Journal of Scientific & Industrial Research
Vol. 82, March 2023, pp. 370-377
DOI: 10.56042/jsir.v82i03.65718

# Investigation of Physicochemical, Mechanical, Thermal and Rheological Properties of *Mrigbahar* Nagpur Mandarin (*Citrus reticulate* Blanco.)

Venkatraman Bansode, Madhuresh Dwivedi*, Rama Chandra Pradhan, Tarak Chandra Panda, Thota Niranjan, Samuel Jaddu & Mahipal Singh Tomar

Department of Food Process Engineering, National Institute of Technology, Rourkela, Odisha, India

*Received 20 August 2022; revised 22 February 2023; accepted 02 March 2023*

Nagpur mandarin (popularly known as Nagpur Santra) is an indigenous fruit with high nutritional and functional value. It is the only cultivar of mandarin grown in *Vidarbha* region of Maharashtra. As per harvesting time they are *ambiabahar* (Ocrober-November) and *mrigbahar* (February-March). Out of these two, *mrigbahar* is unique to Nagpur and of superior quality, hence taken for the study. The physicochemical, thermal, mechanical, rheological and textural properties of *mrigbahar* Nagpur mandarin are studied in this work. The sphericity (0.90) of *mrigbahar* fruit is considered to be spherical. The mean breadth, thickness and length of the fruit are 54.9, 47.3 and 57.9 mm, respectively. The true density, porosity and bulk density are 1.364 $g/m^3$, 65.10% and 0.517 $g/m^3$. The thermal conductivity, thermal diffusivity and specific heat of Nagpur mandarin fruit are 0.588 W/m°C, $11.84 \times 10^{-2}$ $m^2/s$ and 3.909 kJ/kg°C. Under rheological properties of Nagpur mandarin juice, it is observed that as the shear rate increased, viscosity (η) and shear stress (σ) decreased and Herschel Bulkley model is most suitable to characterise flow behaviour. The textural properties reveal that fracturability with 1% load sensitivity is 10.27 N with respective values of stringiness length (4.04 mm). The findings of this investigation would help for the post-harvest handling, processing equipment and value-added products from Nagpur mandarin.

**Keywords:** Color, Sphericity, Stringiness, Sweet orange, Viscosity

## Introduction

Mandarins *(Citrus reticulata)* are popular citrus fruit, but identifying their origins and taxonomy is challenging due to the complexity of citrus biology and culture. It is one of the most important citrus species, ranked second in the world's citrus production (FAO statistics[1]). Mandarins comprises diverse group of citrus fruits characterised by bright-color peel and pulp, excellent flavour, easy-to-peel rind and segments that separate easily.

The *mrigbahar* Nagpur mandarin comes under the 'mandarin' group of citrus fruits grown widely in various states of India. It is generally known as Nagpur Santra. The production of mandarin in India is about 6219 thousand tonnes obtained from 477 thousand hectares (National Horticulture Board).[2] It is the only cultivar of mandarin grown in the Vidarbha region of Maharashtra. It is considered to be the best mandarin in the world due to its quality attributes like color, pleasant flavour and good taste. It occupies a leading position among Indian Mandarins; it is one of the finest mandarins grown in the world.

*Author for Correspondence
Email: madhureshd@gmail.com

In *mrigbahar*, flowering can be included in June-July and harvested in February-March. The flowering season of others persists from the last week of February to March and the harvested during October-November are called *ambiabahar*. The quality of fruit obtained in this *mrigbahar* is excellent compared to *ambiabahar* as reported by Jhade *et al*.[3]

The understanding of physicochemical properties of Nagpur mandarin helps processors as well as researchers in the evaluation of the inner and outer structure of the fruit. The unit operations like cleaning, sorting, grading, peeling and packaging depending on the physical characteristics viz. size, shape, thickness, volume, color, porosity and appearance of the fruit.

The textural and mechanical properties of Nagpur mandarin fruits aid in the quality evaluation of the fruit and the design of the processing machinery. The thermal properties of Nagpur mandarin like thermal conductivity (k), thermal diffusivity (α) and specific heat capacity (Cp) help to know the procuring necessity of fruit for its storage and development of refrigeration system. Rheology is the study of the deformation and flow behaviour of matter. The term viscosity can characterise the consistency of

Newtonian fluids like water and clear juices. Salehi Fakhreddin[4] mentioned that the knowledge of rheological characteristics of fluid food are needed for its sensory evaluation, process mechanization and quality control.

Many studies have been reported for observing fruit mass depending upon their physical properties. Mahawar *et al.*[5] studied the mass modelling of Kinnow Mandarin based on physical attributes. Patil *et al.*[6] performed on the physicochemical properties and mass modelling of Nagpur mandarin fruit. But no detailed study concerning mechanical, thermal, textural and rheological properties of *mrigbahar* has been revealed in the literature. Hence, this specific study was conceived to analyse physical properties which include color values, and frictional, dimensional and gravimetric properties of Nagpur mandarin fruits. This research article also covers the mechanical, thermal, textural and rheological properties of *mrigbahar* fruits. This study may create support for farmers, food scientists, industrial processors, machine design and value addition.

## Materials and Methods

**Raw Material**

The Nagpur mandarin fruits (*Citrus reticulata* Blanco) in *mrigbahar* season were harvested from the experimental blocks of ICAR-Central Citrus Research Institute, Nagpur, India in March month (Fig. 1). The sorting and grading of the fruits were done manually to discard the defective fruits, and remove dirt, surface bruises etc. The maturity of Nagpur mandarin fruits was judged by sensory qualities like color and smell. The fruits were kept for 2 to 5 days after sorting and grading at room temperature for further investigation. The studies on physicochemical, mechanical, thermal, rheological and textural properties were conducted in the Department of Food Process Engineering laboratory of the NIT, Rourkela.

Fig. 1 — Nagpur mandarin fruit

**Glassware, Reagent and Chemicals**

The chemicals required to measure titratable acidity, vitamin C, and standards (Gallic acid, Quercetin) for total phenol content and total flavonoid content were purchased from HiMedia Lab, Mumbai. The required chemicals and glassware used were of standard and analytical grade.

**Determination of Physical Properties**

Different types of physical properties of *mrigbahar* Nagpur mandarin fruits such as breadth (B), thickness (T) and length (L); equivalent diameter ($D_E$); geometric mean diameter ($D_G$); arithmetic mean diameter ($D_A$); aspect ratio ($R_A$); Surface area ($S_A$); sphericity ($\Psi$); criteria projected area ($CRT_A$); oblate spheroid (VOBS) and ellipsoid ($V_{ELLP}$) volume were determined at 100 number of fruits of 89.36% (wb) moisture content as suggested by Pradhan *et al.*[7] The principal dimensions (Length, Breadth and Thickness) of *mrigbahar* Nagpur mandarin fruit were measured by a Digital vernier calliper. The electronic balance with an accuracy of 0.001 g was taken to analyse the mass of each fruit. The formulae used for DE, DG, DA, RA, SA, Ψ, Elongation ratio (ER) and Flakiness ratio (FR) was mentioned by Kambhampati *et al.*[8] as per Eqs (1–8).

**Gravimetric Properties of Nagpur Mandarin Fruit**

The bulk density ($\rho_B$), true density ($\rho_T$), apparent density ($\rho_A$), porosity ($\phi$) and specific gravity includes under the gravimetric properties of materials that determine the fruits' relative heaviness. The specific gravity and density help to evaluate fruits' maturity, the outline of storage bins, this portion of the desired material and the texture of fruits. The true density ($\rho_T$) was determined by the displacement of water after immersing fruit in a container of known volume. The known weight of Nagpur mandarin fruit in a known container of 1000 ml was used to calculate the bulk density. The gravimetric properties are determined by formulae (9 to 12) mentioned by Sonawane *et al.*[9]

$$\rho_{T}=\frac{Weight\ of\ fruit\ in\ water}{Volume\ of\ water\ displaced} \quad \ldots (1)$$

Porosity ($\phi$) or void fraction is a measure of the void spaces in the Nagpur mandarin fruits

$$\text{Porosity}\ (\phi) = \frac{(1-\rho_B)}{\rho_T} \quad \ldots (2)$$

$$\text{Apparent density } (\rho_A) = \frac{weight\ of\ mandarin\ fruit\ in\ container}{fruit\ volume} \quad \ldots (3)$$

$$\text{Bulk density } (\rho_B) = \frac{weight\ of\ mandarin\ fruits\ in\ container}{volume\ of\ container} \quad \ldots (4)$$

$$\text{Specific gravity} = \frac{weight\ of\ fruit\ container \times specific\ gravity\ of\ water}{weight\ of\ displayed\ water} \quad \ldots (5)$$

$$\text{Fruit Volume} = \frac{weight\ of fruit\ in\ water}{water\ density} \quad \ldots (6)$$

**Determination of Frictional properties of Nagpur mandarin**

The types of frictional properties, i.e., coefficient of friction (μ) and angle of repose (Θ) are required for control of losses due to friction of the equipment and design the conveyor, bins, hoppers etc. The angle of repose of Nagpur mandarin is estimated using standard formulae Eq. (7). It determines the height (h) of fruits.

$$\text{Angle of repose} = Tan^{-1}\left(\frac{2h}{D}\right) \quad \ldots (7)$$

The coefficient of static friction was derived with the help of Eq. (8) for 50 fruits and estimated the angle of friction. Determination of the tilt angle on the six different surfaces includes Aluminium, Galvanised iron, Fibre plastic and Plywood on which Nagpur mandarin fruits start to roll.

$$\text{Coefficient of static friction } (\mu_s) = \text{Tan}\alpha \quad \ldots (8)$$

**Thermal properties of Nagpur Mandarin**

The thermal properties like thermal diffusivity, thermal conductivity and specific heat capacity of *mrigbahar* Nagpur mandarin fruits were estimated according to Sonawane *et al.*[9] using Eqs (9–11). The thermal properties are useful to outline the non-thermal and thermal processing systems and disinfection by heat treatment.

$$\text{Thermal diffusivity} = \frac{k}{\rho C_p} \quad \ldots (9)$$

$$\text{Thermal conductivity (W/m°C)} = 0.148 + 0.0049\ \text{mc} \quad \ldots (10)$$

$$\text{Specific heat capacity (kJ/Kg°C)} = 1.675 + 0.025\ \text{mc} \quad \ldots (11)$$

**Textural Properties of Nagpur Mandarin**

The textural analyser (CT3, Brookfield, USA) was used to determine the textural properties of *mrigbahar* Nagpur mandarin fruits. The textural analyser attached with a 10 kg load cell and 6 mm diameter was used with the cylindrical probe. The textural properties such as hardness cycle, percent deformation, peak stress, stringiness length, fracturability etc. were estimated following Mukarkonda *et al.*[10]

**Color Values of Nagpur Mandarin Fruit**

The color values of Nagpur mandarin fruits were measured by a Hunter Lab (Colorimeter). The values of L*, a*, b* shows darkness to lightness (0-100), a* denotes green (negative) to red (positive) and b* denotes blue (positive) to yellow (negative). The Hue angle ($h^o$) and Chroma Value (CV) are mentioned by the following Eqs 12 & 13 as per Singh & Reddy.[11]

$$\text{Hue angle } (h^o) = Tan^{-1}\left(\frac{b}{a}\right) \quad \ldots (12)$$

$$\text{Chroma value (CV)} = \sqrt{a^2 + b^2} \quad \ldots (13)$$

The CV denotes the purity of color and intensity. The higher the CV, the higher the purity of the color appearance. The hue angle ($h^o$) represents a product's color, whether it is red, yellow, orange, blue or green.

**Extraction of Juice from Nagpur Mandarin Fruit and Separation of its Fractions**

The selected fruits (disease free, undamaged) were washed by tap water to remove dust, dirt and insecticidal residues. The manual peeling of fruits was done to extract juice. The power operated juice extractor was used to extract juice. The juice and pomace were obtained separately by using the juice extractor. The obtained juice was filtered through muslin cloth and kept at refrigerator (4°C) for further study. The obtained pomace contains seed and pith residues. It separated manually and dried in hot air oven at 40°C for 24 hrs. The dried fractions (Pith residue and seeds) were converted into powder form by using grinder and used for further analysis.

**Fourier Transform Infrared Spectroscopy (FTIR)**

The FTIR spectra were obtained for Nagpur mandarin fruit juice and its fractions (peel, pith residue and seed powder) with attenuated total reflectance (ATR) using FTIR spectroscopy (Bruker, Alpha E FTIR, Germany). It is one of the non-destructive, rapid and time-saving methods that can detect a range of functional groups. The spectra were measured absorbance (%) at wavelength ranges from 500 to 4000 $cm^{-1}$ with 32 scans per sample.

#### Chemical Properties

The different chemical properties of Nagpur mandarin include moisture content (wet basis %), pH, TA (titratable acidity), TSS (total soluble solids), RI (refractive index), vitamin C, TPC and TFC were estimated according to protocols as briefed below. The moisture content (wet basis) of samples was determined using the standard AOAC[12] procedure. The samples were kept in a hot air oven at 105 ± 5°C up to attaining constant weight. A cyberscan pH meter (±0.01 pH accuracy) was used to determine the pH of the fruit. A digital refractometer (model-rfm700-m) measured the refractive index and total soluble solids (°brix) at the ambient temperature (31.2°C). TA (titrable acidity) of juice samples were measured as per Ghosh *et al.*[13] procedure against 0.1N NaOH and the end point indicator and results were shown in a gram of citric acid equivalents per litre of the sample. The vitamin C (ascorbic acid) was estimated as per AOAC[12] methods by dilution of known volume of juice with 3% metaphosphoric acid as buffer titrated it against 2,6-dichlorophenol indophenol dye solution until the stable pink (faint) color was obtained. The obtained results were expressed in mg per 100 ml of juice. TPC of the Nagpur mandarin and its fractions were analysed at 765 nm spectrophotometric by using the Folin-Ciocalteu method suggested by singleton *et al.*[14] and results were expressed in mg GAE/100g. Similarly, the total flavonoid content of Nagpur mandarin and its fraction was analysed at 420 nm by using colorimetric technique suggested by Sharma *et al.*[15] and the results were indicated in mg of QE/100g of the sample.

#### Statistical Analysis

The statistical analysis of the experiments like minimum, maximum, and mean along with standard deviation for physicochemical, mechanical and thermal properties were determined by MS excel. The entire experiments were carried out in triplicate. The obtained results for various parameters are presented in mean ± SD.

## Results and Discussion

#### Physical Properties

The pertinent details obtained from various physical properties of *mrigbahar* Nagpur mandarin fruit include breadth, length, mass, volume, thickness, geometric mean diameter, aspect ratio, surface area, sphericity, ellipsoid, projected area perpendicular to length ($P_L$), projected area perpendicular to wide ($P_W$) and projected area perpendicular to thickness ($P_T$), flakiness ratio, criteria projected area, elongation ratio, porosity, densities, color values and coefficient of static friction were analysed and summarised in Table 1.

The basic physical properties including breadth, thickness, and length are very helpful in designing, sorting, grading and cleaning machinery and its operations. The Nagpur mandarin fruit had an average volume of 71.5 $cm^3$ and a mass of 86.4 g. The average values of breadth, thickness and length of fruits were found to be 55.9 mm, 47.0 mm, and 58.5 mm. The average values for volumes of Nagpur mandarin fruits like spheroid volume and ellipsoid volume were obtained as 96033.2 $mm^3$ and 80499.1 $mm^3$ respectively. The equivalent diameter ($D_E$), geometric mean diameter ($D_G$) and arithmetic diameter ($D_A$) of the Nagpur mandarin fruit were found to be 53.7 mm, 53.6 mm and 53.8 mm, respectively.

The aspect ratio shows how oblong the fruit is, while the values of sphericity aid to design sizing and separator. The mean aspect ratio, sphericity, elongation and flakiness ratio of Nagpur mandarin fruits were obtained as 95.5, 90.16, 1.0 and 0.6. Various areas of the Nagpur mandarin like $A_{CRT}$ (criteria projected area), $P_L$ (projected area perpendicular to the length), $P_W$ (projected area perpendicular to the width), $P_T$ (projected area perpendicular to the thickness) and surface area, were obtained to be 2363.6 $mm^2$, 25709.62 $mm^2$, 2458 $mm^2$, 2061.8 $mm^2$ and 9009.8 $mm^2$ respectively. The frictional and gravimetric properties of Nagpur mandarin fruits along with maximum, minimum and mean with standard deviation are depicted in Table 1. The gravimetric properties of Nagpur mandarin such as true density, porosity and bulk density, are mentioned as 1.56 $g/m^3$, 0.517 $g/m^3$ and 68.21%. The porosity value signifies the intergranular space compared to the overall occupied space of the fruit. The less porosity of Nagpur mandarin fruits indicates reduced inner granulated pore spaces, which is useful to overcome the inner storage temperature of Nagpur mandarin fruits similar reports mentioned by Rao.[16] for fruits and vegetables.

The frictional properties of Nagpur mandarin, like the coefficient of friction and angle of repose, are useful variables used in designing material for chutes, conveyors and hoppers etc. reported by Elansari & Hobani.[17] The coefficient of static friction of Nagpur mandarin fruits was determined on Aluminium ($\mu_{AI}$), Galvanized iron ($\mu_{GI}$), fibre plastic ($\mu_{FP}$) and plywood ($\mu_P$) the mean value were observed to be 0.37, 0.38,

Table 1 — Physical properties of Nagpur mandarin

| Physical Parameters | Symbol | Maximum | Minimum | Mean ± SD |
|---|---|---|---|---|
| Length (mm) | L | 60.04 | 56.13 | 58.5 ± 1.29 |
| Breadth (mm) | W | 58.68 | 51.97 | 55.9 ± 2.15 |
| Thickness (mm) | T | 49.77 | 45.31 | 47.0 ± 1.50 |
| Mass (g) | M | 106.96 | 45.50 | 86.4 ± 16.03 |
| Volume (mL) | V | 89.00 | 50.00 | 71.5 ± 12.30 |
| Arithmetic mean diameter (mm) | $D_A$ | 56.01 | 51.61 | 53.8 ± 1.30 |
| Geometric mean diameter (mm) | $D_G$ | 55.82 | 51.36 | 53.6 ± 1.28 |
| Equivalent diameter (mm) | $D_E$ | 55.95 | 51.44 | 53.7 ± 1.31 |
| Aspect ratio | $A_R$ | 98.41 | 90.32 | 95.5 ± 2.30 |
| Surface area ($mm^2$) | SA | 9785.53 | 8283.38 | 9009.8 ± 431.76 |
| Sphericity (%) | $\phi$ | 94.00 | 89.62 | 90.16 ± 0.02 |
| Flakiness ratio | $F_r$ | 1.05 | 0.47 | 0.6 ± 0.17 |
| Elongation ratio | $E_r$ | 1.11 | 1.02 | 1.0 ± 0.03 |
| Ellipsoid volume ($mm^3$) | $V_{ELLP}$ | 91045.88 | 70907.97 | 80499.1 ± 5790.20 |
| Spheroid volume ($mm^3$) | $V_{OSV}$ | 108193.03 | 81330.55 | 96033.2 ± 9153.17 |
| Projected area perpendicular with length ($mm^2$) | $P_L$ | 2765.67 | 2347.83 | 25709.62 ± 211.51 |
| Projected area perpendicular with width ($mm^2$) | $P_W$ | 2703.02 | 2120.19 | 2458 ± 187.93 |
| Projected area perpendicular with thickness ($mm^2$) | $P_T$ | 2291.42 | 1848.49 | 2061.8 ± 119.81 |
| Criteria projected area ($mm^2$) | $A_{CRT}$ | 2578.56 | 2105.37 | 2363.6 ± 146.23 |
| Bulk density ($gm^{-3}$) | $\rho_b$ | 0.522 | 0.510 | 0.517 ± 0.36 |
| True density ($gm^{-3}$) | $\rho t$ | 1.766 | 1.416 | 1.56 ± 0.71 |
| Porosity (%) | $\varepsilon$ | 70.23 | 66.52 | 68.21 ± 1.63 |
| Aluminium | $\mu_{AI}$ | 0.42 | 0.34 | 0.37 ± 0.04 |
| Galvanised iron | $\mu_{GI}$ | 0.44 | 0.32 | 0.38 ± 0.02 |
| Fibre plastic | $\mu_{FP}$ | 0.38 | 0.28 | 0.30 ± 0.02 |
| Plywood | $\mu_P$ | 0.34 | 0.26 | 0.28 ± 0.02 |
| Darkness - lightness | L* | 60.54 | 51.42 | 55.54 ± 2.83 |
| Red-green | a* | 18.04 | 9.22 | 12.73 ± 4.06 |
| Yellow-blue | b* | 52.95 | 47.77 | 51.27 ± 4.56 |
| Chroma value | C | 54.22 | 49.09 | 52.75 ± 3.89 |
| Hue angle | $h^o$ | 80.12 | 76.73 | 76.05 ± 3.62 |
| Angle of repose ($^o$) | $\Theta$ | 59.82 | 55.77 | 58.13 ± 1.24 |

0.30 and 0.28. The high rolling resistance was found on all surfaces, and it might be due to the flat shape at one end of the fruit.

Color is an important quality parameter for proposed fruit juices and fresh fruits. The average color values L*, a* and b* of *mrigbahar* Nagpur mandarin fruits were found to be 55.54, 12.73 and 51.27. The mean chroma (C) and hue angle ($h^o$) of the Nagpur mandarin fruits were 52.75 and 76.05 respectively. The results of the physical properties of *mrigbahar* were observed to be similar with Topuz *et al.*[18] for orange fruits.

**Chemical Properties**

The chemical properties of *mrigbahar* Nagpur mandarin fruits were depicted in Table 2. The average moisture content of the fruit was (89.36% wb) and this high moisture content was responsible for speedy microbial growth and physical damage of the fruit. The fruit juice has pH (4.02) and acidity (0.321%). The TSS (12.86$^o$Brix) and RI (1.35) of the fruit were calculated and it was observed that TSS content of *mrigbahar* was higher compared to *ambiabahar* fruits as well as other mandarin cultivars. Citrus fruits are major sources of vitamin C (ascorbic acid) and phytochemicals. The vitamin C content of Nagpur mandarin fruit was 24.11 mg/100ml. The total polyphenol and total flavonoid content of fruits and their fraction were estimated. The

Table 2 — Chemical properties of Nagpur mandarin fruit

| Chemical parameters | Maximum | Minimum | Mean ± SD |
|---|---|---|---|
| Moisture (%) | 89.90 | 89.28 | 89.36 ± 0.442 |
| Acidity (%) | 0.288 | 0.352 | 0.321 ± 0.018 |
| pH | 3.67 | 4.17 | 4.02 ± 0.188 |
| Total Soluble Solids (°brix) | 12.10 | 13.25 | 12.86 ± 0.324 |
| Vitamin C (Mg/100 ml) | 25.07 | 21.53 | 24.11 ± 0.595 |
| Refractive index | 1.35 | 1.34 | 1.35 ± 0.007 |
| Juice | 182.20 | 163.12 | 168.86 ± 0.132 |
| Pith residue | 70.83 | 63.97 | 67.35 ± 0.065 |
| Seed | 78.9 | 62.01 | 70.40 ± 0.160 |
| Peel | 157.4 | 95.35 | 124.92 ± 0.573 |
| Juice | 8.29 | 8.14 | 8.22 ± 0.007 |
| Pith residue | 4.94 | 3.90 | 4.43 ± 0.054 |
| Seed | 1.91 | 1.60 | 1.76 ± 0.015 |
| Peel | 12.5 | 12.3 | 12.4 ± 0.005 |

Table 3 — Textural and thermal properties of Nagpur mandarin fruits

| Textural properties | Maximum | Minimum | Mean ± S.D |
|---|---|---|---|
| Hardness cycle-1 (N) | 13.80 | 8.19 | 10.31 ± 1.59 |
| Percentage deformation at the hardness (%) | 21.70 | 13.80 | 18.65 ± 2.90 |
| Peak Stress (N/m2) | 5808 | 3447 | 4340 ± 671.25 |
| Stringiness length (Mm) | 7.58 | 1.83 | 4.04 ± 2.07 |
| Fracturability (with 1% of load sensitivity) (N) | 13.80 | 8.19 | 10.27 ± 1.59 |
| Hardness cycle-2 (N) | 1.72 | 0.72 | 0.97 ± 0.30 |
| Cohesiveness (J) | 0.07 | 0.02 | 0.05 ± 0.01 |
| Gumminess (N) | 0.82 | 0.17 | 0.53 ± 0.17 |
| Specific heat capacity (Cp) (kJ/kg°C) | 3.922 | 3.898 | 3.909 |
| Thermal conductivity (k) (W/m°C) | 0.591 | 0.586 | 0.588 |
| Thermal diffusivity (α) ($\times 10^{-2}$) $m^2/s$ | 11.86 | 11.83 | 11.84 |

highest total phenols content was observed in juice (168.86 mg GAE/100g) followed by peel (124.92 mg GAE/100g), seed (70.40 mg GAE/100g) and pith residue (67.35 mg GAE/100g). The highest total flavonoid content was observed in peel (12.40 mg QE /100g) followed by juice (8.22 mg QE /100g), pith residue (4.43 mg QE /100g) and seed (1.76 mg QE /100g). The obtained data is good agreement with Bures *et al.*[19]

**Textural Properties**

The textural properties of Nagpur mandarin fruits were carried out and mentioned in Table 3. The textural properties include hardness, the percentage of deformation at hardness, fracturability, peak stress, stringiness strength, cohesiveness and Gumminess. The average value of deformation at hardness and hardness of Nagpur mandarin fruit was found to be 18.65% and 13.80 N. The second cycle has a mean hardness value of 0.97 N. The hardness value of the fruit shows resistance towards the different types of penetrations or deformations caused due to abrasion, scratches, and impact. The similar reports mentioned for *Terminalia chebula* fruits by Pathak *et al.*[20] The mean value of fractrability, peak stress, and stringiness length of Nagpur mandarin fruits was found to be 10.27 N, 4340 $N/m^2$ and 4.04 mm, respectively. Other mechanical properties such as gumminess and cohesiveness were carried out for Nagpur mandarin fruits. The average value for gumminess and cohesiveness was 0.53 N and 0.05 J. This value shows the elastic behaviour of the sample and the property to resist deformation.

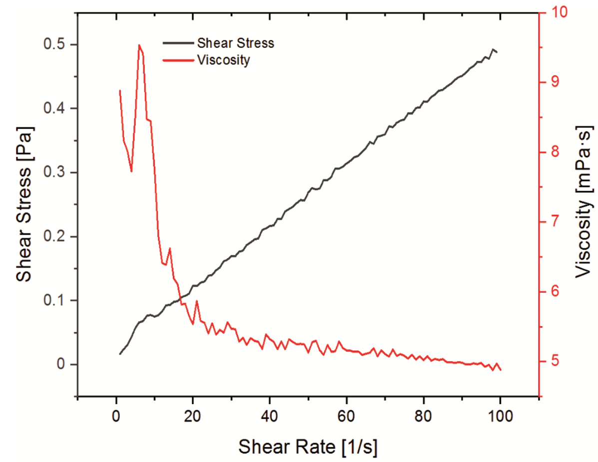


Fig. 2 — Plot of shear stress (σ) and viscosity with respect to shear rate (γ) of Nagpur mandarin fruit

**Rheological Properties**

The rheological behaviour of Nagpur mandarin juice was carried out and shown in Fig. 2. The viscosity ($\eta$) and shear stress ($\sigma$) of Nagpur mandarin juice decreased as the shear rate increased, representing Newtonian characteristics. In the experimental data, herschel- bulkley model was fitted and gave the best fitting $r^2 = 0.99848$, flow index (n) = 1.0139 and consistency index (k) = 0.0044835 pa.$s^n$. Patel *et al.*[21] reported the similar findings for Indian jujube fruit.

**Thermal Properties**

The thermal properties of Nagpur mandarin fruit at 89.36% (w.b.) average moisture content are found to be $11.84 \times 10^{-2}$ $m^2/s$, 3.909 kJ/kg °C and 0.588 W/m °C for thermal diffusivity, specific heat capacity and thermal conductivity. The data on thermal properties are shown in Table 3. The results agree with Singh *et al.*[22] who reported similar results for cashew apple fruit. Studies on the thermal properties of Nagpur mandarin are rare. The thermal properties of Nagpur mandarin fruits are low; it shows that reduced heat flux conducts through fruit, and as the temperature is raised, it needs additional time for thermal processing like freezing as well as drying. The requirement of energy for cooling and heating of Nagpur mandarin is greater than wood apple and the specific heat capacity of the bael fruit is comparatively higher due to the high moisture content of the juice.

**Fourier Transform Infrared Spectroscopy (FTIR) of Nagpur Mandarin Fruit Fractions**

The spectra of FTIR indicate the presence of various functional groups of the bioactive compounds

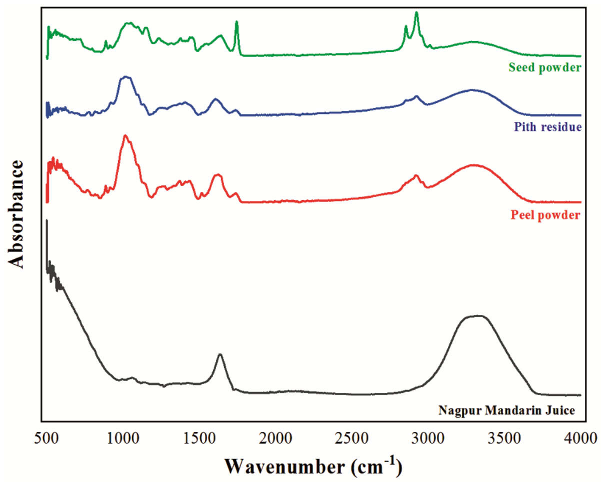


Fig. 3 — FTIR Spectrum of Nagpur mandarin juice and its fractions

Table 4 — FTIR-Band position and their functional groups of Nagpur mandarin juice and its fractions

| SN | Fruit fraction | Band position ($cm^{-1}$) | Functional groups |
|---|---|---|---|
| 1 | Fruit juice | 509 | Halogen compounds |
| | | 1053 | Polysaccharides |
| | | 1628 | Alkene |
| | | 3319 | Amines |
| 2 | Peel powder | 546 | Halogen compounds |
| | | 1031 | CO-groups |
| | | 1643 | Alkene |
| | | 2904 | Alkane |
| | | 3313 | Amines |
| 3 | Pith residue | 1029 | CO-groups |
| | | 1596 | Alkene |
| | | 2921 | Alkane |
| | | 3288 | Amines |
| 4 | Seed powder | 1037 | Polysaccharide |
| | | 1746 | Ester |
| | | 2849 | Alkane |
| | | 2927 | Alkane |

present in the Nagpur mandarin juice and its fractions. The resulting peaks confirmed a wide range of functional groups of bioactive compounds in the samples shown in Fig. 3 and details are mentioned in Table 4.

## Conclusions

The properties of Nagpur mandarin, viz. physico-chemical, mechanical, thermal, textural and rheological data havebeen investigated to produce details that can be applied for the designing of different types of machinery used in the processing of Nagpur mandarin. The mean of physical, thermal and mechanical properties of Nagpur mandarin is within the acceptable range of Standard Deviation. The physical properties of Nagpur mandarin showed that it is nearly spherical ($\phi$ = 90.16%) with true density ($\rho t$ = 1.56 $g/cm^3$) and has a low coefficient of friction for fibre plastic material ($\mu_{FP}$ = 0.28). The thermal diffusivity, thermal conductivity and specific heat capacity of Nagpur mandarin are $11.84\times10^{-2}$ $m^2/s$, 0.588 W/m°C and 3.909 kJ/kg°C respectively. The rheological study of Nagpur mandarin juice showed that Newtonian fluid and the Herschel Bulkley model is most suitable to characterise flow behaviour. The textural properties reveal that fracturability with 1% load sensitivity is 10.27 N with respective values of stringiness length (4.04 mm). The total phenol and flavonoid content of the Nagpur mandarin juice contains 168.86 mg GAE/100g and the peel contains 12.4 mg QE/100g respectively. The details achieved in this investigation are a vital source of information for postharvest operations, machine designing, storage and further product development of Nagpur mandarin fruit.

## References


1 FAOSTAT, Food and Agriculture Organization of the United Nations, (2016), Rome, Italy.

2 National Horticulture Board, Area Production statistics year 2020-21, Government of India, New Delhi.

3 Jhade R K, Huchche A D & Dwivedi S K, Phenology of flowering in citrus: Nagpur mandarin (*Citrus reticulate* Blanco) perspective, *Int J Chem Stud*, **6(2)** (2018) 1511–1517.

4 Salehi Fakhreddin, Physicochemical characteristics and rheological behaviour of some fruit juices and their concentrates, *J Food Meas Charat*, **14** (2020) 2472–2488, doi.org/10.1007/s11694-020-00495-0.

5 Mahawar M K, Bibwe B, Jalgaonkar K & Ghodki B M, Mass modelling of Kinnow mandarin based on some physical attributes, *J Food Process Eng*, (2019) doi.org/10.1111/ jfpe.13079.

6 Patil B N, Gupta S V, Bharad S G, Gahukar S J & Patil N B, Physicochemical properties and mass modelling of Nagpur mandarin (*citrus reticulate*) fruit, *J Pharm Innov*, **10(8)** (2021) 1784–1791.

7 Pradhan R C, Naik S, Bhatnagar N & Vijay V, Moisture dependent physical properties of Jatropha fruit, *Ind Crops Prod*, **29(2-3)** (2009) 341–347, https://doi.org/10.1016/ j.indcrop.2008.07.002

8 Kambhampati V, Mishra S & Pradhan R C, Physicochemical characterization and mass modelling of sohiong (*Prunus nepalensis* L.) fruit, *J Food Meas Charact*, **12(2)** (2018) 923–936, DOI:10.1007/s11694-017-9708-x

9 Sonawane A, Pathak S S & Pradhan R C, Physical, thermal, and mechanical properties of bael fruit, *J Food Process Eng*, 2020, e13393. https://doi.org/10.1111/jfpe.13393

10 Mukarkonda S, Patel G & Dwivedi M, Characterization of engineering properties and modelling mass and fruit fraction of wood apple fruit for post-harvest processing, *J Saudi Soc Agric Sci*, **21** (2022) 267–277, https://doi.org/10.1016/ j.jssas.2021.09.005

11 Singh K K & Reddy B S, Post-harvest physico-mechanical properties of orange peel and fruit, *J Food Eng*, **(73)** (2006) 112–120, http://dx.doi.org/10.1016/j.jfoodeng.2005.01.010

12 AOAC, Official methods of analysis association, *Association of Official Analytical Chemists*, (2002), Washington, DC.

13 Ghosh P, Pradhan R C, Mishra S, Patel A S & Kar A, Physicochemical and nutritional characterization of Jamun (*Syzygium cuminii*), *Curr Res Nutr Food Sci*, **5(1)** (2017) 25–35, http://dx.doi.org/10.12944/CRNFSJ.5.1.04

14 Singleton U L, Orthorofer R & Lamnela-Reventos R M, Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent, *Methods in Enzymology*, **299** (1999) 152–178, https://doi.org/10.1016/S0076-6879%2899%2999017-1

15 Sharma H, Singh A K, Borad S & Deshwal G K, Processing stability and debittering of Tinospora cordifolia (giloy) juice using ultrasonication for potential application in foods, *LWT*, **139** (2021) 110584, https://doi.org/10.1016/j.lwt.2020.110584.

16 Rao C G, Engineering for storage of fruits and vegetables: cold storage, controlled atmosphere storage, modified atmosphere storage, (2015) Academic Press.

17 Elansari A M & Hobani A I, Effect of temperature and moisture content on thermal conductivity of four types of meat, *Int J Food Prop*, **12(2)** (2009) 308–315, https://doi.org/10.1080/10942910701687519

18 Topuz A, Topakci M, Canakci M, Akinci I & Ozdemir F, Physical and nutritional properties of four orange varieties, *J Food Eng*, **66(4)** 519–523, https://doi.org/10.1016/j.jfoodeng.2004.04.024

19 Bures M S, Luna M B & Kristina V K, Determination of bioactive components in Mandarin fruits: A review, *Crit Rev Anal Chem*, (2022), DOI:10.1080/10408347.2022.2035209.

20 Pathak S S, Pradhan R C & Mishra S, Physical characterization and mass modelling of dried *Terminalia chebula* fruit, *J Food Process Eng,* 2019, e12992, DOI:10.1111/jfpe.12992.

21 Patel G, Murakonda S & Dwivedi M, Steady and dynamic shear rheology of Indian Jujube (*Zizipus mauritiana* Lam.) fruit pulp with physiochemical, textural and thermal properties of the fruit, *Measurement: Food,* **5** (2022) 100023.https://doi.org/10.1016/j.meafoo.2022.100023.

22 Singh S S, Abdullah S, Pradhan R C & Mishra S, Physical, chemical, textural and thermal properties of cashew apple fruit, *J Food Process Eng*, 2019, e1394.https://doi.org/10.1111/jfpe.13094.