

Original Research Article

Sensory Quality, Aroma and Shelf-life Enhancement of Vegetables Irradiated with Mid-infrared

Abstract

The perishable nature of vegetables results in early consumption and limits exports. Research on technologies to enhance the shelf life is ongoing. As one of the study, we irradiated the vegetables with 2-6 μm mid-infrared ray. The irradiated vegetables shelf life increased by 16-900% and 9-314% (duration) respectively in room temperature and refrigeration. Also the vegetables taste and aroma enhanced. The favorable changes caused by 2-6 μm mid-infrared in vegetables physico-chemical characteristics are demonstrated with various instrumentation and sensory expert panel results.

Keywords: MIRGA, 2-6 μm mid-infrared, vegetables, irradiation, shelf life, sensory attributes, enhancement, economical

1. Introduction

Owing to the lack of proper storage technology, daily tons of vegetables are thrown away, and the exact quantity calculation is very hard. Around 2.5 decades ago, we consumed “in-season” fresh fruits and vegetables. Trade and commerce now forced to develop an extended shelf life and possibly an enhanced sensory attributes. Shelflife enhancement is extended by conventional, physiological, biochemical and biotechnological techniques, but results are not constant. In this research, we invented a 2-6 μm mid-infrared generating atomizer (MIRGA). The generated 2-6 μm mid-infrared (MIR) was applied over the vegetables. Mid-infrared (MIR) refers to the wavelength range in the electromagnetic spectrum that lies between the near-infrared and far-infrared regions. The electromagnetic radiation from the sun, which includes mid-infrared wavelengths, plays a significant role in the development and evolution of living organisms (Charles, 2022). This region is vital and interesting for many applications since that region coincides with the internal vibration of most molecules (CORDIS, European commission).

2. Materials and Methods

2.1. MIRGA Equipment

MIRGA (patent no.: 401387) is a 20 ml pocket sized atomizer (Pic 1) (Supplementary file – figure F1) containing inorganic waterbased solution in which approximately two sextillion cations and three sextillion anions are contained. During spraying, depending on pressure (vary with the user) applied to plunger, every spraying generates 2-6 μm mid-IR. Design of the MIRGA and emission of 2-6 μm mid-IR has been presented in detail by Umakanthan *et al.*, 2022a; Umakanthan *et al.*, 2022b; Umakanthan *et al.*, 2023c; Umakanthan *et al.*,

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2023d. Every time spraying emits 0.06ml which contains approximately seven quintillion cations and eleven quintillion anions. (details about MIRGA available in supplementary text T1)

The inorganic compounds used in the generation of MIR are a perspective for biomedical applications (Tishkevich *et al.*, 2019; Dukenbayevet *et al.*, 2019). It is also a new synthesis method for preparation of functional material (2-6 μm mid-IR) (Kozlovskiyet *et al.*, 2021; El-Shater *et al.*, 2022). It is well known that the combination of different compounds, which have excellent electronic properties, leads to new composite materials, which have earned great technological interest in recent years (Kozlovskiy and Zdorovets, 2021; Almessiereet *et al.*, 2022).

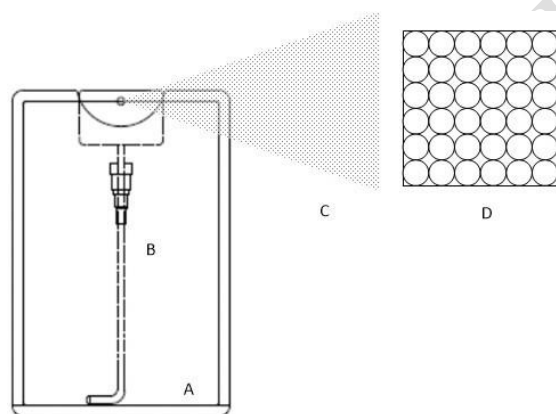


Fig. 1. Schematic of MIRGA equipment. The components of the equipment are (A) container; (B) plunger; (C) mid-IR spray which is used to treat the vegetable sample; (D) vegetables packet that contains the testing sample.

2.2. MIRGA Experimental Set-up

The distance between the spraying orifice of the MIRGA and the packaged vegetable sample is at a range of 0.25 m to 0.50 m. This distance is essential for the MIRGA sprayed chemical solution to form ion clouds and oscillations, and to generate 2-6 μm mid-IR. The MIRGA spray can penetrate the intervening packaged material to act on the vegetables inside. Close spraying does not generate 2-6 μm mid-IR energy. (Method of MIRGA spraying in Supplementary file – video V1)

2.3. Sample Preparation

Fresh vegetable samples and powder vegetable samples were obtained from a local market. The fresh vegetable samples were carrot (*Dacus carota*), beetroot (*Betavulgaris*) and bittergourd (*Momordicacharantia*). In addition, powdered vegetable samples of carrot, beetroot, and bitter gourd were tested. The fresh vegetable samples and powder vegetable samples were treated with MIRGA spray treatments in two separate trials (trial I and trial II), which were

repeated 6 independent times.

Microbial analysis done for the presence of coliforms and *Salmonella* sp. (method 2000.15 and method 967.6).

2.4. Sensory Quality, Aroma Evaluation and Shelf-life Study

The sensory evaluation of the fresh vegetable samples was scored by an expert sensory panel (no.: 6). The sensory panel used an acceptability index based on a hedonic scale with a 9-point nominal structure 1-Dislike extremely, 2-Dislike very much, 3-Dislike moderately, 4-Dislike slightly, 5-Neither like nor dislike, 6-Like slightly, 7-Like moderately, 8-Like very much, 9-Like extremely (Everitt, 2009; Wichchukit *et al.*, 2014). The shelf-life study consisted of evaluating the acceptability index of the fresh vegetable samples and the powder vegetable samples every day. After the shelf-study was finished, the sensory evaluation results were used to calculate the percentage of self-life increase.

2.5. Trial I: Treatment of fresh vegetable samples with MIRGA spraying

Two hundred and fifty grams (250 g) of each fresh vegetable sample was weighed and packed in 50 individual polyethene bags of different thicknesses (upto 70 μm). Air was removed manually by the operator, then the samples were sealed with cellophane. There were 400 packets in total (8 vegetables * 50 bags) to be tested. The control was Non-MIRGA sprayed packets for each vegetable, which accounted for 10 individual polyethene bags out of the 50 (10 x 8 = 80).

20 individual polyethene bags for each fresh vegetable received one MIRGA spray treatment, and another 20 bags received two MIRGA spray treatments (8 x 40 = 320). Each fresh vegetable sample from the control (5 samples), one MIRGA spray treatment (10 samples), and two MIRGA spray treatment (10 samples) groups were stored at room temperature (approximately 32°C), and at refrigeration temperatures (4°C). The fresh vegetable samples were daily subjected to sensory scoring.

2.6. Trial II: Treatment of vegetable powder samples with MIRGA spraying

Powder vegetable samples were packed in polyethene (>51 μm thickness). The control was Non-MIRGA sprayed packets for each powder vegetable (carrot, beetroot, and bitter gourd). Powder vegetable samples were sprayed with MIRGA. After every spraying, powder was taken out, sensory evaluation done and samples taken for analysis. The spraying was until the powders' natural characteristics were nearly or completely lost (i.e. unpalatable). More spraying was performed in comparison to the fresh vegetable samples because extra energy is needed to denature the natural characteristics. The number of spray treatments varied depending on the powder vegetable sample used.

Preliminary analysis demonstrated the number of MIRGA spray treatments that resulted in an increase in palatability, and unpalatability. In the case of powder carrot samples, two MIRGA spray treatments made it more palatable, and seven MIRGA spray treatments made it unpalatable. For beetroot, two MIRGA spray treatments resulted in a more palatable sample, and eight MIRGA spray treatments resulted in unpalatable samples. Finally, bitter gourd became more palatable after four MIRGA spray treatments and unpalatable after twelve spray

treatments. So the control, more palatable and unpalatable samples were subjected to various instrumentalations.

2.7. Effect of MIRGA spraying on Physicochemical Properties of Vegetable Samples

Analytical studies were conducted to evaluate the effect of MIRGA on the physicochemical properties of the vegetables. Gas chromatography mass spectroscopy (GC-MS) was employed to verify the transformation of chemical compounds. Changes in the chemical bonds, structures, and configuration were analysed via Fourier-transform infrared spectroscopy (FTIR), transmission electron microscopy (TEM), and powder X-ray diffraction (PXRD), respectively. Finally, changes in proton resonances were studied by proton nuclear magnetic resonance (¹H-NMR) assays.

GCMS: Instrument: Agilent 7890A GC with 5975C MS system. Column: HP-5. Ionization: EI (70eV). Method: General_1_HP5_80_DEG.M.MSD: Single Quad.

FT-IR: A small quantity of the sample is added to KBr in the ratio 1:100 approximately. The matrix is grind for 3-4 minutes using mortar and pestle. The fine powder is transferred into 13mm diameter die and made into a pellet using a hydraulic press by applying a pressure of 7 tonnes. The fine pellet is subjected to FTIR analysis using universal pellet holder. (a single drop of oil is poured on the KBr pellet in case of liquid samples). Infrared spectral data were collected on Thermo Avtar 370 FTIR spectrometer. Spectra are collected over a range of 4000–400 cm⁻¹ at 4 cm⁻¹ resolution with an interferogram of 32 scans.

PXRD: The sample is smeared over low back ground sample holder (amorphous silica holder) and fixed on the sample stage in goniometer. The instrument is set with B-B geometry. The current and voltage is set to 40 mV and 35 mA and data has been collected. Instrument make: Bruker Model D8 Advance Goniometer: theta/2theta.

TEM: An extremely small amount of material is suspended in water/ethanol (just enough to obtain slightly turbid solution). The solution is homogenised using ultrasonicator to disperse the particles, a drop of the solution is then pipetted out and cast the drop on carbon-coated grids of 200 mesh the grid is dried and fixed in the specimen holder. Instrument Make: Jeol Model JM2100.

¹H-NMR: The experiments were done on a 600 MHz NMR spectrometer (ECZR Series, JEOL, JAPAN) using a 3.2mm CPMAS probe at 150 MHz frequency. All the samples were run at 18 KHz spinning speed at Room Temp and with a delay of 5 sec.

3. Results and Discussion

3.1. Microbial analysis revealed that the vegetables are free of pathogens.

Trial I: Treatment of fresh vegetable samples with MIRGA spraying

The sensory quality, aroma, and shelf-life were enhanced in the fresh vegetable samples in comparison to control samples. Therefore, MIRGA spray treatment resulted in more palatable fresh vegetables, irrespective of stored condition. (Ta

ble 1)

Table 2 shows that, fresh vegetables acquired an enhanced shelf-life of 16-900% at room temperature and 9-314% in refrigeration.

Trial III: Treatment of vegetable powder samples with MIRGA spraying

The sensory panel experts concluded that powder vegetable samples treated by MIRGA spraying twice (carrot and beetroot) and four times (bittergourd) observed an increase in their aroma and sensory quality. Samples that received seven (carrot), eight (beetroot), and twelve (bittergourd) treatments with MIRGA spraying, resulted in a decrease in their aroma and sensory quality to unpalatable levels. These sensory attribute changes were perceived in 1-2 minutes after spraying. (Table 3)

3.2. Instrumentation results with vegetable powders (raw data of instrumentations in Supplementary file – Data D1)

3.2.1. Transformation of Chemical Compounds via GC-MS Analysis

(a) Carrot powder

Control sample contains Z-11-Pentadecanol, 3-Hydroxy Dodecanoic acid as major peaks. In 2 sprayed sample, there was new peak of 13-Heptadecyn-1-ol and 3,3,5-Trimethyl Cyclohexanone but there was no peak of Z-11-Pentadecanol. Additionally, there was new peak of n-Hexadecanoic acid, Octadecanedioic acid and Bicyclohexyl, 4-phenyl. These differences are responsible for enhancement in sweetness and aroma. On the other hand, 7 sprayed sample has shown a unique peak E-z-Octadecadecenoic acid and it was a major peak. There was no peak of 3-Hydroxy Dodecanoic acid but decrease in Z-11-Pentadecanol as compared to control sample. There was a new peak of n-Hexadecanoic acid and 6-Dimethyl(chloromethyl)silyloxy Tetradecane. Overall, these attributed to the reduction of sweetness and taste in 7 sprayed sample.

(b) Beetroot powder

Control sample contains Phytosterols, such as Stigmasterol, Stigmasterol, Estra-1, 3,5 (10)-trien-17 β -ol, and other molecules such as 13-Docosenamide, (Z), Oxirane octanoic acid, 3-octyl-cis, etc. The phytosterol peaks are unique peaks for Beetroot samples, which are disappearing after spraying. In 2 sprayed sample, there was the unique peak of dl-Glyceraldehyde, 1-Nitro-2-propanol, 7-Methyl-Z-tetradecen-1-ol acetate, which was not present in the control. Further, there was a decrease in peak of Estra-1,3,5(10)-trien-17 β -ol in 2 sprayed sample. 8 sprayed sample has shown a unique peak of Monoethanolamine, n-Hexadecanoic acid, Deoxyspergualin, etc., which is responsible for tastelessness, reduction in sweetness and aroma, took time to solubilize. In addition, there was a great increase in peak of 2-Amino-1,3-propanediol as compared to control sample. 9-Octadecenamide and 1,7-Dioxo-10-thia-4,13-diazacycloheptadeca-5,9,12-trione are two peaks which have appeared after spraying.

(c) Bittergourd powder

The control bitter gourd powder contained Methyl 10-Methylundecanoate, Hexadecanoic acid methyl ester, Pentadecanoic acid, 14-Methyl-, methyl ester, n-Hexadecanoic acid, 11-Octadecenoic acid methyl ester, 17-Octadecenoic acid, Octadecanoic acid methyl ester, Pentadecanoic acid, and Octadecanoic acid compounds. After four MIRGA spray treatments, there were new peaks that were not present in control, including Methyl 10-Methylundecanoate and 17-Octadecenoic acid. However, there were unique peaks of Hexadecanoic acid, methyl ester in samples that received 4 MIRGA spray treatments, and Pentadecanoic acid in samples that received 12 MIRGA spray treatments, compared to control. Interestingly, there was a disappearance of 11-Octadecenoic acid methyl ester from the GC-MS spectra of bitter gourd powder due to MIRGA spray treated samples. It was observed that MIRGA spray treatments also caused a gradual increase in the peak of n-Hexadecanoic acid and a gradual decrease in the peak of Octadecanoic acid.

3.2.2. Chemical Bonds Analysis via FTIR

(a) Carrot powder

The FTIR spectra of control carrot powder displayed a big peak was observed at 3396 cm^{-1} , which was specific to carbohydrate and OH-groups from water. Two more peaks were observed: a peak at 2925 cm^{-1} , specific to C-H bonds from organic compounds, and a peak at 1632 cm^{-1} , which resembled N-H bonds (near C=O) from proteins. In carrot powder samples that were MIRGA spray treated 2 times and 7 times, a small increase in the absorbance in all areas was observed compared to in control. The increased absorbance was probably due to increasing the concentration of substance (carbohydrates, OH-groups, organic compounds, or proteins) in the compaction matrix. In samples that were MIRGA spray treated 2 times, the absorbance was lower at 1632 cm^{-1} and 618 cm^{-1} , which was probably caused by a lower protein concentration. The enhanced sweetness was associated with the breakdown of a portion of polysaccharides into monosaccharides (Shah *et al.*, 1978).

(b) Beetroot powder

A big peak was observed at 3392 cm^{-1} , for the FTIR spectra of control beetroot powder, which was specific to carbohydrate and OH-groups from water. Two more peaks were observed: a peak at 2929 cm^{-1} , specific to C-H bonds from organic compounds, and a peak at 1631 cm^{-1} , similar to N-H bonds (near C=O) from proteins. All peaks became smaller after 2 MIRGA spray treatments, compared to the control and 8 sprayed samples. 8 sprayed samples were almost identical to the control samples, except for peaks at 1631 cm^{-1} and 618 cm^{-1} . An explanation for this behaviour is due to protein reduction caused by the MIRGA spray treatments.

(c) Bitter gourd powder

The control bitter gourd powder had a big peak of OH-groups at 3406 cm^{-1} . This peak was specific to carbohydrates and OH-groups from water. Absorbance at this wavelength increased when samples received 4 MIRGA spray treatments and decreased when samples received eight MIRGA spray treatments. It could be proposed that absorbance increased after four treatments because MIRGA spraying caused an increase in the concentration of required substances

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(carbohydrates and OH-groups), and the reduced absorbance after 8 treatments resulted from water evaporation. An increase in the peaks at 2925 cm^{-1} , from C-H bonds of organic compounds, and at 1741 cm^{-1} , possibly C=O bonds from carbohydrates, were observed for samples that received 4 MIRGA spray treatments. The increase in the peaks at 2925 cm^{-1} and 1741 cm^{-1} were more pronounced in the sample that received eight MIRGA spray treatments. Therefore, the concentration of carbohydrates seemed to increase with a higher number of MIRGA spray treatments. The opposite trend was observed for proteins. A peak at 1631 cm^{-1} , similar to N-H bonds (near C=O) from proteins, decreased slightly after 8 MIRGA spray treatments, and it was highly reduced after 4 MIRGA spray treatments.

3.2.3. Particle Structure Analysis via TEM

(a) Carrot powder

As shown in fig. 3b, carrot powder samples which received 2 MIRGA spray treatments showed minor changes of morphology and matrix structure, and negligible or no changes of the atomic arrangement, compared to control samples. In contrast, carrot samples that received 7 MIRGA spray treatments were visibly affected in terms of morphology and matrix structure, compared to control samples. Therefore, as the number of MIRGA spray treatments increased, more noticeable changes may occur in the morphology and matrix of carrot powder.

(b) Beetroot powder

MIRGA spraying had different effects on the size and shape of matrix components of beetroot powder, therefore it changed the overall sample structure. In fig. 3a, the main matrix components of the beetroot control samples can be identified as amorphous-shaped fragments, but in the samples that received 2 MIRGA spray treatments the fragments were clustered in large aggregates, and in the samples that received 7 MIRGA spray treatments the size of the fragment was noticeably smaller.

(c) Bitter melon powder

Alterations in the structure, matrix components in numerosity, shape, and morphology were observed on bitter melon powder samples that received MIRGA spray treatments compared to control. However, the atomic arrangement was only slightly affected as seen in Fig. 3a. Peculiarly, 4 MIRGA spray treatment caused more evident changes than 12 MIRGA spray treatments.

3.2.4. Chemical Configuration Analysis via PXRD

(a) Carrot powder

As seen in fig. 4, all three carrot powder samples showed a large volume (%) of amorphous phases reflected by one broad peak centred on 17° . A general trend was observed where the broad peak shifted to the right with an increased number of MIRGA spray treatments. The control samples and the samples that received 2 MIRGA spray treatments showed broader and overlapping peaks (10° - 28°) compared to samples that were MIRGA spray treated 7 times. The prominent peak at 31° had a fixed location in all the control and sprayed samples, even as the number of MIRGA spraying increased. Samples that received 2

MIRGA spraying had one more peak at 29.07°, which suggested an increase of the crystalline phase. Most peaks below 31° in all the samples agree with the values presented by **Rocha et al., 2011**.

(b) Beetroot powder

The spectra of beetroot powders showed good signal-to-noise ratios, allowing the identification of several peaks. Control samples had the least intense peak reflection. Samples that were MIRGA spray treated 2 times presented more peaks in their spectra than samples that were MIRGA spray treated 8 times, although the latter showed a relatively intense peak at 35.59°. The peak around 24.80° is highest for samples that received 2 MIRGA spray treatments, followed by samples that received 8 MIRGA spray treatments, and control samples had the smallest peak. In the case of beetroot powder that received 2 MIRGA spray treatments, new peaks at 27.81° and 35.59° were displayed compared to control samples. Samples that received 8 MIRGA spray treatments also showed new peaks at 35.69°, but with higher intensity than for samples that received 2 treatments.

(c) Bittergourd powder

Consistent with the literature (**Mariselviet al., 2017; Singh et al., 2017**), all bittergourd powder samples had characteristic peaks at around 14°, 21°, and 26° for their pattern of XRD (Fig. 4). Control samples had the least number of prominent peaks among the three samples (control, and samples that received 4 or 12 MIRGA spray treatments). Sample that received 4 MIRGA spray treatments had the highest number of intense, narrow peaks, while the samples that received 12 MIRGA spray treatments showed the best signal-to-noise ratio. A considerable change in the presence of new peaks was observed in samples that received 4 MIRGA spray treatments, particularly at 28.25°, indicating the formation of a new crystalline phase in the samples. More drastic changes in the structure were observed in samples that received 12 MIRGA spray treatments, where the intensity of the peak at 21.49° was reduced, and the peak at 26.66° became the most prominent, compared to control samples and samples that received 4 MIRGA spray treatments. Samples that received 12 MIRGA spray treatments had the largest volume (%) crystalline phase among the three samples (control, and samples that received 4 or 12 MIRGA spray treatments). Control samples and samples that received 4 MIRGA spray treatments had a similar structure. The peak centred around $2\theta = 26^\circ$ in each of the three samples (control, and samples that received 4 or 12 MIRGA spray treatments) changed in terms of breadth and intensity, indicating a change in crystallinity as the number of MIRGA spray treatments increased.

3.2.5. Nuclear Resonance Analysis via ¹H-NMR

(a) Carrot powder

Sweetness and aroma of carrot powder depended on sugars and terpenoid compounds. The control samples showed a profile compatible with a sugar-rich composition and other minor components. The interpretation of ¹H-NMR spectra was challenging due to signal overlap. However, it is possible to infer from Fig 5 that the MIRGA spray treatment affected the concentration, or the integrity of molecules involved in the sweetness and aroma of carrot powder.

(b) Beetroot powder

An increase of sweetness, aroma, and solubility was observed in samples that received 2MIRGA spray treatments. Sweetness, aroma, and solubility were directly related to the increase in the concentration of sucrose, geosmin, and soluble compounds, respectively. The integral corresponding to the region of the signals coming from sucrose was higher than that from the control samples. Since geosmin is a minor component, its variation was hidden by the overlap of its signal with more intense signals. In the case of samples that received 8MIRGA spray treatments, changes followed the opposite trend: a drastic reduction in the concentration of sucrose, geosmin, and soluble compounds was observed. Therefore, sweetness, aroma, and solubility were reduced.

(c) Bittergourd powder

Bittergourd powder sample that received 4MIRGA spray treatments showed a reduction in the concentration of terpenoids and polyphenols, which could be attributed to a reduced bitterness. Terpenoids and polyphenols are involved in the bitter taste of bitter gourd powder, but they are composed of a breath of relatively complex molecular structures with different chemical groups. For this reason, it was difficult to interpret which variations in the NMR spectra correspond to changes in the concentration of molecules involved in the perception of bitterness.

In the case of sample that received 12MIRGA spray treatments, an increase in bitter compounds was observed in the spectra. Paradoxically, all the integrals showed a reduction in bitter compounds for samples that received 12 MIRGA spray treatments, compared to the control samples. A possible explanation for this result would be that there were minor components in bitterness, and the augmentation effect that they have on the perception of bitterness was hidden by the overlap with signals coming from more concentrated components.

3.3. Action of mid-IR on vegetables

Invention background, definition, technique of mid-IR generation from MIRGA, toxicological study on MIRGA, safety of the MIRGA sprayed usables and primeval and future scope of MIRGA have been described by **Umakanthan et al., 2022a** and **Umakanthan et al., 2023d** (detailed discussion on MIRGA available in supplementary text T2).

Commonly vegetables shelf life is improved by treating vegetables with microorganism derived preservative, followed by preservative gas package (**Prosekov et al., 2018**), nanotechnology related strategies such as nano-zinc dioxide and silver nanoparticles (**Wenchao et al., 2020**), edible coating with pulsed light treatment (**Annachiara et al., 2021**) and evaporation cooling system (**Ayobami et al., 2023**). Infrared was found to influence the vegetables shelf life (**Faisal et al., 2008**). The sensory quality of vegetables is improved through seasonings (**Ulla et al., 2021**). Not in this study simultaneously enhanced the shelf life and sensory qualities by exposing vegetables to 2-6 μm mid-infrared.

At present, chemical preservatives and ultraviolet, microwave, pulsed electric fields, gamma and infrared radiations are used for food processing. Except infrared, other radiations are ionizing, hence lethal, uneconomical and non-friendly to user and ecology (**Lopez-Maloet et al., 2004**; **Gautam et al., 2016**; **Vasuja et al., 2018**;

Aboud *et al.*, 2019). Thus the use of infrared in food processing is a future option (Aboud *et al.*, 2019). Though infrared radiation use has many advantages than the conventional method but not without challenges and research (Das *et al.*, 2014). It is concluded that MIRGA overcomes the disadvantages of present food processing technologies and expected to convince the industry and consumer.

Similar desirable results in coffee, tea, cocoa, edible salts and terminalia were achieved using MIRGA spraying by Umakanthan *et al.*, 2022a; Umakanthan *et al.*, 2022b; Umakanthan *et al.*, 2023c; Umakanthan *et al.*, 2023d.

4. Conclusion

Through sensory trials and various instrumentations, we demonstrated that MIRGA spraying (from 0.25-0.50 meter) treatments altered the chemistry of polythene packaged vegetable samples and made them more desirable in terms of aroma, taste and shelf life enhancement. The impact of this study involves the development of a processing technology that could improve the aroma, sensory quality, and shelf-life of vegetables without genetic manipulation. Without two decades experience with MIRGA spraying technology, it is possible to further enhance the sensory quality, aroma, and shelf-life by altering the MIRGA formulation.

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Data and materials availability

All data is available in the manuscript and supplementary materials.

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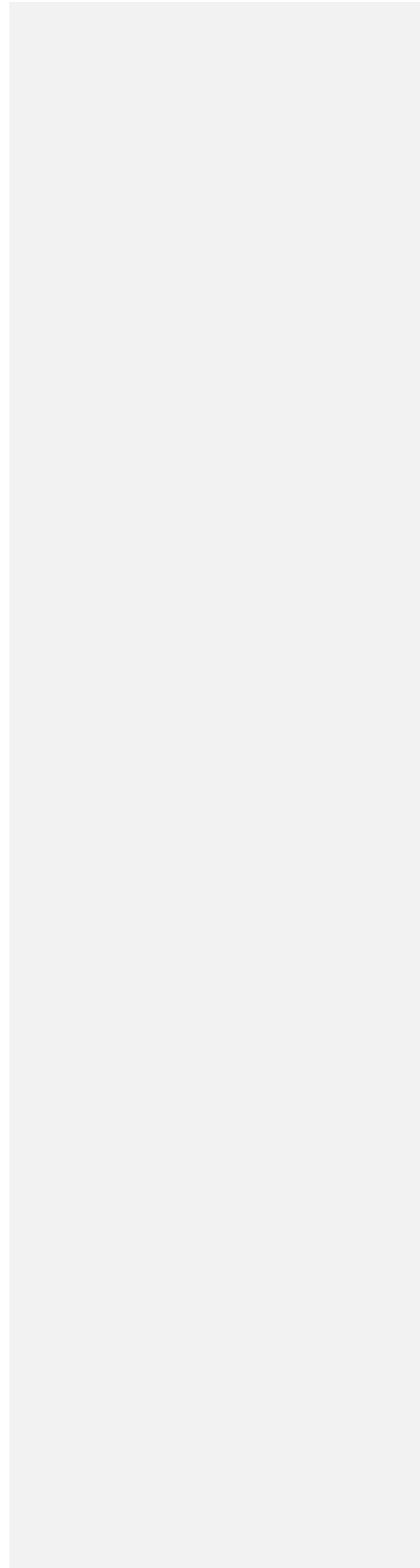
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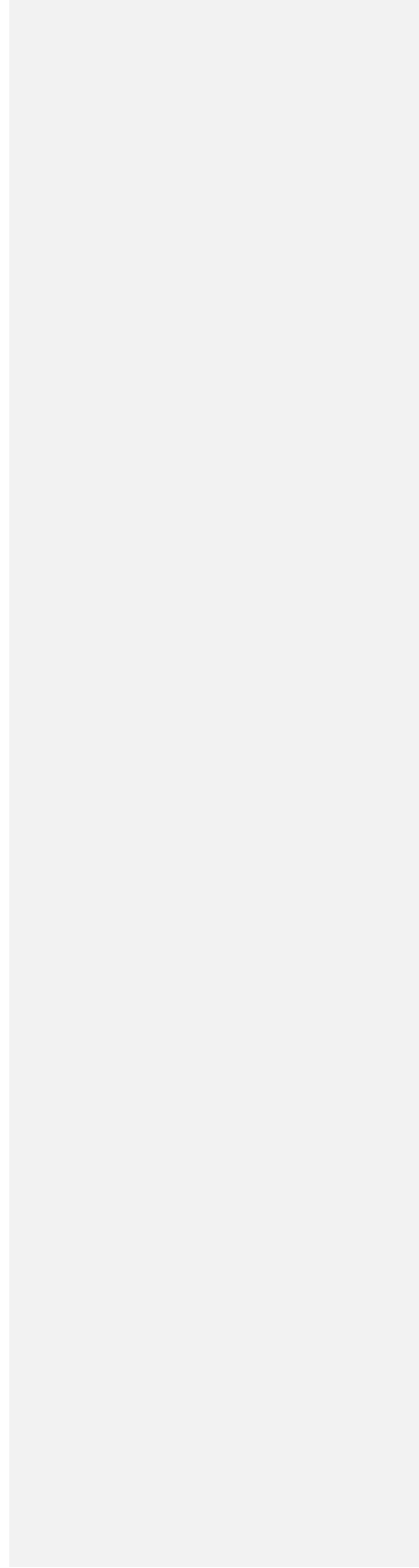


Table1:Sensoryprofilingoffreshvegetables

No. ofMI RGA sprayings	Freshvegetables															
	Lady'sfinger		pumpkin		Beans		Carrot		Brinjal		Bottlegourd		Beetroot		Bittergourd	
	Taste	Aroma	Taste	Aroma	Taste	Aroma	Taste	Aroma	Taste	Aroma	Taste	Aroma	Taste	Aroma	Taste	Aroma
Control	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
1	7	6	7	5	7	5	8	6	7	6	6	5	7	6	6	7
2	8	6	8	6	8	6	8	6	8	6	8	6	7	7	6	6

Table 2. Shelf-life study of fresh vegetable samples based on the comparison of the number of days that the samples remained unspoiled at room temperature (app. 32 °C) and refrigeration temperature (4 °C) (standard deviation ± one day)

Number of MI RGAs spray treatments	Fresh vegetable sample	Number of days unspoiled at room temperature (app. 32 °C)	Shelf-life increase at room temperature (%)	Number of days unspoiled at refrigerated temperature (4 °C)	Shelf-life increase at refrigeration temperature (%)
0 (control)	Lady's finger	6	-	15	-
0 (control)	Pumpkin (sliced)	2	-	10	-
0 (control)	Carrot	3	-	10	-
0 (control)	Beans	5	-	10	-
0 (control)	Beetroot	5	-	14	-
0 (control)	Brinjal	4	-	7	-
0 (control)	Bottle guard	3	-	10	-
0 (control)	Bitter guard	3	-	7	-
1	Lady's finger	24	16	42	180
1	Pumpkin (sliced)	12	71	20	100
1	Carrot	30	900	38	280

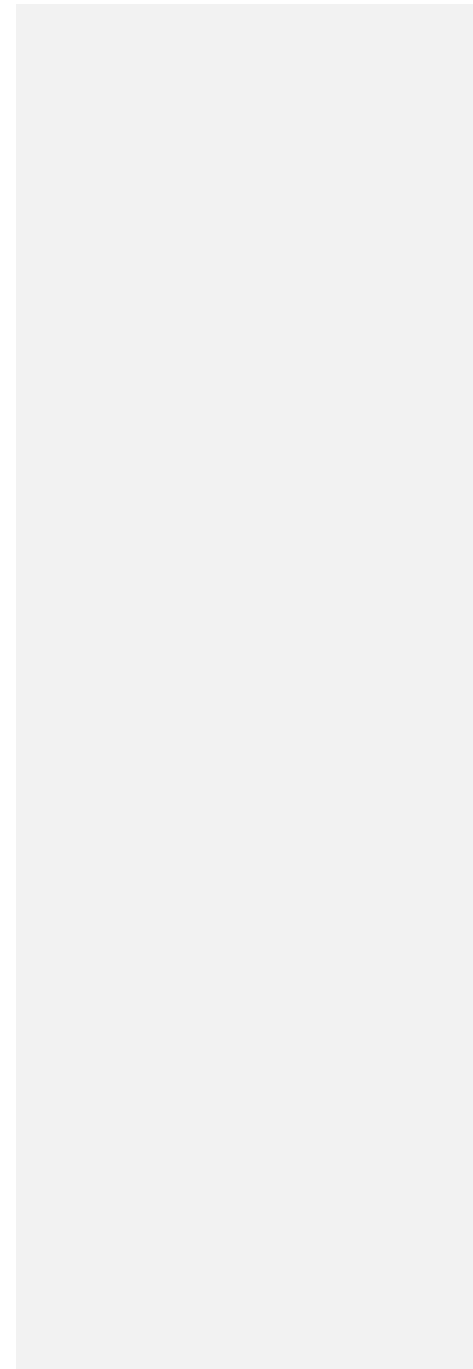
1	Beans	15	200	22	120
1	Beetroot	7	40	65	9
1	Brinjal	15	275	29	314
1	Bottleguard	25	733	37	270
1	Bitterguard	13	333	17	142
2	Lady'sfinger	13	116	28	86
2	Pumpkin	9	350	16	300
2	Carrot	21	600	30	200
2	Beans	19	280	21	110
2	Beetroot	9	80	24	71
2	Brinjal	8	100	11	57
2	Bottleguard	19	533	32	220
2	Bitterguard	10	233	16	128

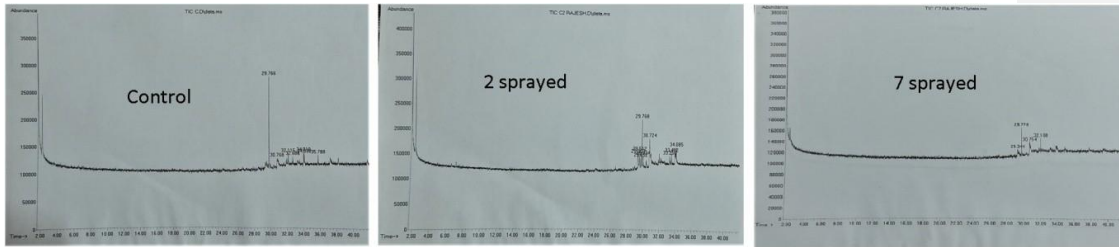
**Table3:Sensoryprofilingofvegetable
powders**

No.ofMIRGAspr ayings	Vegetablepowder s					
	Carrotpowder		Beetrootpowder		Bittergourdpowder	
	Tast e	arom a	Tast e	arom a	Taste	Arom a
Contro l	5	5	5	5	5	5
1	7	6	6	5	5	5
2	8	7	8	7	5	6
3	8	6	7	7	7	7
4	5	5	6	5	9	8
5	3	5	5	5	7	7
6	3	3	5	5	7	6
7	2	3	3	4	5	5
8			2	4	5	4
9					4	3

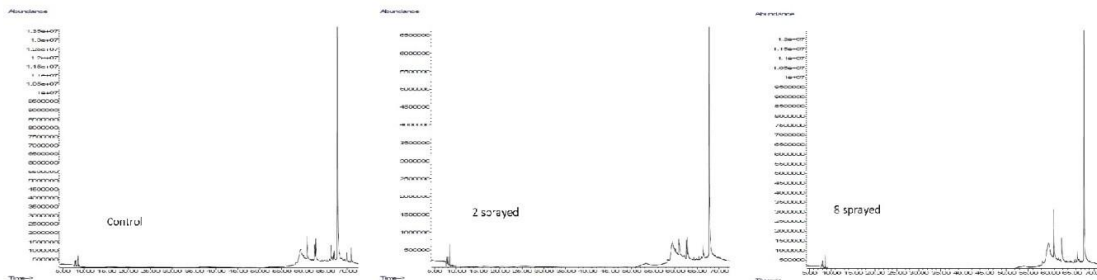
10					2	3
11					1	3
12					1	1

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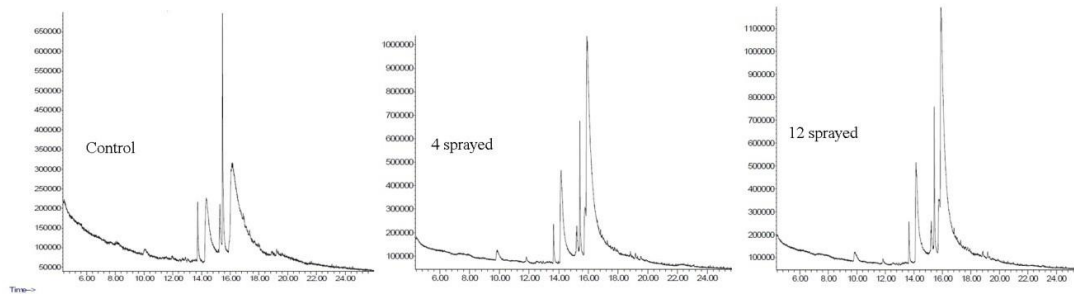




(a) GCMS - Carrot powder



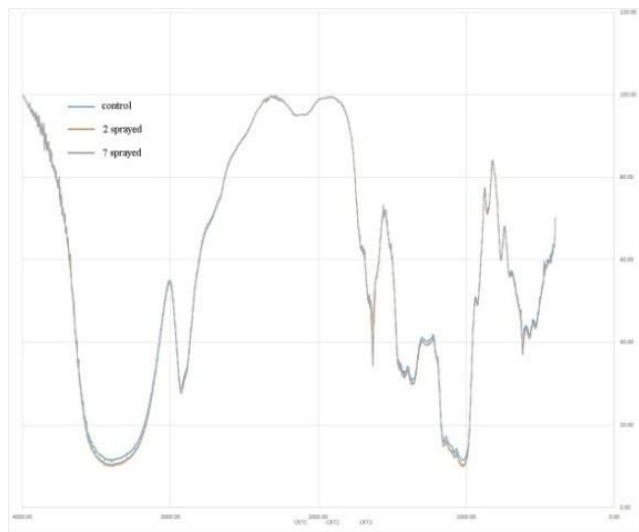
(b) GCMS - Beetroot powder



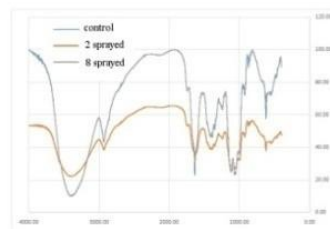
(c) GCMS - Bitter gourd powder

Fig.1.GC-

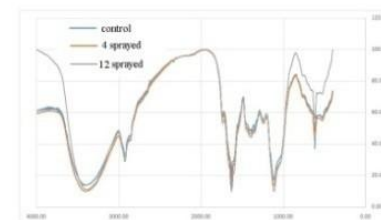
MSchromatographofpowder(a)beetrootpowder,and(b)bittergourdreatedwithMIRGAspraying.



(a) FTIR - Carrot powder



(b) FTIR - Beetroot powder



(c) FT-IR Bitter gourd powder

Fig.2. FTIR spectra of (a) carrot powder, (b) beetroot powder, and (c) bitter gourd powder treated with MIRGA spraying.

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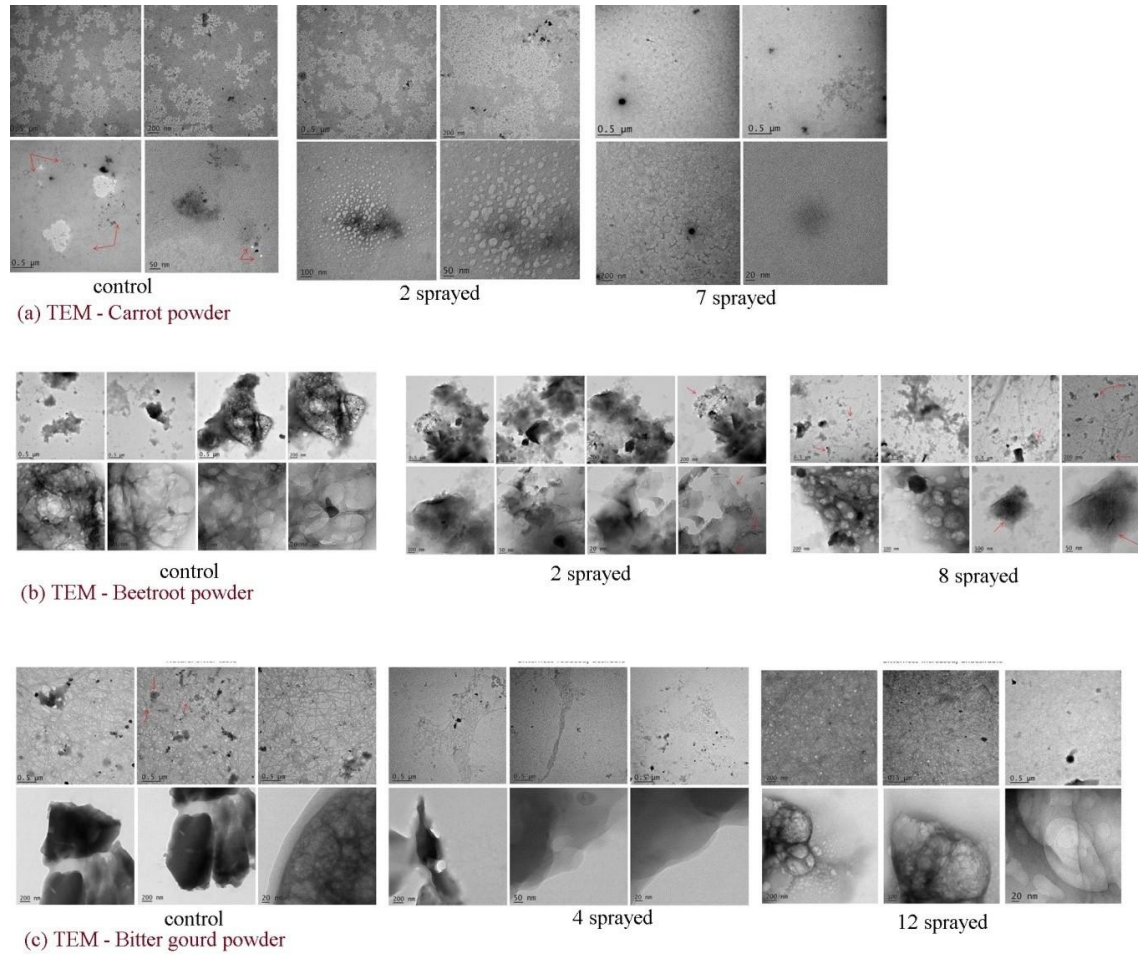
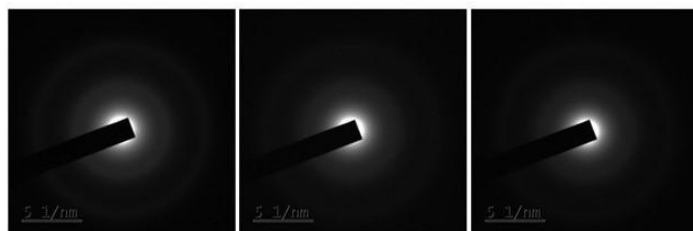
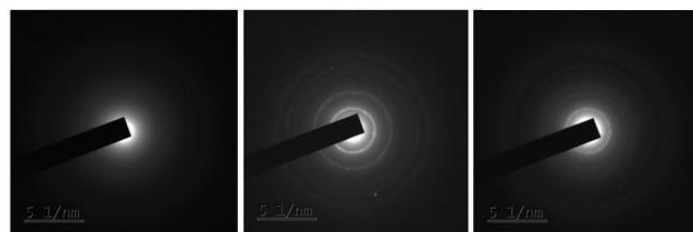


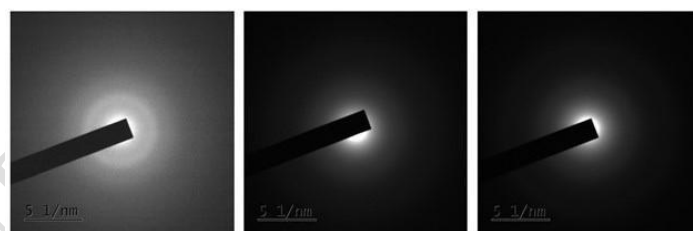
Fig.3a. TEM-Brightfield images of (a) carrot powder, (b) beetroot powder, and (c) bitter gourd powder treated with MIRGA spraying.



(a) Carrot powder

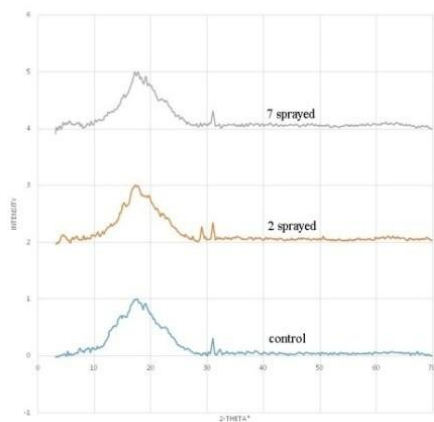


(b) Beetroot powder

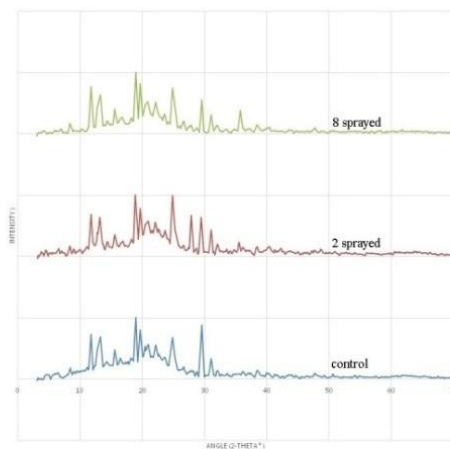


(c) Bitter gourd powder

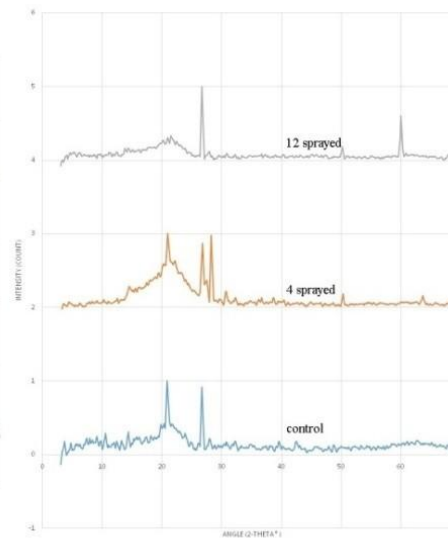
Fig.3b. TEM–Electron diffraction patterns of (a) carrot powder, (b) beetroot powder, and (c) bitter gourd powder treated with MIRGA spraying.



(a) PXRDS - Carrot powder



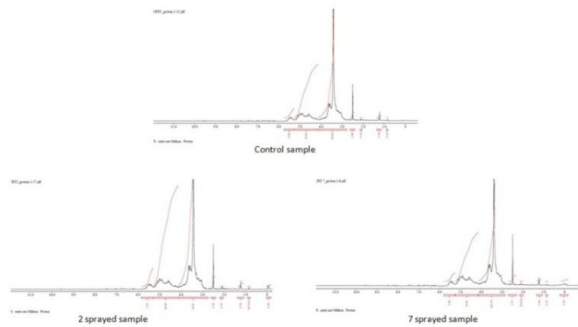
(b) PXRDS - Beetroot powder



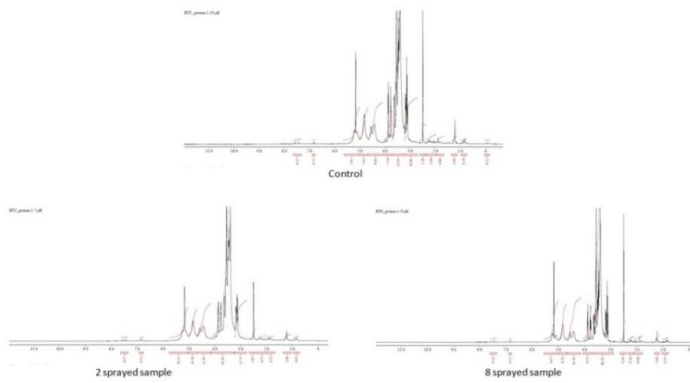
(c) PXRDS - Bitter gourd powder

Fig4. PXRDS spectra of (a) carrot powder, (b) beetroot powder, and (c) bitter gourd powder treated with MIRGA spraying.

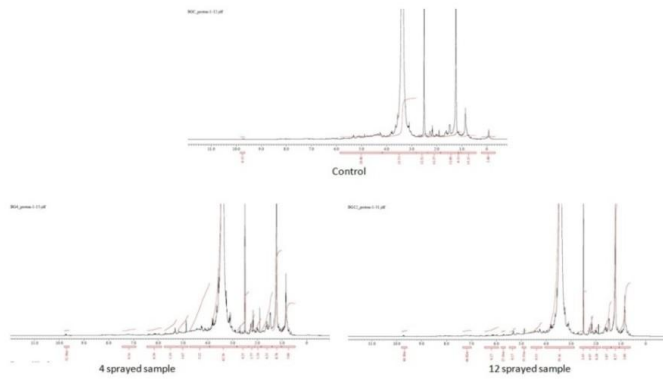
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(a) NMR- Carrot powder



(b) NMR - Beetroot powder



(c) NMR - Bitter gourd powder

Fig5. H-NMR spectra of (a) carrot powder, (b) beetroot powder, and (c) bitter gourd powder treated with MIRGA spraying

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