed (Eqn. 6 & 7). The similarity values were calculated by comparing sensory data with a standard fuzzy scale to rank the samples based on overall quality. The sum of sensory scores for quality attributes as represented in Table 4.13 evaluates various turmeric beverage samples based on four sensory quality attributes: Color, Flavor, Homogeneity, and Taste. Additionally, in Table 4.14 the importance of these attributes was assessed, with ratings ranging from "Not Important" to "Extremely Important”.

Each sensory attribute was recorded individually based on the scores shown in Table 4.13 and the significance of each attribute rating detailed in Table 4.14. For the color attribute, Sample 2, which underwent ICPD and Refractance window drying, consistently received high ratings of 7 for "Good" and 8 for "Excellent," indicating that its fuzzy membership function aligns more closely with the F5 or F6 scale and suggests a strong resemblance to excellent color quality. In contrast, Sample 4, labeled as the market sample, garnered 9 ratings in the "Poor" category, resulting in a membership function that approximates F1, highlighting its inferior color quality. Regarding the flavor attribute, Sample 2 again excelled with a flavor profile marked by 7 ratings for "Good" and 6 for "Excellent," implying a stronger correlation to the F6 scale and an overall perception of excellent flavor. Conversely, Sample 4 predominantly received low ratings of "Poor" and "Fair," indicating its lower ranking on the flavor similarity scale. When assessing homogeneity, Sample 2 maintained a strong performance, with numerous ratings falling within the "Excellent" range, further indicating its high similarity to the F6 scale for this characteristic. Sample 4's poor ratings for homogeneity resulted in a diminished similarity score with higher fuzzy scales like F5 or F6, signifying inconsistency. Lastly, the taste attribute was identified as the most crucial, rated as "Extremely Important" with a score of 9. Sample 2 demonstrated consistently high ratings for taste, suggesting it aligns most closely with the F6 scale for this vital attribute. In contrast, Sample 4 again received predominantly "Poor" ratings, contributing to its lower similarity score with the higher sensory scales.

Table 4.13: Sum of sensory scores for quality attributes of turmeric drinks

	Quality attributes	Poor	Fair	Medium	Good	Excellent	Sum
	Color						
ICPD+Hot air dried	Sample 1	0	0	6	4	5	15
ICPD+Refractance window dried	Sample 2	0	0	0	7	8	15
Hot air dried	Sample 3	0	10	2	2	1	15
Market sample	Sample 4	9	3	2	0	0	14
	Flavor						
ICPD+Hot air dried	Sample 1	0	2	4	5	4	15
ICPD+Refractance window dried	Sample 2	0	0	2	7	6	15
Hot air dried	Sample 3	0	4	5	5	1	15
Market sample	Sample 4	8	7	0	0	0	15
	Homogeneity						
ICPD+Hot air dried	Sample 1	0	0	5	3	7	15
ICPD+Refractance window dried	Sample 2	0	0	0	5	10	15
Hot air dried	Sample 3	0	8	3	2	2	15
Market sample	Sample 4	5	7	3	0	0	15
	Taste						
ICPD+Hot air dried	Sample 1	0	0	6	3	6	15
ICPD+Refractance window dried	Sample 2	0	0	0	6	9	15
Hot air dried	Sample 3	0	9	3	1	2	15
Market sample	Sample 4	7	6	2	0	0	15

Table 4.14: Sensory evaluations are used to assign weight to drink quality attributes.

Quality attribute	Not Important	Somewhat important	Important	Highly important	Extremely important
Color	0	0	6	3	6
Flavor	2	5	5	3	0
Homogeneity	3	8	2	2	0
Taste	0	0	2	4	9

Thus, it can be inferred that Sample 2 (ICPD + RW dried) ranks as the best overall performer in all categories, particularly in Color, Homogeneity, and Taste. However, Sample 4 (Market sample) performed the worst in most attributes, especially in Color and Flavor. Overall, Taste is regarded as the most crucial attribute for evaluators followed by Color. Homogeneity, while important, is not considered extremely important.

4.4.6 Storage Study of Drink

The stability of bioactive compounds in turmeric, such as Total Phenolic Content (TPC) and curcumin, is significantly influenced by storage conditions, particularly temperature. High temperatures can accelerate degradation reactions, while low temperatures may preserve these compounds more effectively. Below is an analysis of the effects of storage at different temperatures on the percentage loss of TPC and curcumin.

Mechanism of TPC Degradation

- TPC comprises a range of phenolic compounds, which are sensitive to oxidative and hydrolytic reactions.
- Elevated temperatures increase the rate of these reactions, leading to a higher loss of phenolics.

Temperature Effects:

- Low Temperatures (4°C or Below):
    - Minimal degradation of TPC.
    - Loss is typically in the range of 5-10% over extended storage (e.g., 3-6 months), depending on humidity and packaging.
- Room Temperature (25°C):
    - Moderate degradation due to increased oxidative reactions.
    - TPC loss may range from 15-30% over the same storage period.
- High Temperatures (40°C and Above):
    - Accelerated degradation, with losses often exceeding 40% due to faster phenolic oxidation and thermal breakdown.

- Losses may be higher in poorly sealed packaging or under humid conditions.

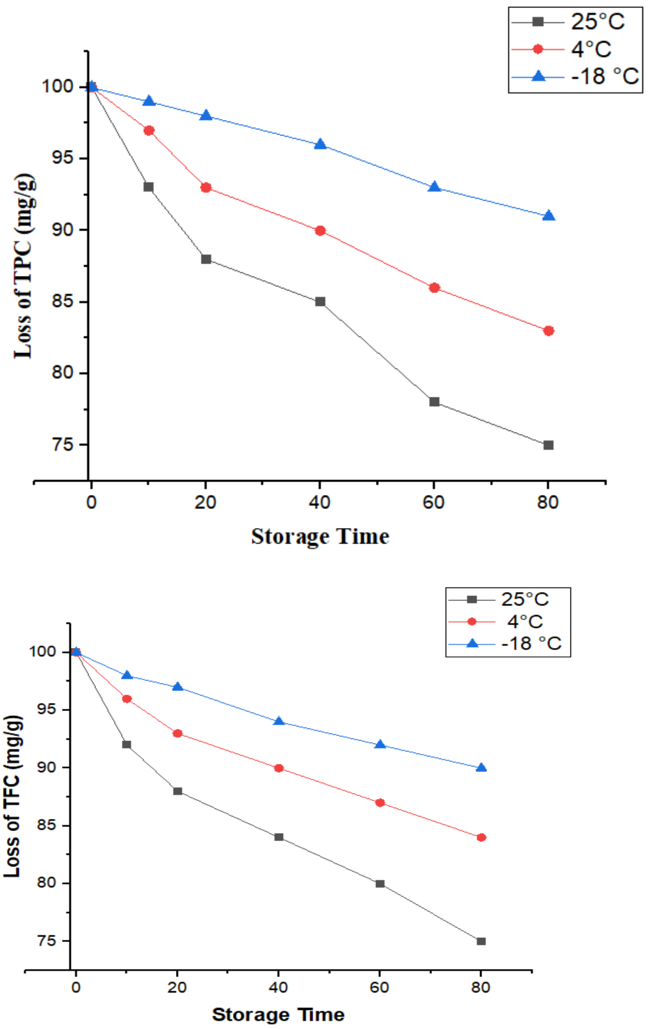

Fig 4.35 Effect of storage at different temperature on loss of TPC activity and loss of Curcumin in percentage

The stability of turmeric's antioxidant activity, commonly measured by the DPPH radical scavenging assay**,** and the bioactive compound curcumin**,** is strongly influenced by storage temperature. Higher temperatures accelerate degradation processes, reducing both DPPH activity and curcumin content, while lower temperatures can help preserve these properties over time (Fig 4.35).

- Low Temperatures (4°C or Below):
  - Minimal reduction in DPPH activity.

- Loss ranges between 5-10% over long-term storage (e.g., 6 months), depending on storage conditions (e.g., light and humidity).

- Room Temperature (25°C):
  - Moderate decline in DPPH activity due to oxidative and thermal degradation of phenolic compounds.
  - Loss ranges between 15-30% over a few months.
- High Temperatures (40°C and Above):
  - Significant reduction in DPPH activity, often exceeding 40-60% over the same period.
  - Higher temperatures accelerate phenolic degradation and disrupt antioxidant capacity.
  - Substantial curcumin degradation, with losses exceeding 50% in as little as 3 months.
  - Losses can approach 70-90% at temperatures above 50°C, especially in unprotected samples.

A comparative Analysis: DPPH Activity vs. Curcumin Loss during storage is given in table 4.15.

Table 4.15: Comparative Analysis: DPPH Activity vs. Curcumin Loss During Storage

Storage Temperature	DPPH Activity Loss (%)	Curcumin Loss (%)
Low (4°C)	5-10%	5-10%
Room (25°C)	15-30%	15-30%
High (40°C)	40-60%	50-70%
Very High (>50°C)	>60%	>70-90%

- Both DPPH activity and curcumin degrade faster at higher temperatures.
- Curcumin loss often correlates with reduced antioxidant activity, as curcumin is a significant contributor to DPPH scavenging.

Storage temperature plays a crucial role in preserving the antioxidant activity (DPPH) and curcumin content in turmeric. Lower temperatures (e.g., refrigeration) are ideal for maintaining stability, while higher temperatures cause significant degradation. Packaging, light exposure, and humidity further influence the rate of degradation. For practical applications, adopting proper storage conditions and protective strategies is essential to preserve turmeric's bioactive properties.

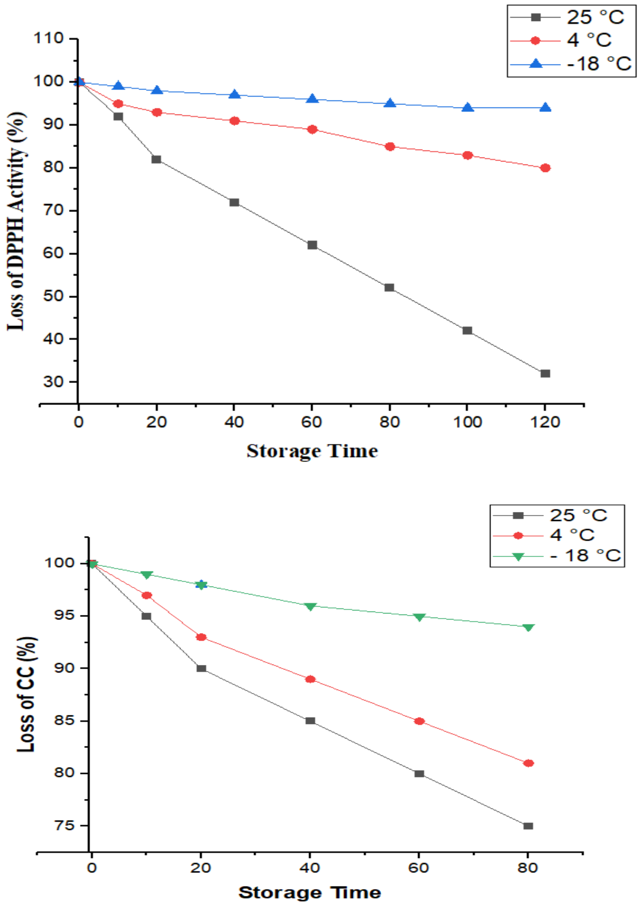

Fig 4.36 Effect of storage at different temperature on DPPH activity and Curcumin loss in percentage

4.4.7 Degradation of pH During Storage

The term "pH degradation" refers to the decline or change in pH levels over time in turmeric beverages during storage (Fig 4.36). This phenomenon occurs due to various chemical, biochemical, and microbial processes that alter the acidity of the beverage. Here's a detailed explanation of the degradation of pH during storage in turmeric beverages.

4.4.8 Infusion Mix Therapeutic Potential

Curcumin, the principal bioactive compound in *Curcuma longa* (turmeric), is widely recognized for its potent antioxidant, anti-inflammatory, antimicrobial, and anticancer properties. Despite its therapeutic potential, curcumin's poor bioavailability attributed to low aqueous solubility, rapid metabolism, and limited gastrointestinal absorption remains a major challenge for effective clinical and dietary applications. The proposed formulation of a curcumin-rich infusion mix, utilizing IDASC-treated turmeric powder, along with ginger and black pepper, is a scientifically grounded response to these challenges. This formulation is not only designed to improve bioaccessibility and absorption but also aims to deliver a functional, palatable health drink with enhanced therapeutic value. The formulation includes a defined ratio of IDASC-processed turmeric powder to water, supplemented with ginger (Zingiber officinale) and black pepper (Piper nigrum). Each component contributes both physicochemical functionality and bioactive synergy

The IDASC technique induces microstructural expansion, enhancing the porosity and surface area of turmeric particles. This modification improves the reconstitution properties in water, leading to faster dispersion and better curcumin release into the aqueous phase. IDASC also preserves thermolabile compounds like curcumin more effectively than conventional drying methods, ensuring a higher baseline content in the final product. Ginger contains gingerols which have complementary anti-inflammatory and digestive benefits. It also acts as a natural flavor enhancer, improving palatability without compromising the health benefits of the formulation Importantly, ginger stimulates digestive enzymes and increases gastrointestinal motility, which may indirectly support curcumin absorption. Piperine is a well-documented bioenhancer, known to increase curcumin bioavailability by up to 2000%. It works by inhibiting hepatic and intestinal glucuronidation, slowing curcumin metabolism, and enhancing intestinal permeability. Its role in this formulation is central to overcoming the pharmacokinetic limitations of curcumin.

The proposed curcumin-rich infusion mix represents a scientifically rational and practically viable solution to the long-standing challenge of curcumin bioavailability. By integrating IDASC-enhanced powder dispersion, ginger's digestive support, and black pepper's bioenhancing action, the formulation effectively transforms turmeric into a therapeutic, functional drink. Its efficacy is not just theoretical but backed by known biochemical mechanisms and supported by evidence-based synergism. With proper standardization and sensory refinement, this drink has the potential to become a cornerstone of preventive health nutrition, bridging traditional wisdom with modern functional food science.

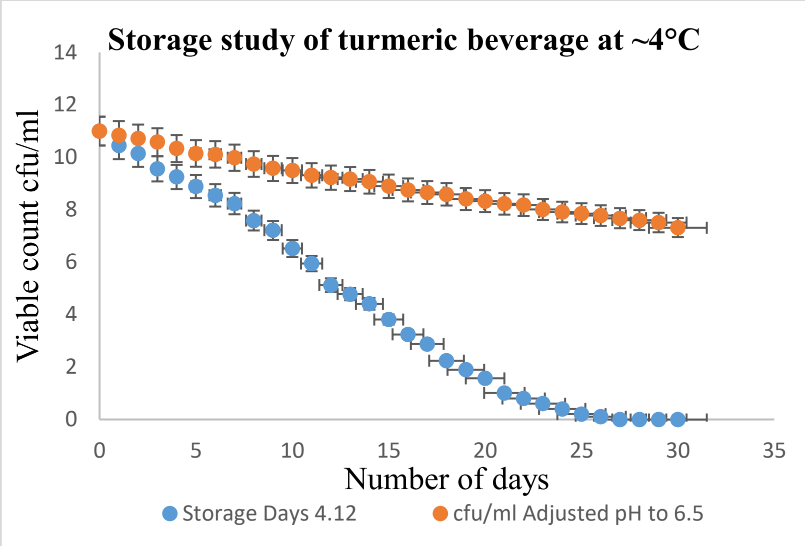

Fig 4.37 Storage study of turmeric drink and pH change in under ±4 ºC

During storage, some residual microbial activity (even in pasteurized products) can lead to the fermentation of sugars into organic acids like lactic acid, citric acid, or acetic acid. Fig 4.37 shows acids contribute to a gradual decline in pH, making the beverage more acidic. Phenolic compounds in turmeric, including curcumin, undergo oxidation during storage. Oxidative byproducts often lower the pH of the beverage. Poor packaging can allow oxygen ingress, which accelerates oxidative reactions and pH degradation. Leaching of compounds from packaging materials (in rare cases) may also impact pH.