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Research Article

Antimicrobial potential of selected fruit peel extracts against multidrug-resistant bacteria: An eco-friendly approach

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Abstract
The rapid rise of multidrug resistance (MDR) bacteria due to the misuse of antibiotics necessitates the discovery of alternative therapeutic agents. This study investigates the antimicrobial properties of methanolic extract of selected fruit peels: *Carica papaya*, *Ananas comosus*, *Musa acuminata*, and *Punica granatum.* These extracts were tested against gram-positive bacteria (*Staphylococcus aureus*) and gram-negative bacteria (*Pseudomonas aeruginosa* and *Klebsiella pneumoniae*). The findings indicated that all four fruit peel extracts exhibited antimicrobial activity against all the selected pathogenic strains. The effectiveness of the extracts followed the following orders: *P. granatum* > *M. acuminata* > *C. papaya* > *A. comosus* for *S. aureus*, *P. granatum* > *C. papaya* > *M. acuminata* > *A. comosus* for *P. aeruginosa*, and *A. comosus* > *M. acuminata* > *C. papaya* > *P. granatum* for *K. pneumoniae*. Notably, *K. pneumoniae* demonstrated high sensitivity to *A. comosus* extract with a Minimum Inhibitory Concentration (MIC) of 6.25 mg/mL. *S. aureus* inhibition was observed with a MIC of 12.5 mg/mL for both *P. granatum* and *M. acuminata* extracts, while *P. aeruginosa* showed a MIC of 12.5 mg/mL for both *P. granatum* and *C. papaya* extracts. Qualitative phytochemical analysis along with structural elucidation using Gas chromatography with Mass Spectrometry (GCMS) and Fourier Transform Infrared Spectroscopy (FTIR), identified medicinally significant compounds like Tetracyclononane hexamethyl, phthalic acid, 9-octadecenal, 7-methyl undecane, 2-dodecyl-propanediol in these peels, likely contributing to their antimicrobial activity. Thus, this study demonstrates the potential of these fruit peels as effective antimicrobial agents and highlights their role in sustainable waste management.

Keywords: Antibacterial activity; Fruit peels; Phytochemistry, Sustainability, Waste management.

INTRODUCTION

Multidrug resistance (MDR) is the most serious global threat to the health sector (Chinemerem *et al*., 2022), escalating steeply over the years due to inappropriate usage and disposal of millions of antibiotics into the environment (Saleem and Saeed, 2020). Antibiotic resistance spreads mainly through horizontal gene transfer in bacteria and poses an enormous challenge for the successful treatment of infectious diseases, causing a steep increase in the death rate (Lerminiaux and Cameron, 2019). MDR is responsible for causing about 700,000 deaths each year, and if it continues to rise at this rate, it is expected to increase to 10,000,000 deaths per year by 2050 (Gelband *et al*., 2015). Amongst the MDR strains, ESKAPE pathogens namely, *Enterococcus faecium, Staphylococcus aureus, Klebsiella pneumoniae, Acinetobacter baumannii, Pseudomonas aeruginosa,* and *Enterobacter species*, are the major reason for the spread of nosocomial infections in ICUs and are capable of aggressive outbreaks (Santajit and Indrawattana, 2016). WHO designated the “priority status” to the MDR ESKAPE pathogens, stating the urgent need for antimicrobial development for these pathogens (World Health Organization, 2017). One of the strategies recommended for combating antibiotic resistance is the use of non-antibiotic compounds with significant antimicrobial activity in combination with failed antibiotics, thereby enhancing antimicrobial efficacy (Brown, 2015). Hence, there is an immediate need to discover antimicrobial agents against MDR pathogens, which can substantially reduce the burden of antibiotic resistance on the health sector.

Plants have been used to treat diseases since time immemorial (Jones, 1996). Researchers are focused on isolating and identifying new bioactive compounds from various plant components such as fruit, flowers, leaves, and stems to develop better drugs to combat antibiotic resistance (Saleem and Saeed, 2020). Though extensive work has been done on the antimicrobial activity in most plant species (Khameneh *et al*., 2019), studies on the antimicrobial potential of non-edible parts of fruits such as fruit peels are very limited. Fruit peels of *Carica papaya* (papaya), *Ananas comosus* (Pineapple), *Musa acuminata* (Cavendish banana), and *Punica granatum* (Pomegranate) are rich in bioactive compounds and have potential pharmacological applications (Bhavani *et al*., 2023; Jeon *et al*., 2022; Meena *et al*., 2022; Mo *et al*., 2022). Studies have shown fruit peels have a much higher antimicrobial activity than fruit pulp (Jain, 2011; Neglo *et al*., 2021). Therefore, the isolation of antimicrobial compounds from fruit peels can help enhance antimicrobial activity by acting alone or in combination with antibiotics (Fazly *et al*., 2018).

Fruit peels are considered agro-waste and are discarded in large quantities by the food industry throughout the year (Ain *et al*., 2020), accounting for about 60% of the total fruit and vegetable waste generated (Zhang *et al*., 2020). Hence, the utilization of these fruit peels as a potential antimicrobial agent is an eco-friendly approach to providing a solution to antibiotic resistance and waste management. The present study aimed to analyze the antimicrobial activity of the fruit peels of *Carica papaya* (papaya), *Ananas comosus* (Pineapple), *Musa acuminata* (Cavendish banana), *Punica granatum* (Pomegranate) peels against selected MDR ESKAPE pathogens namely, *Pseudomonas aeruginosa* (MTCC 424), *Klebsiella pneumoniae* (MTCC 109), and *Staphylococcus aureus* (MTCC 3160). The qualitative screening of phytochemicals and structural elucidation using Gas chromatography-mass spectrometry (GC-MS) and Fourier Transform Infrared Spectroscopy (FT-IR) was done to identify and detect the compounds that could be responsible for the antimicrobial activity. Furthermore, this study aimed to encourage the sustainable utilization of fruit peels as an effective, low-cost, natural antimicrobial agent that could serve as an alternative to antibiotics and minimise the agro-waste generated, thereby providing a healthy environment for mankind.

MATERIALS AND METHODS

Collection of fruit peel and preparation of fruit peel powder

Fresh fruits of *C. papaya*, *A. comosus, M. acuminata*, and *P. granatum* peels were obtained from the local market in Bengaluru, Karnataka, India, in 2023. They were cleaned and washed, and the peels were separated. The peels were dried in a hot air oven at 40-45°C for 6 days. The dried sample was then powdered using a grinder and stored in airtight containers at 4°C.

Preparation of fruit peel extract

The fruit peel extract was prepared by adding 10 g of each powdered peel sample separately into a conical flask containing 50 ml of methanol, followed by extraction for 2 days. After extraction, the samples were evaporated using a rotary evaporator to obtain the concentrated extract (RE100-S LED Digital Rotary Evaporator). The yield of each fruit peel sample was calculated as gram (g) of extract per 10 g of dried peel. The concentrated extract was then mixed in DMSO (Dimethyl sulfoxide). The stock solutions were prepared by dissolving each extract in an appropriate amount of DMSO to get a 1g/mL concentration. The dilutions for the antibacterial activity were done using the stock solution of the extract. These were stored at 4^{o}C for antibacterial sensitivity assay.

Pathogenic bacteria and culture

The pathogenic bacterial strains, *Pseudomonas aeruginosa* (MTCC 424), *Klebsiella pneumoniae* (MTCC 109) (gram-negative bacteria), and *Staphylococcus aureus* (MTCC 3160) (gram-positive bacteriae) were obtained from Microbial Type Culture Collection and Gene Bank (MTCC), Chandigarh, India. The pure bacterial cultures were sub-cultured in Mueller Hilton broth (MHB) and incubated at 37°C for 24 h. They were used as the inoculum for the antibacterial sensitivity test.

Antibacterial activity of extracts by well diffusion method

The antibacterial activity of the selected fruit peels was measured using the agar well diffusion method (Martin, 2003). The Mueller Hilton agar (MHA) medium was poured into sterile petri plates, followed by which 100 µl of the bacterial suspension was spread uniformly over the MHA media. The media was then punched with 5mm diameter wells using a sterile cork borer. The wells were then loaded with various concentrations of the extracts such as 100 mg/mL, 80 mg/mL, 60 mg/mL, 40 mg/mL, 20 mg/mL). The plates were then incubated at 37ºC for 24 h, and then the zone of inhibition was measured (in mm). Each extract was tested three times to obtain triplicates and the obtained data was tabulated for each fruit peel extract against each of the tested pathogenic bacteria. Streptomycin (300 mcg) and DMSO were used as positive control and negative control, respectively.

Minimum Inhibitory Concentration (MIC)

The lowest concentration of the extract that inhibits the visible growth of the pathogenic strains is referred to as the Minimum inhibitory concentration (MIC) (Zaki *et al*., 2022), which was determined by broth dilution assay

(Agarwal *et al*., 2020). The MIC values were expressed as mg/mL. The control wells contained MHB and inoculum of the bacterial strains. The percentage of antibacterial activity was estimated using the formula (Eq. 1).

$$\text{Inhibition (\%)} = \frac{\text{O.D (control)} - \text{O.D (sample)}}{\text{O.D (control)}} \times 100$$

Eq.1

Qualitative phytochemical screening

The fruit peel powder of *C. papaya*, *A. comosus, M. acuminata*, and *P. granatum* were subjected to qualitative phytochemical analysis to detect the presence of various phytochemical constituents (phenols, tannins, glycosides, saponins, flavonoids, alkaloids, terpenoids, and steroids) using standard procedures (Dubale *et al*., 2023; Harborne, 1973).

Structural Elucidation- FT-IR and GC-MS analysis

The detection of the bioactive components present in the fruit peel extracts was determined by FT-IR and GC -MS analysis (Hadi *et al*., 2016). Structural determination of the various functional groups present in the fruit peel extract was carried out using a Shimadzu FTIR spectrophotometer, IRSpirit^{TM}, equipped with an attenuated total reflectance (ATR) accessory, QATR-S^{TM}. The FT-IR spectra were recorded at a scanning range of 400-4000 cm^{-1}. Gas chromatography and mass spectrometry analysis of the fruit peel extracts was carried out in Shimadzu GC-MSQP2010SE system. The chloroform extract of the fruit peel (1 µL) was injected through the GC-MS system. This instrument contains a quadrupole mass detector fitted with a capillary column of thickness 30 m x 0.25 µm and 0.25 µm. Helium (99.99%) was used as the carrier gas. The compounds in the extracts were identified by matching the mass spectra with NIST (National Institute of Standards and Technologies) USA, Library (Irawan *et al*., 2017).

Statistical analysis

The data obtained were expressed as mean ± standard deviation (SD). Statistical analysis was performed using one-way ANOVA with SPSS software, version 24, and a significance level of p-value < 0.05.

RESULTS AND DISCUSSION

Antibacterial activity of fruit peel extracts by well diffusion method

The antibacterial activity of the selected fruit peel extract, namely *C. papaya*, *A. comosus*, *M. acuminata*, and *P. granatum* against selected pathogenic strains at different concentrations are presented in Table 1. The results of the Well-diffusion method measured by the

Table 1. Zones of Inhibition (mm) of the fruit peel extracts against the selected microbial strains

No.	Pathogenic microbes	Peel extract	Zone of inhibition (mm)					Positive Control	Negative Control
			20 mg/ml	40 mg/ml	60 mg/ml	80 mg/ml	100 mg/ml	Streptomycin	DMSO
1	*S. aureus*	*P. granatum*	12.10 ± 0.10^{e}	13.10 ± 0.10^{d}	14.10 ± 0.10^{c}	15.10 ± 0.06^{b}	20.10 ± 0.06^{a}	20.06 ± 0.05	NA
		C. papaya	6.10 ± 0.10^{f}	7.10 ± 0.10^{e}	8.06 ± 0.10^{d}	9.13 ± 0.06^{c}	10.10 ± 0.10^{b}		NA
		A. comosus	NA	NA	NA	8.10 ± 0.10^{c}	10.20 ± 0.10^{b}		NA
		M. acuminata	9.10 ±	11.10 ±	11.17 ±	12.13 ±	13.23 ±		NA
2	*P. aeruginosa*	*P. granatum*	11.10 ±	14.17 ±	16.17 ±	18.13 ±	20.13 ±	6.06 ± 0.06	NA
		C. papaya	8.13 ± 0.10^{d}	10.17 ± 0.06^{c}	11.13 ± 0.15^{b}	11.17 ± 0.15^{b}	15.20 ± 0.10^{a}		NA
		A. comosus	NA	6.10 ± 0.10^{e}	9.10 ± 0.10^{d}	11.10 ± 0.10^{c}	15.13 ± 0.06^{b}		NA
		M. acuminata	NA	8.03 ±	11.07 ±	12.07 ±	13.07 ±		NA
3	*K. pneumoniae*	*P. granatum*	NA	NA	NA	NA	6.10 ±	20.20 ± 0.10	NA
		C. papaya	NA	NA	NA	8.10 ± 0.10^{c}	11.20 ± 0.00^{b}		NA
		A. comosus	7.10 ± 0.10^{f}	8.10 ± 0.10^{e}	14.10 ± 0.10^{d}	19.10 ± 0.10^{c}	22.23 ± 0.32^{a}		NA
		M. acuminata	NA	NA	6.10 ± 0.10^{d}	12.17 ± 0.21^{c}	14.10 ± 0.10^{b}		NA

Values are expressed as mean ± SD of triplicate tests with standard deviation. Zone of inhibition (mm) includes the diameter of the well, which is 5 mm. Positive control: Streptomycin (300 µg). Negative control: DMSO - Dimethyl sulfoxide. NA: not active, no inhibition.

zone of growth inhibition reveal that all the selected fruit peel extracts produced notable antibacterial activity against both gram-positive (*S. aureus*) and gram-negative bacteria (*P. aeruginosa* and *K. pneumoniae*) (Table 1). It was observed that there was a significant increase ($p<0.05$) in the antimicrobial activity of the fruit peels with an increase in the concentration of the extract (Table 1). It was observed that the effectiveness of the fruit peel extracts against *S. aureus* (gram-positive bacteria) was in the order of *P. granatum* > *M. acuminata* > *C. papaya* > *A. comosus* at 100mg/mL concentration. The *P. granatum* extracts showed a high inhibition zone at 100mg/ml (20.10 ± 0.06 mm) concentration against *S. aureus*, which was comparable to the positive control, streptomycin (20.06 ± 0.05 mm). Also, it was noted that *S. aureus* was resistant to the antibacterial activity of *C. papaya* peel at lower concentrations (20-60 mg/mL).

The antibacterial activity of the fruit peel extract against the selected gram-negative bacteria namely, *P. aeruginosa* and *K. pneumoniae,* was in the order *P. granatum* > *C. papaya* > *M. acuminata* > *A. comosus,* and *A. comosus* > *M. acuminata* > *C. papaya* > *P. granatum* respectively. It was observed that all the fruit extracts were highly effective against *P. aeruginosa,* and the Zone of Inhibition (ZOI) of *P. granatum* (11.10 ± 0.10 mm) at a concentration as low as 20mg/ml, which was significantly higher than the positive control, streptomycin (6.06 ± 0.06 mm). However, *K. pneumoniae* was found to be resistant to fruit peel extracts at concentrations of 20-80mg/mL in *P. granatum,* 20-60mg/mL in *C. papaya,* and 20-40 mg/mL in *M. acuminate.* Interestingly, the extract of *A. comosus* was effective against *K. pneumoniae* at a concentration as low as 20 mg/mL, and showed a significantly high inhibition zone (22.23 ± 0.32 mm), when compared to the control streptomycin (20.20 ± 0.10 mm).

Hence, it was noted that the fruit peels show comparable activities with the tested standard antibiotic (Streptomycin) and show high antibacterial efficacy against the tested pathogens, especially at 100mg/mL. This could be due to the wide spectrum of bioactive compounds like polyphenols, flavonoids, tannins, and anthocyanins, which possess antimicrobial potential in fruit peels (Zaki *et al*., 2022). The present study showed that the antimicrobial efficiency of *A. comosus* was in the order: *P. aeruginosa* < *K. pneumoniae* < *S. aureus* which followed the trend observed by Okoh *et al*. (2019). The present results were also consistent with the findings of Zaki *et al.* (2022) and Hanafy *et al.* (2021) who showed that *P. granatum* has stronger antibacterial activity than *M. acuminate* peels against *S. aureus* and *P. aeruginosa*. However, limited or no findings have been reported on the efficacy of *P. granatum* against *K. pneumoniae.* Also, there are numerous findings on the antimicrobial activity of *C. papaya* fruit and leaf extract (Sharma *et al*., 2020; Dagne *et al*., 2021; Romasi *et al*., 2013; Singh *et al*., 2020), however, there is limited or no information regarding the antimicrobial efficiency of *C. papaya* peel. Hence, the present study would help understand fruit extracts' role as a natural antimicrobial agent in disease treatment.

Minimum Inhibitory Concentration (MIC)

The Minimum Inhibitory Concentration of the pathogenic strains against the selected fruit peel extracts was determined and tabulated in Table 2. Under visual inspection, the MIC of the tested fruit peel extracts ranged from 6.25 to 100mg/mL for the tested bacteria. The results showed that all four fruit peel extracts (*C. papaya*, *A. comosus*, *M. acuminata*, and *P. granatum*) showed significant antibacterial properties. *P. granatum, C. papaya* and, *M. acuminata* showed lower MIC values (better antibacterial activity) (12.5 mg/mL), against *S. aureus* when compared to *A. comosus* (50 mg/mL). The MIC value of *M. acuminate* and *P. granatum* (12.5 mg/mL), against *S. aureus* was following the findings of Zaki *et al.* (2022) and Nozohour *et al.* (2018) respectively. Additionally, *P. granatum* and *C. papaya* also showed lower MICs against *P. aeruginosa* (12.5 mg/mL) compared to *A. comosus* and *M. acuminata* (50 mg/mL). However, when tested against *K. pneumoniae, A. comosus* showed very low MIC value (6.25 mg/mL), followed by *M. acuminata* (25 mg/mL), *C. papaya and P. granatum* (100 mg/mL). The MIC value of *M. acuminate* (50 mg/mL), against *P. aeruginosa* was in accordance with Sirajudin *et al.* (2014).

Spectrophotometric readings gave values of MIC ranging from 6.25 to 100mg/mL It was observed that all the fruit peels demonstrated similar antibacterial activities as visually determined MIC against *P. aeruginosa.* However, there were slight variations in MIC values

Table 2. Minimum Inhibitory Concentration (MIC) values of fruit peel extract against selected microbial strains (mg/mL)

No.	Pathogenic microbe	Visual MIC (mg/mL)				Spectrophotometric MIC (mg/mL)			
		P. granatum	*C. papaya*	*A. comosus*	*M. acuminata*	*P. granatum*	*C. papaya*	*A. comosus*	*M. acuminata*
1	*S. aureus*	12.5	12.5	50	12.5	12.5	25	50	12.5
2	*P. aeruginosa*	12.5	12.5	50	50	12.5	12.5	50	50
3	*K. pneumoniae*	100	100	6.25	25	100	100	6.25	50

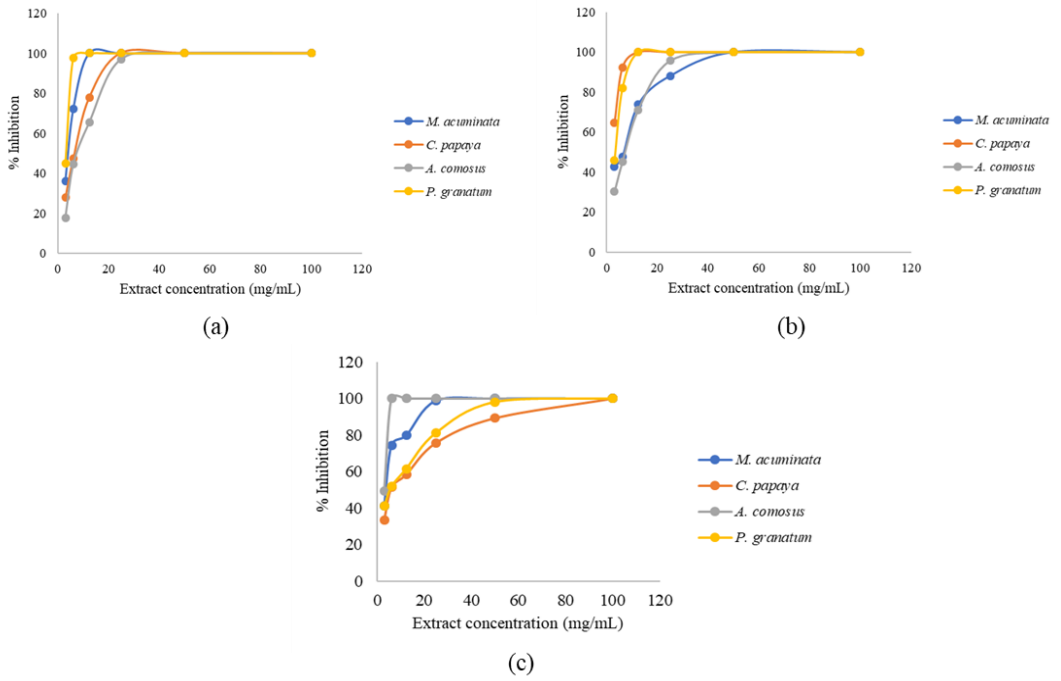

Fig. 1. *Inhibition of the growth of (a) S. aureus (b) P. aeruginosa (c) K. pneumoniae caused by fruit peel extracts at different concentrations (3.125-100 mg/mL)*

tested against *S. aureus* and *K. pneumoniae* compared to the visual MIC. *C. papaya* showed higher spectrophotometric MIC values (25 mg/mL) when compared to the visual MIC (12.5 mg/mL) against *S. aureus*. However, *M. acuminata* showed higher spectrophotometric MIC values (50 mg/mL) when compared to the visual MIC (25 mg/mL) against *K. pneumoniae*, which is consistent with the findings of Ramadani *et al.* (2022). Fig. 1 shows the bacterial growth inhibition (% Inhibition) pattern of *S. aureus, P. aeruginosa,* and *K. pneumoniae,* respectively, due to the exposure to different concentrations of fruit peel extracts.

Qualitative phytochemical screening

Data presented in Table 3 show the qualitative phytochemical screening of the fruit peels. The present study showed the presence of medicinally important phytochemical compounds in the peels of *C. papaya*, *A. comosus*, *M. acuminata*, and *P. granatum* such as phenols, tannins, glycosides, saponins, flavonoids, alkaloids, terpenoids, and steroids. The phytochemical screening of *M. acuminata* and *C. papaya* was consistent with the findings of Siddique *et al.* (2018), who reported that *M. acuminata* and *C. papaya* are rich sources of alkaloids, tannins, phenols, flavonoids and saponins, which exhibit potent antibacterial activity against *S. aureus*, *B. subtilis*, *P. aeruginosa*, and *E. coli*. Similarly, the fruit peels of *A. comosus exhibited moderate to high concentrations of flavonoids, phenols, tannins, saponins, alkaloids, and terpenoids in the present study*. These findings align with the study by Hikal et al. (2021), which demonstrated that the phytochemical constituents of *A. comosus* peels contribute to their antibacterial activity against *S. aureus*, *Vibrio cholerae*, *P. aeruginosa*, and *E. coli*. Phytochemical screening of *P. granatum* peels showed high levels of phenols, tannins, and flavonoids, consistent with Gopalraaj and Velayudhannair's findings (2024). Similar findings were reported by Sweidan *et al.* (2023), who reported the richness of phytochemicals, especially phenols, flavonoids and tannins in *P. granatum,* which have significant antioxidant and antimicrobial activity against *P. aeruginosa*, and *Micrococcus luteus.* Hence, the antibacterial activity exhibited by the fruit peel extracts are

Table 3. Qualitative phytochemical screening of fruit peels of *P. granatum, C. papaya*, *A. comosus,* and *M. acuminata*

Fruit peel	Phenols	Tannins	Glycosides	Saponins	Flavonoids	Alkaloids	Terpenoids	Steroids
P. granatum	++++	++++	+++	+++	++++	+++	+++	+++
C. papaya	+	++	+++	+++	++	++	+	+
A. comosus	++	++	+	+++	++	+++	++	+
M. acuminata	++	++	+	+++	++	++	+++	+

+Trace, ++Moderate, +++High, ++++Very High −Absent

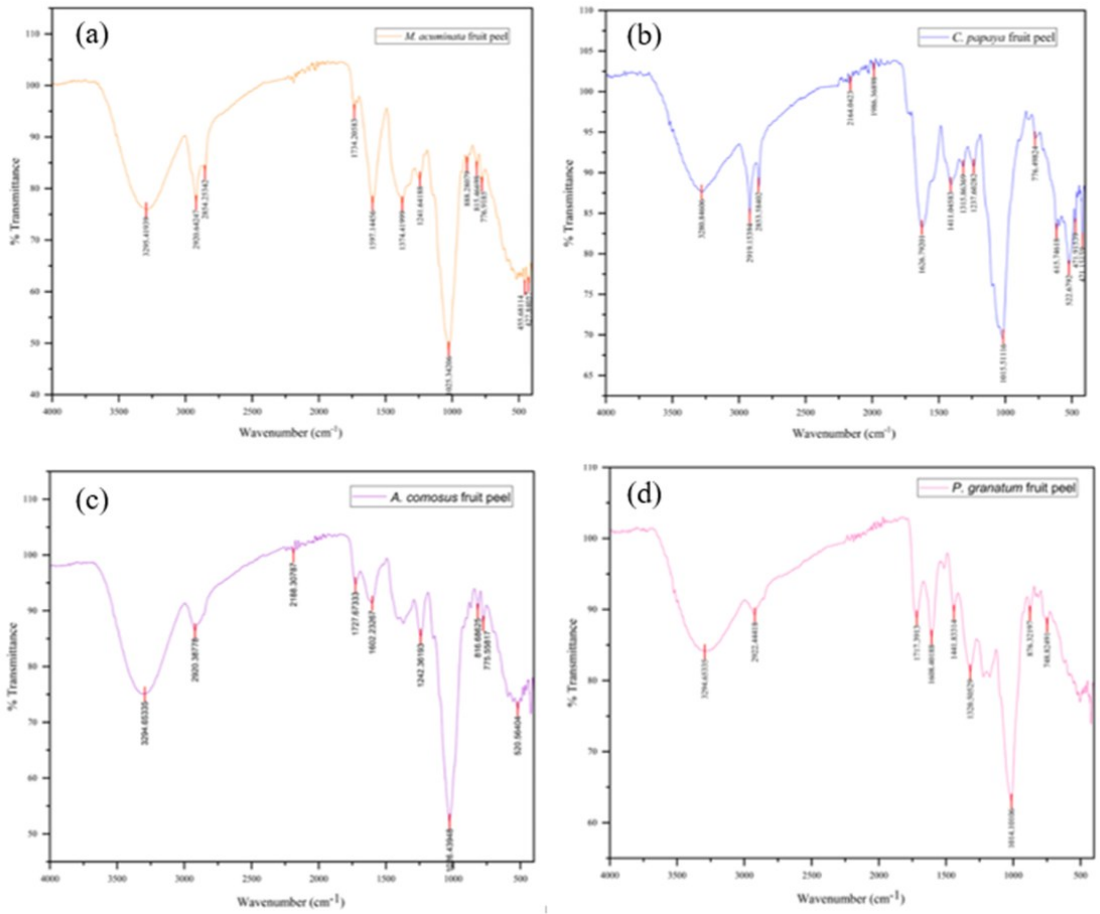

Fig. 2. *FT-IR profile of (a) M. acuminate (b) C. papaya (c) A. comosus (d) P. granatum fruit peels*

majorly due to the presence of these phytochemical compounds. Flavonoids and phenols are highly effective against gram-positive bacteria by acting on the peptidoglycan layer and damaging the cell membrane (Hikal *et al*., 2021). This justifies the present observation that all the selected fruit peels, especially *P. granatum* with very high levels of flavonoids and phenols were highly effective against gram-negative bacteria, *S. aureus*. Most of the phenolic compounds from plant sources are non-toxic for human consumption and, hence, could be effectively used to prevent the growth of these microbes (Hikal *et al*., 2021). Saponins are known to increase bacterial cell wall permeability, allowing antibacterial substances to enter the cells and cause cell lysis (Eshamah *et al*., 2013). Tannins work against microorganisms by hydrogen bonding, iron deprivation, or specific interactions with essential proteins in the microbial cell (Hikal *et al*., 2021). Glycosides (Křen and Řezanka, 2008), alkaloids (Huang *et al*., 2022), terpenoids (Huang *et al*., 2022), and steroids (Dogan *et al*., 2017) inhibit bacterial growth by increasing cell permeability and inhibiting protein synthesis in microbes. Hence, these important phytochemical compounds could be responsible for the antimicrobial activity shown by these fruit peels.

Structural elucidation: FT-IR and GC-MS analysis

The FT-IR and GC-MS Analysis was performed to identify the bioactive compounds responsible for the antimicrobial activity in the fruit peels of *C. papaya*, *A. comosus*, *M. acuminata*, and *P. granatum.* The FT-IR analysis was done to detect the major functional groups present in the fruit peel extracts as shown in Fig. 2. The IR spectra of *M. acuminate*, *C. papaya*, *A. comosus*, and *P. granatum* were similar to each other, indicating that they possess similar functional groups. Major functional groups that were identified in the fruit peels included alcohol, alkane, aromatic compound, fluoro compound, alkyl aryl ether group, alkene, halo compounds, metal carbonyl, aliphatic nitrile, aliphatic carboxylic acid, aliphatic aldehyde, aliphatic amine, aliphatic ester, and aliphatic silicon compounds. The functional groups identified using FT-IR analysis in the present study are in agreement with the findings of Hadi *et al*. (2016) for *P. granatum*; Naksing *et al*. (2021) for *M. acuminate*; Balavijayalakshmi and Ramalakshmi (2017) for *C. papaya*, and Mishra *et al*. (2010) for *A. comosus*.

Natural products, including secondary metabolites produced by plants and microorganisms, have long been studied for their antimicrobial activity in the search for eco-friendly substitutes for synthesized chemi-

Table 4. Chemical composition of fruit peels of *P. granatum, C. papaya*, *A. comosus,* and *M. acuminata*

No.	Compound	Fruit peels							
		P. granatum		*C. papaya*		*A. comosus*		*M. acuminata*	
		Retention time (min)	Area %	Retention time (min)	Area %	Retention time (min)	Area %	Retention time (min)	Area %
1	Tridecane, 4-methyl-	8.611	1.43	-	-	8.612	0.15	8.612	0.52
2	9,19-Cycloergost-24(28)-en-3-ol, 4,14-dimethyl-, acetate, (3.beta.,4.alpha.,5.alpha.)	-	-	-	-	12.690	34.89	-	-
3	Tetracyclo[6.1.0.0(2,4).0(5,7)]nonane, 3,3,6,6,9,9-hexamethyl-,	10.162	59.13	10.161	36.51	10.165	9.40	-	-
4	Phthalic acid, butyl oct-3-yl ester	12.284	22.67	-	-	-	-	12.281	8.13
5	n-Hexadecanoic acid	12.346	10.87	-	-	-	-	-	-
6	Octadecane, 4-methyl-	-	-	-	-	-	-	11.222	4.23
7	Ethanone, 1-(1,2,2,3-tetramethylcyclopentyl)-, (1R-cis)-	-	-	8.887	0.62	-	-	-	-
8	Sulfurous acid, 2-propyl undecyl ester	-	-	11.407	1.74	-	-	-	-
9	2-Methyltetracosane	-	-	-	-	-	-	12.669	0.71
10	Nonadacane	-	-	-	-	-	-	12.704	2.59
12	1,3-Propanediol,2-dodecyl	-	-	-	-	-	-	12.955	13.59
13	Benzene, 1,3,5-trichloro-2,4-dinitro-	-	-	12.280	4.46	-	-	-	-
14	1-Acetoxy-cis-2-benzoyloxy-6-methoxy-1,2,3,4-tetrahydronaphthalene	-	-	12.345	37.23	-	-	-	-
15	11-Methyldodecanol	-	-	13.051	1.59	-	-	-	-
16	1-Nonene, 4,6,8-trimethyl-	-	-	-	-	8.823	0.54	8.955	1.62
17	2,6,10,14-Hexadecatetraen-1-ol, 3,7,11,15-tetramethyl-, acetate, (E,E,E)	-	-	-	-	12.617	18.70	-	-
18	Kauren-18-ol, acetate, (4.beta.)-	-	-	-	-	12.788	11.59	-	-
19	Kauran-18-al, 17-(acetyloxy)-, (4.beta.)-	-	-	-	-	12.882	24.42	-	-
20	2,5-cyclohexadiene-1,4-dione, 2-(1,1-dimethylethyl)-5-(2-methyl-2-propen-1-yl)	-	-	-	-	-	-	10.159	36.36
21	1-Undecene, 7-methyl-	-	-	-	-	-	-	10.360	6.43
22	Sulfurous acid, dodecyl 2-propyl ester	-	-	12.893	0.72	-	-	11.405	3.94
23	9-Octadecenal	-	-	12.956	7.06	-	-	-	-
24	Nonadecanoic acid	-	-	12.988	8.93	-	-	12.350	19.34
25	2,4,6,8-Tetramethyl-1-undecene	8.822	5.91	8.821	1.13	8.886	0.30	8.821	1.53

cals (Atanasov *et al*., 2015). GC-MS analysis was performed for the selected fruit peels and based on their retention times and mass spectral fragmentation pattern, the compounds present in the peels were identified qualitatively. The fruit peels showed the presence of 7 compounds in *P. granatum*, 12 compounds in *C. papaya*, 9 compounds in *A. comosus*, and 17 compounds in *M. acuminate*, tabulated in Table 4. Tetracyclo[6.1.0.0(2,4).0(5,7)]nonane, 3,3,6,6,9,9-hexamethyl-, was recorded with the highest peak area percentage of 59.13% in *P. granatum* and 36.51% in *C. papaya* which are known to possess potential antiviral properties. The compound Phthalic acid, butyl oct-3-yl ester was found in significant levels in peels of *M. acuminate* (8.13%) and *P. granatum* (22.67). Phthalic acid esters (PAE) have shown antimicrobial properties by interfering with quorum sensing mediated virulence factors and biofilm formation in *P. aeruginosa* (Rashiya *et al*., 2021). n-hexadecanoic acid has also shown significant antimicrobial activity by inhibiting biofilm formation in *Pseudomonas aeruginosa* (Sajayan *et al*., 2023). The 9 - Octadecenal (7.06%) have also been reported to have antibacterial and antioxidant properties (Aanand *et al*., 2017). 1-Undecene, 7-methyl- was recorded in *M. acuminate* peels (6.43%), which is a volatile compound, highly effective in treating pulmonary diseases by direct inhalation in addition to antibiotic treatment (Corre *et al*., 2021). 1,3-propanediol, 2-dodecyl found in *M. acuminate* peels (13.59%) are effective antimicrobial agents and are highly effective against *E. coli* and *P. aeruginosa* (Iwasaki *et al*., 2023).

Conclusion

This study quantitatively assessed the antimicrobial potential of fruit peel extracts from *C. papaya*, *A. comosus*, *M. acuminata*, and *P. granatum*, highlighting their potential use as innovative, low-cost antimicrobial agents contributing to agro-waste management. These findings offer a promising alternative to conventional antibiotics, addressing the growing concern of untreatable bacterial infections due to rising multidrug resistance and the associated global health impact. The fruit peels demonstrated effectiveness against both gram-positive (*S. aureus*) and gram-negative bacteria (*P. aeruginosa* and *K. pneumoniae*), likely due to the presence of bioactive phytochemicals such as phenols, tannins, glycosides, saponins, flavonoids, alkaloids, terpenoids, and steroids, known for their antimicrobial properties. Additionally, GC-MS and FT-IR analyses confirmed the presence of functional groups and compounds with potent antimicrobial activity. Therefore, the findings suggest that the fruit peels of *C. papaya*, *A. comosus*, *M. acuminata*, and *P. granatum* hold potential as effective antimicrobial agents, though further research is needed to optimize formulation, dosage, and assess potential side effects.

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Conflict of interest

The authors declare that they have no conflict of interest.

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