
CHAPTER V

SUMMARY AND CONCLUSION

The present study, entitled “**Sustainable Solutions: Edible Millet Tableware as a Substitute for Single-Use Cutleries in the Food Service Sector**” provides an insight on the formulation, standardisation and characterisation of edible millet cup, bowl, katori, spoon and plate from pearl millet and sorghum (unprocessed, germinated and roasted millet flour). The study also emphasized on the standardisation and characterisation of flower-enriched millet tableware.

The two major millets, Pearl millet (*Cenchrus americanus* (L.) Morrone) and Sorghum (*Sorghum bicolor* (L.) Moench), were chosen for the present study based on their nutritional benefits and cost-effectiveness. Four edible flowers, namely Moringa (*Moringa oleifera* Lam.), Hibiscus (*Hibiscus rosa-sinensis* L.), Rose (*Rosa damascena* Herrm.), and Agathi (*Sesbania grandiflora* (L.) Poir.), were selected for the present study due to its well-documented antioxidant properties, cost effectiveness and local availability.

The study was conducted after obtaining approval from the Institutional Human Ethical Committee (approval number: AUW/IHEC/FSN-21-22/XPD-31) and the plant authentication was obtained from The Director, The Rapinat Herbarium and Centre for Molecular Systematics (RHT), St. Joseph College, Tiruchirappalli, Tamil Nadu. Authentication numbers were assigned as D.S.M 005 for Sorghum, D.S.M 006 for Pearl millet, D.S.M 001 for Moringa, D.S.M 002 for Hibiscus, D.S.M 003 for Rose, and D.S.M 004 for Agathi.

The production and utilization of SUP, particularly single-use conventional cutlery and crockery, is increasing day by day due to its durability and convenience, but it has an enormous negative impact on the ecosystem. Developing and standardising edible and eco-friendly cutlery from edible and biodegradable sources is a novel and emerging research area. The research combining pearl millet and sorghum with edible flowers like hibiscus and rose to develop edible millet tableware is limited. Previous studies have primarily focused on the individual applications of pearl millet, sorghum and edible flowers in food products, but its integration into a functional, sustainable packaging solutions remain unexplored.

The present research addresses the gap by developing and standardising the edible pearl millet and sorghum tableware, enhancing its functionality through roasting and

incorporating antioxidant-rich edible flowers like hibiscus and rose powder. The present study evaluates the sensory acceptance, functional properties and texture analysis of standardised pearl millet and sorghum tableware. Exposure test, microbial load analysis, cytotoxicity and biodegradability were also assessed to find its suitability as a sustainable alternative to SUPs for serving snacks and savories across the food service sector to airline catering. The present study is an innovative approach that offers a unique contribution to sustainable packaging solutions and supports a shift towards environmentally responsible consumption practices.

The standardised proportion and composition can be used to formulate any sized cutlery and crockery. Germinating and roasting the pearl millet and sorghum increased the texture property and holds liquids or solids at ambient, hot and cold temperature for more than 30 minutes to one hour with enhanced overall acceptability. The present innovation eliminates the traditional waste management cycle and ensures sustainable zero waste management. Edible tableware from millets not only adds nutrients to the food but also degrades naturally, if thrown away. It is a small initiative towards achieving several Sustainable Development Goals including zero hunger, good health and well-being, climate change, to save life below water and on land.

The study was conducted in five phases including procurement of raw materials (pearl millet, sorghum, hibiscus, agathi, moringa and rose), developing and characterizing millet tableware enriched with edible flowers.

Phase I was the selection of major millets, based on its nutrient profile, availability (mass cultivation and production) that suits to develop millet tableware. The selected major millets, pearl millet and sorghum were then, sorted, cleaned and used for further conventional processing (germination and roasting). Pearl millet and sorghum were germinated for 35 hours at 30 - 32°C with 60 per cent of humidity whereas roasting of millets was done till popping of few grains. Then the germinated millet was shade dried (for upto 10 hours), milled and stored in an airtight container. Roasted millets were also milled and stored in an airtight container for further processing. Unprocessed, germinated and roasted pearl millet and sorghum grain were characterised based on their physical, optical, technological and functional properties. Total phenolic content and antinutritional factors were also assessed to facilitate in the formulation and standardisation of millet tableware.

Phase II was the formulation, standardisation and characterisation of millet tableware from pearl millet and sorghum in unprocessed, germinated and roasted flour in different

permutations and combinations. Millet tableware was formulated and standardised in a closed specific mold including frustum-shaped cup mold for cup, four-inch rectangular shaped for bowl and circular shaped mold for katori and 5.11 inches mold for spoon and six-inch circular mold for plate and baked at 70°C to 90°C for 8 to 18 minutes under 1500 psi pressure. Millet flour, binder, water along with a minimal quantity of oil and salt were used as the raw material and tried in different variations. The standardised millet tableware was characterised in respect to its nutrient analysis, sensory evaluation, functional properties and texture analysis. It showed that unprocessed and roasted tableware exhibited better properties whereas, germinated millet tableware showed the least properties which was excluded for further analysis. The best variation and proportion were selected for further edible flower enrichment and characterisation.

Phase III was the selection and processing of native edible flowers. The selection was based on its local availability, well-documented antioxidant activity and low cost. Moringa (*Moringa oleifera* Lam.), hibiscus (*Hibiscus rosa-sinensis* L.), rose (*Rosa damascena* Herrm.) and agathi (*Sesbania grandiflora* (L.) Poir.) were the selected edible flowers to incorporate in millet tableware. The selected flowers were collected between 8 a.m. and 9 a.m. to ensure its freshness which was shade dried upto 72 hours and stored in an airtight container at refrigerated temperature (4°C). Nutritional profile, phytochemical screening, antioxidant activity and optical properties were evaluated and hibiscus and rose flower in the dried powder form was selected based on its strong antioxidant activity and it enhance the appearance of the millet tableware.

Phase IV is the formulation, standardisation and characterisation of flower-enriched millet tableware. The flower powder was incorporated into the standardised millet tableware finalized from Phase – II. 3 g of flower powder for cup, whereas, 4 g of flower powder for bowl and katori, 1.5 g and 8 g of flower (hibiscus and rose) powder for spoon and plate, respectively were standardised proportion for enriching millet tableware. Nutrient content, antioxidant activity, optical property, functional properties and texture analysis of the standardised flower-enriched unprocessed and roasted pearl millet and sorghum tableware (cup, bowl, katori, spoon and plate) were carried out in this phase.

Phase V was the analysis of shelf life, toxicity, biodegradability and cost calculation of the standardised flower-enriched pearl millet and sorghum to analyse the suitability in food service sector to replace conventional SUP. Shelf life was analysed through microbial

load, and change in weight for a period of 120 days. Toxicity was evaluated by brine shrimp lethality assay while biodegradability was assessed through soil burial test. The cost of millet tableware was also calculated. Data from the present study was statistically analysed using one-way ANOVA in SPSS software (IBM SPSS Statistics, version 25).

The salient findings of the study are as follows,

Property Analysis of Selected Major Millets

The physical characteristics of pearl millet and sorghum grains differed significantly. The length of the pearl millet grains ranged from 0.34 ± 0.01 mm (PMGG) to 0.47 ± 0.01 mm (PMUG), while sorghum grains were longer, which SGG exhibited 0.56 ± 0.04 mm and SUG exhibited 0.61 ± 0.01 mm length. Sorghum also had broader grains, with SUG showed 0.69 ± 0.02 mm, compared to pearl millet's 0.25 ± 0.02 mm in PMUG.

The length/breadth ratio was higher in pearl millet, especially PMRG (2.19 ± 0.28 mm), while sorghum grains have a lower ratio, generally below 1. In terms of thickness, sorghum grains were significantly thicker (0.53 – 0.58 mm) when compared to pearl millet (0.18 – 0.21 mm). Sorghum grains also have a much higher thousand grain weight and volume, with weight ranged from 23.24 ± 0.08 g (SGG) to 29.43 ± 0.12 g (SUG), and thousand grain volume from 36.05 ± 0.07 ml to 44.63 ± 0.08 ml, compared to pearl millet, which ranged from 8.40 ± 0.03 g to 8.86 ± 0.01 g in weight and 16 ± 0.57 ml to 29.11 ± 0.13 ml in volume. The F-values for these parameters were significant, that confirmed the effects of conventional processing on grain quality.

Germination and roasting of millets also influenced the flour yield. Germinated millets yielded higher flour due to better water retention, while roasted millets had lower yields due to moisture loss during heating. As, PMUG yielded 90.4 per cent flour, while PMGG yielded the highest at 94 per cent. In sorghum, SGG exhibited the highest yield with 92.6 per cent, while SUG and SRG yielded around 90 per cent.

Germination of millets significantly reduced the bulk density and enhanced moisture content while negatively affecting water and oil absorption capacities. Roasted millets showed an improved water and oil absorption capacities with decreased moisture content. Swelling capacity was lowest in germinated pearl millet ($2.32 \pm 0.1\%$) and sorghum ($2.40 \pm 0.03\%$) while roasted pearl millet ($3.25 \pm 0.04\%$) and unprocessed sorghum flour ($3.59 \pm 0.03\%$) exhibited the highest swelling capacity. Ash content was significantly similar among unprocessed and processed millet flour from 19.03 ± 1.65 per cent (PMRF) to 20.46 ± 0.06 percent (SRF). Total phenolic content was highest in roasted pearl millet and sorghum flour

followed by germinated and unprocessed millet flour. Antinutritional factors, namely, phytic acid, tannin, and saponin was reduced after germination of pearl millet and sorghum. Processing of pearl millet and sorghum considerably lowered the phytic acid and tannin levels ($p < 0.05$) that enhanced the nutritional content and bioavailability of the millet tableware.

The FTIR spectra of unprocessed, germinated, and roasted pearl millet and sorghum flours revealed significant compositional and structural differences. Unprocessed flour showed characteristic peaks for hydroxyl, amine, and aliphatic hydrocarbon groups, and a strong peak at 1743 cm^{-1} (aldehyde groups and tannin) which was absent or weak in processed flour. Roasted flour exhibited broader O–H stretching peaks, indicating stronger hydroxyl interactions or hydrogen bonding, and distinct peaks in the fingerprint region ($995.27, 856.39, 648.08\text{ cm}^{-1}$), suggesting better-organized structural features. Germinated flour displayed sharper peaks at 1080.14 and 439.77 cm^{-1} , reflecting unique molecular arrangements. The variations in peak highlighted the distinct structural and molecular characteristics among the unprocessed, germinated and roasted pearl millet and sorghum flour.

The unprocessed pearl millet and sorghum flour had the highest crystallinity with sharp, well-defined peaks, whereas germinated pearl millet and sorghum flour exhibited reduced crystallinity due to structural disruption of double helices, as evidenced by lower peak intensities and smaller crystal sizes. Roasted pearl millet and sorghum flour increased the crystallinity, resulting in intermediate crystal sizes and sharper peaks than germinated millet flour, indicating that thermal processing of molecular and structural organization.

Unprocessed and processed pearl millet and sorghum exhibited significant differences in physical and technological properties. Total phenolic content was increased after roasting millets whereas, antinutritional factors were decreased after u processing of millets. FTIR showed sharp peaks between amylose and amylopectin region and XRD showed decreased crystalline size after processing. The findings of Phase-I aided in the formulation of thick batter for millet tableware standardisation with varying proportions of millet flour and binder.

Characterisation of Standardised Millet Tableware

The weight of the standardised millet tableware varied and processing of millets played a vital role. The average weight of the cup, bowl, katori, spoon and plate were $15.14 \pm 3.19\text{g}$, $20.87 \pm 3.58\text{ g}$, $19.20 \pm 2.35\text{ g}$, $8.51 \pm 1.29\text{ g}$ and $42.32 \pm 4.69\text{ g}$, respectively.

Nutrient analysis showed that, sorghum tableware generally had higher moisture when compared to pearl millet tableware, with unprocessed sorghum tableware ($3.57 \pm 0.04\%$) exhibited the highest moisture content. Ash content was highest in germinated pearl millet ($12.94 \pm 0.10\%$) as compared to its counterparts. Carbohydrate content was higher in sorghum tableware, than pearl millet tableware. Protein content was highest in roasted sorghum tableware among all tableware, whereas fat content was significantly lower in sorghum tableware, especially in germinated and roasted forms. Fiber content was higher in pearl millet and sorghum tableware, particularly in roasted form. Vitamin C was marginally higher in sorghum tableware especially in germinated form, while roasted pearl millet tableware showed the highest calcium and iron content. Phosphorus content was highest in pearl millet tableware. Roasted pearl millet tableware exhibited higher nutrient content, especially fiber, iron, and phosphorous content, while sorghum tableware excelled in carbohydrate, protein, and calcium content.

Sensory evaluation of the standardised millet cup, bowl, katori, spoon and plate showed a score between 6.7 to 8.9 which was slightly liked to extremely liked category. All the tableware were standardised in a unique mold; hence the shape or appearance are uniform and scored above 7. The colour of roasted tableware was darker that scored less as compared to its germinated and unprocessed counterparts, exhibiting lighter shade. Similar pattern was found in taste, flavour and crispiness preferences, indicating germinated tableware scored better as compared to unprocessed and roasted counterparts. The overall acceptability of all the tableware scored under liked moderately to liked extremely category.

FTIR of pearl millet tableware showed that, PMUT, PMRT, and PMGT highlighted a progressive change in molecular structure from unprocessed to roasted and germinated forms. PMUT retained its original moisture and hydroxyl properties, but PMRT has significant crystallinity and less moisture, and PMGT has mild structural alterations. Whereas, SUT has a greater abundance of organic functional groups, such as hydroxyls, carbonyls, and amides and SGT, emphasized on inorganic compounds and less organic compounds whereas SRT had inorganic compounds that showed consistent mineral residues or simple structures.

TGA of millet tableware found that, a total degradation of 77.6 per cent, 88.8 per cent and 123.7 per cent in unprocessed, germinated and roasted pearl millet tableware and 82.8 per cent, 99.8 per cent, and 100.3 per cent in unprocessed, germinated and roasted sorghum tableware was observed. This showed that sorghum tableware exhibited more thermal degradation than pearl millet tableware.

At ambient temperature, water absorption rate of the cup showed that, the highest absorption rate was found in PMUC (14.97 %) after exposing for 40 minutes and sorghum cups showed a lesser absorption rate. Germinated millet bowl (9.85% in PMGB, 13.43 % in SGB) exhibited the highest water absorption rate followed by its unprocessed and roasted counterparts. Unprocessed pearl millet katori (7.24%) and roasted sorghum katori (8.19%) has the least water absorption rate whereas the highest rate was observed in PMGK (12.69%) and SGK (11.59%). PMGS showed the highest water absorption rate at initial (21.05%) which was decreased (14.07%) after exposing in water for 40 minutes while SGS showed an overall highest water absorption rate. Among millet plate, PMGP and SUP showed the highest water absorption rate after 40 minutes of exposure.

At hot temperature (80°C), water absorption rate was highest among all tableware as compared with, exposing it at ambient temperature (32°C). Millet spoon showed the highest rate, particularly for PMGS (35.14–56.73%) and SGS (31.34–54.35%). Millet katori also absorbed significant amount of water, with PMGK and SGK exhibited 43.42 per cent and 36.45 per cent of water at 40 minutes. Millet bowl exhibited moderate absorption, peaking at 38.24 per cent in PMGB and 32.14 per cent in SGB at 40 minutes. Millet cup and plate exhibited comparatively lower rates, as PMGC and SGC, PMGP and SUP absorbed more water when compared to its pearl millet and sorghum counterparts, respectively. Sorghum tableware showed lower water absorption than pearl millet tableware, which withstood for prolonged duration, exhibited its hydrophilic nature.

At cold temperature, Millet bowl and millet plate showed the highest water absorption, particularly for PMGB (28.78%) and PMGP (31.53%) when exposed upto 40 minutes. Millet katori also demonstrated significant water absorption, with 24.12 per cent in PMGK and 27.45 per cent in SGK after 40 minutes of exposing in water. In contrast, millet cup and millet spoon displayed lower absorption rates as compared to millet bowl, plate and katori, with PMGS (14.54%) and PMGC (2.93%) reaching its highest absorption rate at 40 minutes. Water absorption test of millet tableware showed that pearl millet absorbed more water than sorghum cups at ambient, hot and cold temperatures. Germinated tableware absorbed more water as compared to its roasted and unprocessed counterparts.

The texture analysis of pearl millet and sorghum cup, bowl, katori, spoon, and plate revealed significant difference influenced by processing methods. Germinated tableware exhibited the lowest hardness and elasticity, indicating softer texture, while roasted tableware consistently demonstrated enhanced hardness and structural strength. Germinated pearl millet (PMGC, 31.64 ± 3.16 N) and sorghum (SGC, 16.33 ± 0.04 N) cup showed the

lowest hardness force, while PMGC had the highest elasticity ($63.93 \pm 5.49\text{N/mm}^2$). Among bowl, roasted sorghum (SRB, $50.94 \pm 6.92\text{ N}$) displayed the highest hardness and elasticity, as compared to unprocessed and germinated bowl. In katori, roasted pearl millet (PMRK) showed the best hardness and elastic force, while germinated katori were weakest. For spoon, unprocessed sorghum (SUS) improved elasticity, when compared to pearl millet though germination increased hardness in PMGS. In plate, roasting enhanced hardness, while unprocessed plates retained the highest elasticity. Texture analysis of millet tableware showed that roasted millet tableware exhibited the highest hardness, break force and elastic force, followed by unprocessed millet tableware. Germinated pearl millet and sorghum tableware exhibited the least texture properties.

Drop test showed that, sorghum tableware showed a highest resistance as compared to its pearl millet counterparts, particularly in its roasted form with the highest durability. Millet cups had drop resistance upto 70 cm and completely broken at 110 cm expect PMRC and SRC which broken at 130 cm and above. Pearl millet and sorghum bowl exhibited no cracks upto 90 cm and its germinated variants broken completely at 140 cm whereas, PMUB and SUB broken at 150 cm and PMRB and SRB were not broken at 150 cm. Millet katori showed that, katori withstood upto 70 cm without any cracks, unprocessed and roasted katori was completely broken at 110 cm and 120 cm respectively whereas PMRK and SRK broken when dropped from a height of 130 cm. The lowest drop resistance was found in millet spoon which started to broke at 40 cm in germinated variants and 50 cm in unprocessed and roasted variants. PMRS and SUS exhibited highest drop resistance among spoon that broken at 80 cm. Millet plate showed no cracks upto 80 cm and PMUP, PMGP, SUP and SGP was completely broken when dropped from 130 cm and PMRP and SRP broken at 140 cm.

Pearl millet and sorghum tableware showed an optimum quantity of macro and micronutrients. Pearl millet has the highest fat, fiber, iron and phosphorus content, while sorghum tableware exhibited highest carbohydrate, and protein content. Moisture and ash percentage, Vitamin C and calcium content of millet tableware were also showed significant difference. Sensory evaluation of germinated tableware scored better overall acceptability followed by its unprocessed and roasted counterparts and all the standardised millet tableware scored between slightly liked to liked extremely category. FTIR showed varying sharp to weak peaks in unprocessed and processed tableware. Roasted tableware exhibited highest thermal properties followed by germinated and unprocessed counterparts. By considering the results obtained from the properties including water absorption rate, texture

analysis and drop test, the unprocessed and roasted pearl millet and sorghum tableware (cup, bowl, katori, spoon, and plate) showed better properties which was selected for further enhancement and characterisation. Conversely, the variants of germinated pearl millet and sorghum were not included in the subsequent flower powder enrichment and characterisation as they showed the least properties.

Property Analysis of Native Edible Flowers

Moringa flower powder (MFP) had the highest moisture per cent ($8.9 \pm 0.19\%$), protein (5.85 ± 0.09 g), vitamin C (108.66 ± 5.68 mg), iron (3.85 ± 0.05 mg), and calcium (82.7 ± 0.24 mg) content, while rose flower powder (RFP) showed highest carbohydrates (15.08 ± 0.09 g) and fiber (8.92 ± 0.05 g) content. Hibiscus flower powder (HFP) had the highest fat content (4.21 ± 0.05 g) and agathi flower powder (AFP) showed the highest ash content (9.77 ± 0.09 %). The nutrient analysis of selected edible flower powder showed a significant difference between each flower powder.

Moringa flower powder (MFP) exhibited a rich presence of amino acids, carbohydrates, phenols, glycosides, and tannins across all tested solvents and phytic acid, alkaloids, flavonoids, saponin, anthocyanins and terpenoids were absent in aqueous extract. Rose flower powder (RFP) was similarly rich, showing strong presence of alkaloids, amino acids, flavonoids, carbohydrates, phenols, phytic acid, saponin, and tannin, although slightly less consistent than HFP. Agathi flower powder (AFP), exhibited good levels of amino acids, carbohydrates and exhibited a weaker presence of alkaloids, anthocyanins, terpenoids, phytic acid and tannin in aqueous and ethanol solvents. The results highlighted that HFP and RFP showed the highest presence of phytochemical content, followed by MFP and AFP. HFP and RFP were the most diverse, while AFP and MFP demonstrated more selective profiles, making them suitable for specific applications. Antioxidant activity of the edible flowers showed that, the IC_{50} values of RFP showed strong (46.69 μ l/ml) antioxidant activity, followed by HFP (54.92 μ l/ml), AFP (78.09 μ l/ml), which possessed moderate activity, and MFP (139.88 μ l/ml) showed weak activity. These findings highlighted the significant antioxidant potential of RFP and HFP, making it as an ideal choice for enhancing the millet tableware.

Flower enhancement increases the optical property of millet tableware. AFP exhibited the highest lightness (48.56 ± 1.12) indicating a lighter appearance, while Hibiscus flower powder (HFP) had the lowest lightness (14.3 ± 0.20). HFP (20.16 ± 1.01) and RFP (19.37 ± 0.41) displayed the most intense red tones, while MFP had the least redness (6.43

± 0.08). Yellowness (b^*) was more intense in MFP (15.28 ± 0.14) and minimal in RFP (2.35 ± 0.15). The ΔE values indicated overall colour differences, ranged from 0.49 ± 0.16 in MFP to 1.78 ± 0.81 in AFP, showing minor overall colour variation among the flower powder. The F-values confirmed significant differences ($p < 0.05$) for L^* , a^* , and b^* parameters that emphasised the distinct optical characteristics of selected edible flower powder.

A comprehensive evaluation of hibiscus (HFP), rose (RFP), moringa (MFP), and agathi (AFP) flower powder highlighted their unique nutritional, phytochemical, antioxidant activity and optical properties. Nutritionally, RFP had the highest carbohydrate and fiber content, while MFP excelled in protein, calcium, and vitamin C. Optical properties showed HFP and RFP darker and redder shades, while MFP exhibited the highest yellowness. Antioxidant activity was strongest in RFP, followed by HFP that showed strong inhibition activity with strong IC_{50} values. HFP and RFP were selected for enhancing millet tableware due to its nutrient profile, strong antioxidant activity with vibrant red hues. Incorporation of HFP and RFP into unprocessed and roasted pearl millet and sorghum tableware (cups, bowls, katori, spoons, plates), enhances the nutrient content, antioxidant activity and functional properties.

Characterisation of Standardised Flower-Enriched Millet Tableware

The nutrient analysis of pearl millet and sorghum flower-enriched tableware revealed significant difference after roasting of millets and flower powder enrichment. Pearl millet tableware showed that, moisture content ranged from 3.20 ± 0.02 per cent (PMUT) to 3.91 ± 0.05 per cent (PMRT) respectively. PMRHT showed highest carbohydrate (66.38 ± 0.08 g) and PMRT showed highest protein (12.94 ± 0.47 g) content. Fat content was highest in PMURT (8.56 g) and the least content was observed in PMRT (5.74 g). Fiber content was increased in flower-enriched tableware, particularly in hibiscus-enriched (12.42–12.86 g) variant. Vitamin C content was exhibited similar results (0.29–0.39 mg) in all variants. Iron content (6.43–7.46 mg) and calcium content (32.34–34.44 mg) were improved in roasted pearl millet with flower-enriched variants. Phosphorus content consistently increased with roasting and flower enrichment, and the highest content was observed in PMRHT (206.26 mg).

Sorghum tableware showed that, the moisture content was between 3.40 to 4.10 per cent whereas, ash content was between 6.12 to 6.41 per cent, respectively. Carbohydrate content increased notably in unprocessed and flower-enriched tableware and the highest content was observed in SUHT (78.13 ± 0.03 g), whereas protein content was highest in

roasted sorghum with hibiscus enriched tableware (SRHT, 12.19 ± 0.13 g). Fiber content is consistently elevated in flower-enriched tableware, with hibiscus and rose showed the highest content (13.64–13.7 g). Fat content moderately increased after flower enrichment, and vitamin C remained low across all variants (0.27–0.37 mg). SRRT showed the highest iron content (5.50 ± 0.80 mg) and calcium content (33.96 ± 0.03 mg). Phosphorus content was significantly improved in SURT, SRHT and SRRT (158 mg). The findings demonstrated that the nutrient content was enhanced in roasted and flower-enriched tableware, particularly in carbohydrates, protein, fiber, and iron, making it a sustainable and nutrient-dense option.

Antioxidant value of flower-enriched pearl millet and sorghum showed that flower enrichment increased the IC_{50} values. Hibiscus enriched pearl millet tableware and rose enriched sorghum tableware showed highest inhibition rate with strong antioxidant property (PMUHT exhibited $46.81 \mu\text{g/ml}$ and PMRHT exhibited $89.93 \mu\text{g/ml}$, whereas SURT showed $39.87 \mu\text{g/ml}$ and SRRT showed $46.76 \mu\text{g/ml}$, respectively). Roasted millet tableware (PMRT, $144.76 \mu\text{g/ml}$ and SRT, $72.99 \mu\text{g/ml}$), showed slightly lesser antioxidant activity than its unprocessed millet tableware (PMUT, $88.34 \mu\text{g/ml}$ and SUT, $51.91 \mu\text{g/ml}$).

The optical property of pearl millet and sorghum tableware were significantly influenced by processing millet (roasting) and shade dried flower powder enrichment (hibiscus and rose powder). Pearl millet tableware exhibited lightness (L^*) values ranged from 12.35 (PMUHT) to 16.35 (PMRHT) and sorghum tableware ranged from 9.74 (SRT) to 14.57 (SRRT) due to the Maillard reaction and pigment retention. Redness (a^*) values showed significant variations, with pearl millet having lower red tones (0.39–1.62) and sorghum exhibiting slightly higher values (1.38–4.01) among millet tableware. Yellow hue (b^*) were enhanced in roasted and flower-enriched variants, with values reaching 6.32 in pearl millet (PMRHT) and 7.53 (SRRT) in sorghum, attributed to caramelization and stable pigments. Total colour differences (ΔE) were most prominent in roasted tableware (10.3 for pearl millet and 8.18 for sorghum), reflecting the combined effects of roasting and flower incorporation. Statistically significant F values ($p < 0.05$) confirmed the effect of roasting and flower enrichment on optical property of flower-enriched millet tableware that increased the visual appeal to produce sustainable tableware.

Sensory evaluation of pearl millet and sorghum cup enriched with flower powder revealed that appearance and colour of the roasted millet cup enriched with hibiscus and rose flower exhibited liked very much category. While taste, flavour, crispiness and overall acceptability showed a least sensory scores in flower enriched cup, when compared to its unprocessed and roasted cup which showed better scores. Among flower-enriched pearl

millet and sorghum bowl, katori and plate showed that, shape or appearance and colour parameters has not affected in roasted millet or its flower enriched variants. Flavour, crispiness and overall acceptability of flower enriched bowl was around liked moderately category whereas roasted and unprocessed bowl scored liked extremely category. Flower-enriched pearl millet and sorghum spoon showed that shape or appearance and colour scored similar results whereas the other parameters including crispiness, flavour, taste and overall acceptability was slightly altered by flower powder enrichment and moderately liked by semi-trained panel members as compared to its unprocessed and roasted pearl millet and sorghum spoon.

The FTIR spectra demonstrated that roasted pearl millet and sorghum with hibiscus or rose flower powder enrichment significantly influenced the structural and functional properties of the tableware. Unprocessed forms retain more moisture and hydroxyl groups, while roasted variants exhibit molecular rearrangements, especially in polysaccharides, lipids, and aromatic compounds and flower powder enrichment showed additional peaks that confirmed the presence of functional compounds. Both pearl millet and sorghum tableware enriched with edible flower powder showed different sharp to broad and weak peaks that confirmed the presence of O-H stretching, C-H stretching of aliphatic compounds, C=O stretching associated with esters or carboxylic acids, and N-H bending indicative of amides. The presence of FTIR spectra showed the impact of processing and flower enrichment which significantly altered the biochemical and structural properties of the tableware, enhancing its functional profile.

The TGA analysis of flower-enriched pearl millet and sorghum-based tableware demonstrated distinct thermal degradation behaviour influenced by processing (roasting) and flower enrichment (hibiscus and rose). Moisture and volatile losses (20°C–200°C) vary across tableware, with roasted variants exhibiting slightly higher thermal degradation. Decomposition of organic compounds took place between 300°C–680°C and the highest mass reduction in unprocessed flower-enriched millet (74.8% for PMUHT) and roasted sorghum (78% for SRT), indicating loss of high organic content. Minimal inorganic contributions are reflected in modest residues after 700°C, with unprocessed samples retaining slightly more inorganic matter compared to its roasted variants. Total mass loss highlighted the impact of flower enrichment and roasting, with pearl millet and sorghum showing significant variations in stability and degradation profiles. Roasted samples exhibit complete thermal decomposition, while flower enrichment enhances organic compounds.

The exposure test of flower-enriched pearl millet and sorghum tableware (cups, bowls, katori, spoons, and plates) revealed the suitability for serving food and beverages under ambient, hot, and cold conditions. Flower-enriched cups could hold ambient and hot liquids for 25 minutes and 12 minutes, respectively while it could hold cold liquids for 60 minutes, with roasted variants showing slightly better water resistance. Edible cup could be used to serve any beverages at temperature below 80°C. Flower-enriched millet bowl and katori resisted water absorption for 40 minutes at ambient temperature, 30 minutes at hot temperature and 60 minutes at cold temperature with no traces of water absorption that aided in serving snacks, side dishes, ice cream and salads. The flower-enriched pearl millet and sorghum spoon showed no water absorption till 20 minutes, 25 minutes and 45 minutes at ambient, hot and cold temperatures respectively, which demonstrated versatility for various culinary services. Unprocessed flower-enriched pearl millet and sorghum plate exhibited no absorption till 35 minutes, 30 minutes and 45 minutes at ambient, hot and cold temperatures, respectively whereas its roasted variants hold to ambient, hot and cold temperatures for 40 minutes, 30 minutes and 60 minutes respectively, that making them suitable for serving dry and wet snacks and small meals. Flower enrichment slightly reduced water-holding duration compared to its unprocessed and processed variants but maintained functionality, that highlighted its potential as sustainable tableware for diverse food service applications.

Water absorption rate showed that cup absorbed highest amount of water when exposed at hot temperature followed by exposure at ambient and cold temperatures. Pearl millet showed highest absorption rate as compared to sorghum and flower enrichment increased the water absorption rate at all the three temperatures. Flower-enriched millet bowl absorbed 5.08 per cent to 12.12 per cent at ambient temperature, 22.78 per cent to 33.25 per cent at hot water and 17.85 per cent to 22.96 per cent of water absorbed when exposed at cold liquids for 40 minutes. Flower-enriched bowl absorbed more percentage of water when compared to its unprocessed and roasted millet bowl. Flower-enriched millet katori exhibited, 7.24 – 10.93 percentage, 25.87 – 34.87 percentage and 19.56 – 21.87 percentage of water absorbed when exposed for 40 minutes at ambient, hot and cold water. The water absorption rate in flower enriched spoon was between 11.11 per cent (SRHS) to 16 per cent (PMRS) at ambient temperature, whereas the highest water absorption rate was observed in PMURS (40.98%) and the lowest rate was observed in PMRHS (34.51%) at hot temperature and at cold temperature, water absorption rate was ranging between 9.25 per cent (SRS) to 15.24 per cent (PMUHS, PMRRS), respectively. Flower enrichment enhanced water absorption of millet plate in which, rose-enriched (PMURP and SRRP) and hibiscus-

enriched plate (PMUHP and SRHP) was higher than its unprocessed and roasted counterparts. Water absorption rate was higher at the initial phase (within 20 minutes) as compared to water absorption at 40 minutes across all variants of flower-enriched millet tableware.

Texture analysis showed that sorghum tableware was harder than pearl millet tableware, and hibiscus enrichment further enhanced hardness in both unprocessed and roasted variants. Flower-enriched millet cup showed the highest hardness and break force which was observed in SUHC (86.28 ± 1.13 N) and the lowest was found in PMRC (40.15 ± 2.26 N) whereas PMURC (189.3 ± 2.83 N/mm²) and PMRC (0.06 ± 0.02 N/mm²) exhibited the highest and lowest elastic force. In, Flower-enriched millet bowl, the highest hardness and break force and elastic force was observed in SRRB (49.53 ± 3.34 N) and SRB (373.16 ± 8.17 N/mm²) whereas the lowest was found in PMRB (21.71 ± 2.76 N) and PMRRB (70.55 ± 12.98 N/mm²) respectively which showed that sorghum bowl exhibited better hardness and elastic force than its pearl millet counterparts. SRRK (100.51 ± 2.41 N) and SURK (39.06 ± 0.51 N) showed the highest and lowest hardness force whereas, PMRK (112.2 ± 5.56 N/mm²) and PMUK (40.87 ± 2.49 N/mm²) exhibited the highest and lowest elastic force among flower-enriched millet katori. The hardness force of flower-enriched millet spoon was ranging between 47.28 ± 0.66 N (SURS) to 64.20 ± 3.28 N (PMRHS) and the elastic force was between 57.32 ± 0.72 N/mm² (SUHS) to 97.76 ± 0.84 N/mm² (SRS), respectively. Flower-enriched millet plate showed that sorghum plate (49.48 ± 1.43 N to 76.06 ± 0.81 N) has the highest hardness force as compared to its pearl millet (48.06 ± 2.14 N to 55.72 ± 1.66 N) counterparts. The highest elastic force was observed in SUHP (275.64 ± 3.33 N/mm²). Flower enrichment in millet tableware showed a positive impact on texture analysis.

Roasting significantly enhanced the impact resistance of pearl millet and sorghum tableware, including cup, bowl, katori, spoon, and plate, while flower enrichment slightly reduced its drop resistance in unprocessed variants. Unprocessed pearl millet and sorghum cups withstood up to 70 cm without cracks, and first crack at 80 - 90 cm and completely broken at 110 cm and flower enrichment showed its first crack earlier at 80 cm for PMUHC, PMURC and completely broken at 110 cm whereas roasted cups, however, resisted cracks up to 100 cm and broken at 110 cm. Similar trends are observed in bowl, katori, spoon, and plate, where unprocessed variants have lower drop resistance than roasted tableware, and flower-enriched variants cracked earlier. Flower-enriched bowl exhibited its first crack at 130 cm and completely broken at 150 cm except roasted bowl which showed cracked at

bottom and corners at 150 cm. Flower-enriched katori withstood drop resistance upto 90 cm and completely broken between 110 cm to 120 cm except its roasted variant which exhibited its bottom crack at 120 cm. Flower-enriched millet spoon exhibited the lowest drop resistance which exhibited no cracks when dropped from 30 cm and completely broken at 70 cm expect PMRS and SUS. Flower-enriched millet plate exhibited drop resistance upto 80 cm and completely broken between 110 cm to 130 cm expect PMRP and SRP. Drop resistance of flower-enriched millet tableware exhibited cracks and broken earlier as compared to its unprocessed and roasted tableware.

Analysis of Shelf Life, Toxicity, and Biodegradability of Standardised Millet Tableware

Sorghum tableware generally exhibited a decreased colony count than pearl millet tableware and roasting of millets further reduced the microbial load. SRT was the superior variant with decreased microbial load and flower powder enrichment has not also increased the microbial load as compared to its unprocessed and roasted millet tableware that indicated the anti-microbial activity of selected edible flowers.

Sorghum and pearl millet tableware exhibited gradual weight increase over a 120-day storage period, with sorghum cups (SUHC) showing the highest increase from 13.42 g to 14.07 g, indicating steady moisture absorption, while PMRC, PMURC and PMUC showed more stable moisture retention with minimal increase. Sorghum bowl (SUHB) exhibited an highest increase from 18.47 g to 19.32 g, while pearl millet bowls (PMUB) exhibited highest increase from 22.72 g to 23.57 g by Day 120. Flower-enriched millet katori showed a weight gain of 0.2 g to 0.37 g and the highest weight gain was observed in SURK (18.3 g on day 1 to 18.67 g on day 120) whereas the lowest weight gain was observed in PMUK, PMRRK and SRK. Flower-enriched millet spoon showed a weight gain of 0.30 g to 0.45 g and the highest weight gain was found in SRHS (7.81 g on day 1 to 8.26 g on day 120) while the lowest was found in PMRHS (8.12 g on day 1 to 8.42 g on day 120) and SUS (7.9 g to 8.2 g from day 1 to day 120). Flower-enriched millet plate showed a total weight gain between 0.3 g and 0.53 g from day 1 to day 120. The highest weight gain was observed in SRP with 0.53 g of weight gain (45.09 g on day 1 to 45.62 g on day 120) and the lowest weight gain (0.30 g) was observed in SUP (46.17 g to 46.47 g from day 1 to day 120) respectively.

The cytotoxicity of pearl millet and sorghum tableware was evaluated brine shrimp lethality assay. Pearl millet tableware, exhibited low lethality at lower concentrations upto 750 µg/ml, which was slightly increased at higher concentrations (1000 and 1500 µg/ml).

10 percentage of mortality was observed in PMUHT, PMURT and PMRRT whereas 7 per cent in PMRHT and three per cent in PMUT and PMRT after 24 hours of treatment. Sorghum tableware exhibited a three to ten percentage of mortality rate where SRT has the lowest mortality percentage (3 %) whereas SUT, SRHT and SRRT showed seven per cent and SUHT and SURT exhibited 10 per cent of mortality rate. Flower incorporation increased the brine shrimp mortality rate due to the presence of phenolic compounds that alter the pH of brine solution.

Soil burial test observed that the millet tableware was completely degraded within 12 days in wet top soil with a gradual weight loss. PMRRT, SUHT and SRHT showed the highest weight residual on initial days and flower enrichment slightly affected the degradation at initial stage. The standardised flower-enriched tableware was completely biodegradable.

Feasibility Analysis of Millet Tableware

The cost for unprocessed tableware was around Rs.150/- for cup, Rs.180/- for bowl and katori, Rs.100/- for spoon and Rs.200/- for plate respectively. Rs. 10 for roasted millet tableware and Rs.15/- for flower-enriched tableware was increased as the processing and raw material cost. Hence, the cost of the millet cup per piece is Rs.1.5/- to Rs. 1.65/-, for bowl and katori, Rs.1.80/- to Rs.1.95/-, for spoon, Rs.1/- to Rs.1.15/- and for plate, Rs.2/- to Rs.2.15/- respectively.

CONCLUSION

The characterisation of standardised flower-enriched millet tableware involves a multifaceted evaluation, including nutrient composition, functional properties, texture analysis and consumer acceptability. The results of the property analysis highlighted the potential of millet tableware as a sustainable alternative to single-use plastics, offering both functional properties and health benefits due to the inclusion of antioxidant-rich flower powder. The characterisation ensured that the tableware is not only eco-friendly but also meets the sensory and structural integrity for its practical use in food service applications.

The physical, technological, and nutritional properties of pearl millet and sorghum grains, emphasised the impact of processing methods such as germination and roasting. Sorghum grains are larger and thicker than pearl millet, with higher weight and volume, while pearl millet exhibited a higher length-to-breadth ratio. Germination enhanced flour yield and reduced antinutritional factors, such as phytic acid and tannin. Roasted millets exhibited improved water and oil absorption capacity, decreased moisture content, and enhanced total phenolic content. Functional properties revealed that germination reduced crystallinity and disrupts molecular organization, whereas roasting promoted molecular packing in millet flour.

The millet tableware standardised from pearl millet and sorghum, focused on the effects of processed (roasting, germination) and unprocessed variants, on its nutrient profile, functional properties and texture analysis. Roasted pearl millet tableware exhibited highest nutrient content, especially fiber, iron and phosphorous content, while sorghum tableware excelled in carbohydrate, protein and calcium content. Sensory evaluation of millet tableware was between moderately liked to liked extremely category. Roasting enhanced texture analysis, whereas its germinated counterparts showed reduced hardness and break force and elasticity but increased water absorption rate. Water absorption rate demonstrated that all the tableware absorbed water at initial phase and exhibited a reduced absorption after 30 minutes of exposure. FTIR and TGA analyses revealed compositional and thermal stability differences, with roasted tableware exhibited complete thermal degradation. Drop tests further confirmed the highest resilience of roasted tableware as compared to its germinated counterparts. Roasted millet tableware emerged as an optimal formulation due to its nutrient density, and better texture analysis, making it as a sustainable alternative to single-use plastics. Germinated tableware was excluded from further development due to its decreased texture properties.

Four edible flowers (Agathi, Moringa, Hibiscus and Rose) were selected, and it has good quantity of micronutrients. Phytochemical screening of selected edible flowers confirmed the presence of bioactive compounds. Strong antioxidant activity was found in hibiscus and rose flower powder and its enrichment in millet tableware enhanced the optical and functional properties.

The characterisation of flower-enriched millet tableware highlighted the impact of roasted millet and flower enrichment (hibiscus and rose) on its nutritional, sensory, and functional and texture properties. Roasting and flower enrichment significantly improved the nutritional profile, boosting carbohydrates, protein, fiber, and iron, with hibiscus-enriched variants excelled in fiber and antioxidant activity. Roasting of millets enhanced visual appeal, crispiness, and consumer acceptability, while flower enrichment introduced unique sensory attributes and high consumer acceptance was noted in roasted variants. FTIR and TGA revealed molecular and thermal changes, and flower powder enrichment contributed distinct functional groups and roasted tableware exhibited highest thermal degradation. Roasted tableware exhibits superior impact resistance, water retention, and texture analysis compared to its unprocessed and flower-enriched counterparts. Roasted millet flower-enriched tableware exhibited as the nutrient rich variants with better sensory scores and enhanced texture properties that emerged as a sustainable alternative for diverse culinary applications and a sustainable eco-friendly innovation. Shelf life analysis showed that roasted and flower-enriched tableware exhibited lowest microbial load as compared to its unprocessed counterparts. Change in weight exhibited that the tableware showed a minimal weight gain due to moisture absorption and roasted variants exhibited lowest weight gain indicating better moisture resistance. Cytotoxicity tests confirmed ten percentage of mortality due to the presence of phenolic content but within safe limits. All the tableware was degraded within 12 days in wet top soil. Cost analysis highlighted the affordability of the millet tableware, with slight cost increases for processing and flower enrichment. The flower-enriched millet tableware standardised in the present study is a promising solution to replace and reduce single-use cutlery in food service sector. Its nutritional profile with enhanced functional properties and biodegradability defines as a sustainable and viable solution for diverse culinary applications.

Strength of the Study

1. The present study proved that the standardised edible millet tableware could be a better replacement for single use cutleries in food service sector.
2. Flower enrichment in millet tableware increased the nutrient profile, antioxidant activity, and sensory appeal with better functional and mechanical properties.
3. Edible millet tableware is less toxic with a shelf life for 120 days and easily degradable within 15 days under soil burial test.

Limitations of the Study

The study focused only on two major millet and four locally available edible flowers, by restricting variety of raw materials which could be investigated further.

Future Recommendations

1. Conduct long-term studies on storage stability and degradation under diverse conditions.
2. Perform exposure tests in various conditions, including oil, alkaline, and acidic medium.
3. Analyse long-term biodegradability under varying environmental conditions.
4. Incorporating bioactive compounds or nanoparticles could improve the antioxidant and functional properties of millet tableware.
5. Consumer acceptability can be done.