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ORIGINAL ARTICLE

Characterization and sustainable utilization of *Punica granatum* and *Citrus limetta* peels: Insights for biomass valorization

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Abstract

The sustainable valorization of agricultural biomass waste is gaining momentum as an effective waste management strategy. Pomegranate *(Punica granatum)* and sweet lemon *(Citrus limetta)* peels, abundant by-products from the fruit processing industry, are currently underutilized and discarded as waste. This study aims to assess the suitability of pomegranate and sweet lemon peels for sustainable biomass valorization through a comprehensive characterization study. Biomass waste is processed and subsequently, various characterization techniques are applied to unveil its intrinsic properties. These methods encompass Field Emission Scanning Electron Microscope (FESEM), Energy-dispersive X-ray spectroscopy (EDS), Differential Scanning Calorimetry (DSC) and Fourier Transform Infrared Spectroscopy (FTIR). Elemental analysis reveals the predominance of carbon and oxygen in both peel types. Pomegranate peels and sweet lemon peels exhibit carbon content of 56.43% and 55.89%, respectively. FTIR analysis revealed a diverse range of functional groups in both peel types. Pomegranate peels contain O–H, C-H, C = O, C = C, O–H, C-N, C-O, C = C, and C–Cl. Whereas, sweet lemon peels display functional groups including O–H, C-H, N–H, C-O, C = O, and C-N. The findings indicate that the biomass derived from pomegranate and sweet lemon peels holds potential for efficacious resource utilization.

Keywords Biomass · *Punica granatum* · *Citrus limetta* · Waste utilization

1 Introduction

The increasing demand for sustainable and eco-friendly technological solutions has led to extensive research on the valorization of biomass waste. Agro-industrial residues and food waste are significant contributors to the growing environmental challenges, as their disposal not only leads to pollution but also represents a missed opportunity for resource recovery [1, 2]. Agro-food waste originating from the farming and food processing industrial sector represents nearly one-third of the global agricultural output [3, 4]. The sustainable development goals (SDGs) of the United Nations, which outline a broad range of global objectives for holistic development, underline the necessity of creating valorization pathways [5]. Agro-waste management strategies can be broadly classified into following categories, namely, reduction, utilization, treatment, and disposal of waste. Among these, waste utilization has enormous potential as it can play a crucial role in changing the paradigm of waste being realized as an untapped resource for useful purposes [6]. Biomass waste utilization is being investigated in terms of reuse, recovery, and recycling for various applications [7–10].

In the context of utilization of biomass waste, fruit peels have garnered considerable attention due to their abundance, high organic content, and potential for multifarious applications [11, 12]. Pomegranate (*Punica granatum*) and sweet lemon (*Citrus limetta*) peels are particularly promising candidates for biomass valorization. Pomegranate peels, by-products of the thriving pomegranate juice and food processing industries, contain valuable chemical constituents such as phenolic compounds, flavonoids, and dietary fibers [13, 14]. Similarly, sweet lemon peels, generated in large quantities from juice extraction and citrus processing operations, possess a rich array of bioactive compounds, including limonoids, flavonoids, and essential oils [15]. Although these valuable components are very useful, their extraction may not always be viable considering the intricacies of extraction

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processes and concentration of these compounds present in the peels [16]. Hence, there is a need to explore other techniques as well for utilizing fruit peel waste that are simple, less energy-intensive, and easy to implement for beneficial practical applications [17, 18].

The efficient utilization of pomegranate and sweet lemon peels is not only an eco-friendly approach to address disposal challenges but also offers immense prospects in the production of high-value products across various industries. Of particular promise is the conversion of these peels into biosorbents and biofuels [19–21]. While biogenic materials are being extensively explored as adsorbents for abatement of a wide array of contaminants, including heavy metals, dyes, drugs, and other emerging pollutants, as well as bioenergy sources, there remains an intriguing research lacuna in unraveling their full potential as sustainable alternatives [22–25]. A significant knowledge gap exists in comprehensively characterizing the properties of biomaterials derived from pomegranate and sweet lemon peels. Such characterization is essential to ascertain their practical suitability for diverse applications. Insights into the physicochemical, thermal, and structural properties of biomaterials sourced from fruit peels can offer a deeper understanding of their potential applications [26].

In this work, a detailed characterization study of pomegranate and sweet lemon peels is presented with a specific focus on their valorization potential. A range of analytical techniques are employed, including spectroscopy, microscopy, and thermal analysis, to evaluate various properties, including morphology, elemental composition, chemical structure and thermal stability of these biomaterials. By elucidating the intrinsic properties of biomass obtained from pomegranate and sweet lemon peels, this study contributes to the advancement of sustainable biomass valorization strategies. The findings can aid researchers, industries, and policymakers in developing innovative technologies for the efficient utilization of fruit peels.

2 Material and methods

Two types of biomasses, namely pomegranate peels and sweet lemon peels, are investigated in the study.

2.1 Material collection and preparation

Pomegranate peels and sweet lemon peels, two waste biomass samples, were obtained from a local commercial store. Following their acquisition, both samples underwent a cleaning process to remove impurities. Subsequently, they were exposed to sunlight for five days for solar drying, and then further dried at 60 °C for 24 h in a thermal oven [27, 28]. The dried peels were then ground and milled to obtain a powdered form [29, 30]. A screening process was implemented to eliminate larger particles from the ground peels. After the screen analysis the both biomasses have diameter around 0.23 mm using rotary sieving. Thereafter, both biomass samples were subjected to characterization. The schematic diagram of biomass processing flow sheet is shown in Fig. 1.

2.2 Characterization

Field Emission Scanning Electron Microscope (FESEM), Energy-dispersive X-ray spectroscopy (EDS), Differential Scanning Calorimetry (DSC) (DSC-60 Plus, Shimadzu Corp. Kyoto, Japan), Fourier Transform Infrared Spectroscopy (FTIR) were used for analysis of physicochemical characteristics of biomass samples. Morphological micrographs were generated using a FESEM equipped with EDX (Sigma-300 with EDX, Ametek). FTIR analysis was performed using an IR-Prestige 21 spectrophotometer (Shimadzu Corporation, Japan). X-ray diffraction patterns were obtained using a diffractometer operated at 40 kV, 40 mA, and 9 kW (Smart Lab, Rigaku, Japan). DSC was employed to measure heat-related properties, with the test sample and reference materials maintained at a constant temperature at 25 °C throughout the analysis.

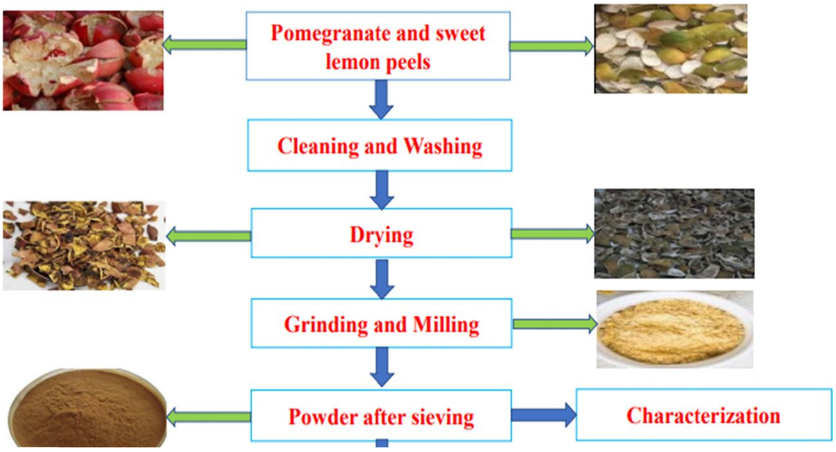

Fig. 1 Process flow Diagram of Biomass Valorization

3 Results and discussion

3.1 FESEM analysis of biomass

The surface morphology of raw *Punica granatum* peel powder was characterized using FESEM. Two different magnifications of the surface are shown in Fig. 2. Analysis of the FESEM images revealed that the surface of *Punica granatum* peels was notably rough and uneven, featuring distinct pores. Similar observations have been documented in previous studies on various biomasses, where the surfaces were described as coarse and rough [31]. Other studies on these peels also reported amorphous irregular surface structures and platy particles with unequal sizes and shapes [32]. These findings collectively indicate that the surface of *Punica granatum* peels is characterized by its rough, uneven, and porous structure [33].

Likewise, FESEM analysis of raw *Citrus limetta* peels, presented in Fig. 3 at two different magnifications, revealed a consistently rough, uneven and porous surface. These observations align with prior studies that have described the surface morphology of peels-derived biomasses as uneven and irregular [34]. Notably, micrographs from analysis conducted in other studies also indicated a rough surface of biomass [35]. Other studies also observed that surface morphology of biomaterial derived from *Citrus limetta* peel was uneven and porous, characterized by particles of irregular size [17].

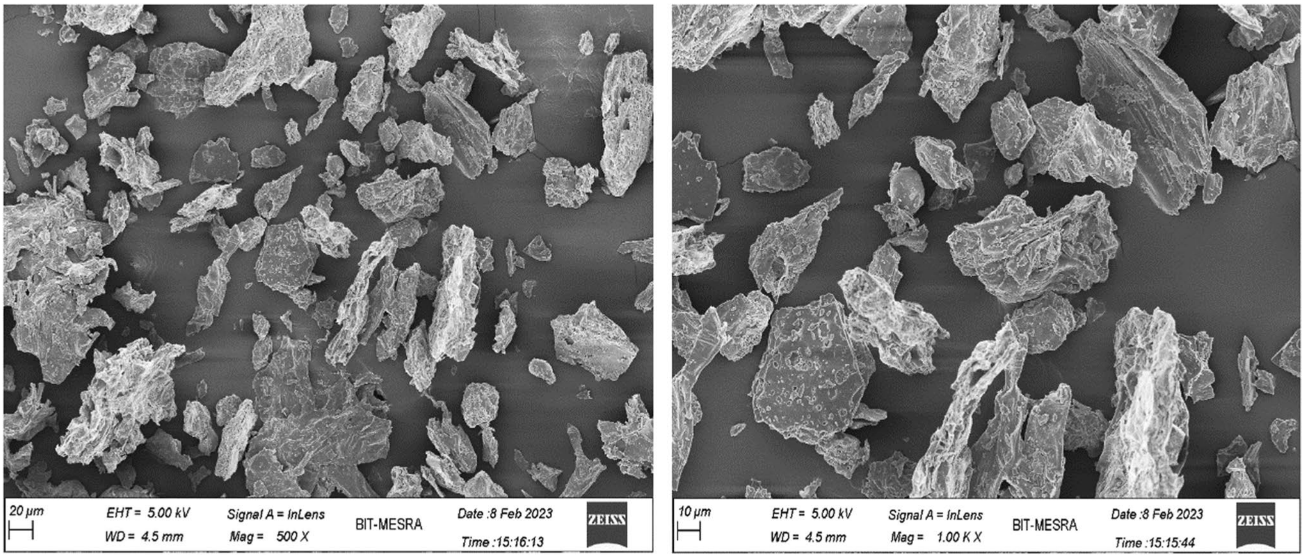

Fig. 2 FESEM micrograph of *Punica granatum* peel powder

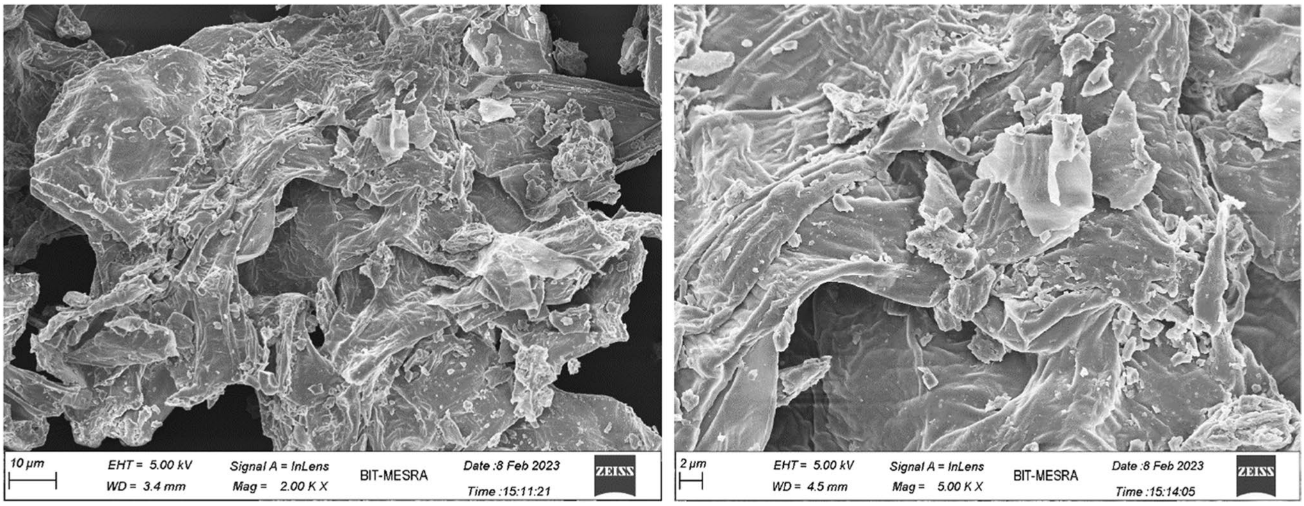

Fig. 3 FESEM micrograph of *Citrus limetta* peel powder

3.2 EDS Analysis of biomass

EDS is utilized to determine the elements that constitute *Punica granatum* and *Citrus limetta* peels. The EDS spectra and elemental analysis of *Punica granatum* peels are shown in Fig. 4. The EDS spectra *Punica granatum* Peels show two major peaks of carbon and oxygen with 56.43% and 39.28% (weight basis) respectively. In general, the substantial percentages of C and O are inherent to the nature of the *Punica granatum* peels. Moreover, some minor peaks are also observed, including K (2.86%), Ca (0.51%), Cl (0.53%), and P (0.40%). Other authors have also reported similar elemental compositions for different biomaterials derived from various parts of *Punica granatum*. In prior studies, the EDS results for *Punica granatum* activated carbon indicated two major peaks of C and O along with some minor peaks of Mg, Si and K [36]. Furthermore, the EDS spectra of *Punica granatum* leaf powder exhibited the presence of O (39.52%) and C (60.48%), along with some minor peaks of other elements [37].

The EDS spectra and elemental analysis of *Citrus limetta* peels are presented in Fig. 5. The EDS spectra of peels reveal two major peaks corresponding to carbon and oxygen, constituting 55.89% and 40.34% (weight basis) respectively. The significant percentages of carbon and oxygen are related to the nature of *Citrus limetta* peels. Additionally, minor peaks are identified, including Ca (2.07%), S (0.61%), P (0.58%), and K (0.51%). Similar elemental compositions have been reported in literature for various biomasses, including *Citrus limetta* peels. In previous studies, the EDS results for

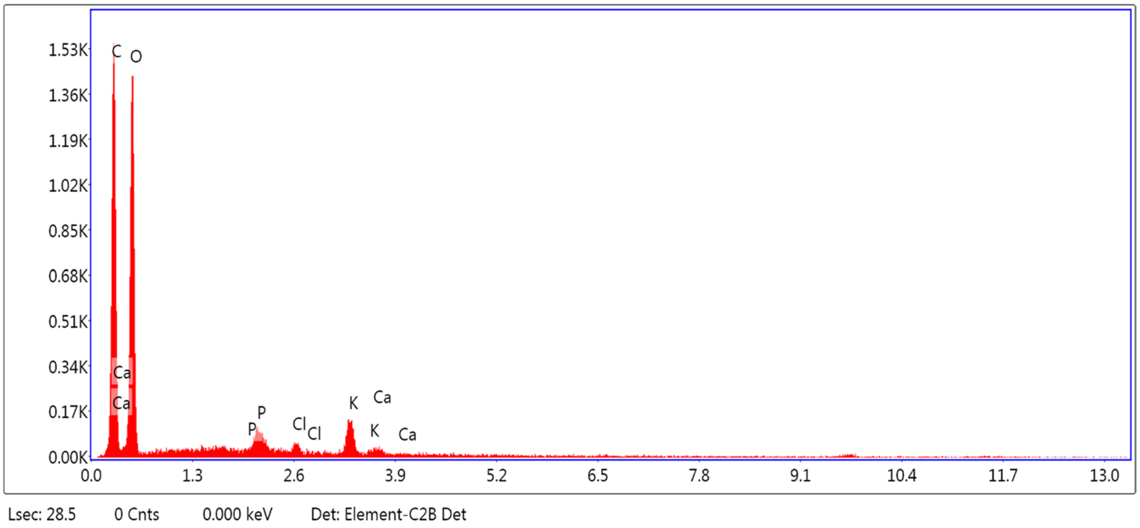

Fig. 4 EDS spectra of *Punica granatum* peel powder

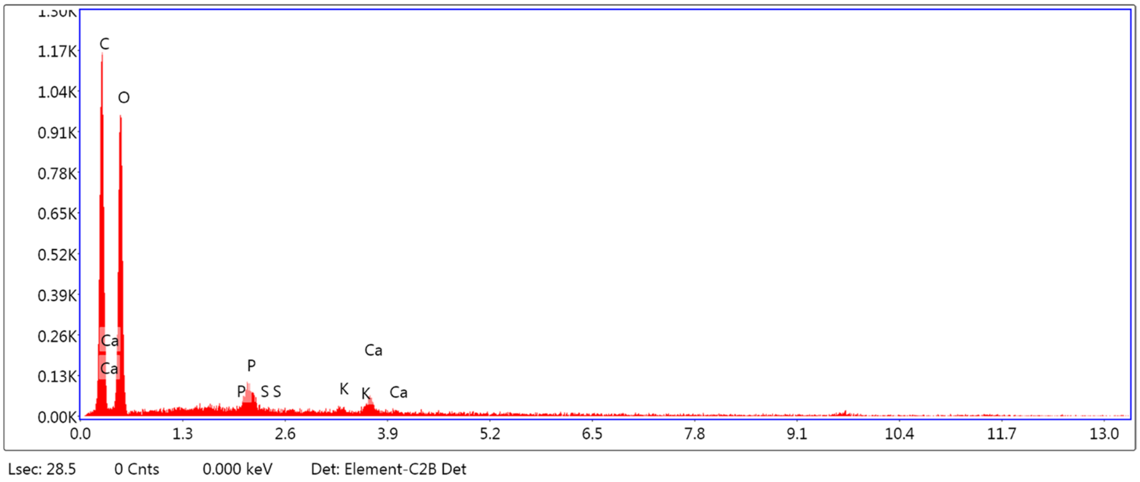

Fig. 5 EDS Spectra of *Citrus limetta* peel Powder for Elemental Analysis

Citrus limetta showed the presence of two major peaks for C (61.28%) and O (35.74%) along with a minor peak for S (2.98%) [17]. Another investigation showed considerably high carbon content (62.6%) in *Citrus limetta*, along with some presence of Fe, Al, K, Ca and Mg [38].

3.3 DSC Analysis of biomass

The transition temperature of the biomaterial sample was determined by taking the first evolution of the thermograms. The glass transition temperature (T_g) lies at the middle point of the initial and final temperature. Thermal stability test unravels the thermal degradation behavior of the sample. The transition temperatures of PGP and CLP samples are reported graphically in Figs. 6 and 7. The peak temperature value of the specimen is determined as the highest value corresponding to the witnessed endothermic transition. The results showed that the transition temperature of the PGP sample was the highest at 323.58 °C, whereas the peak temperature of the CLP sample was 338.96 °C. A similar transition temperature trend for pure PGP was reported by [39]. Their observations indicated that after raising the concentration of peel extract, the transition temperature of the sample declined. Other studies reported a decline in thermal integrity of starch-based samples on adding natural antioxidants possibly on account of depolymerization and dehydration of matrix [40]. The exothermic enthalpy for PGP sample was observed to be 80.47 J/g at 81.59 °C whereas endothermic enthalpy was 3.08 J/g at 242.69 °C, which further increased to 15.92 J/g at overall peak temperature of 323.58 °C. On the other hand, the thermal analysis of CLP sample revealed that exothermic enthalpy was 91.18 J/g at 83.79 °C and 51.37 J/g at 186.52 °C. A transition to endothermic enthalpy of 28.78 J/g was observed at overall peak temperature for 338.96 °C for CLP sample.

3.4 FTIR Analysis of biomass

The FTIR spectrum of *Punica granatum* peel is shown in Fig. 8. The analysis reveals peaks at various wavenumbers, indicating specific molecular vibrations. These include the peak near 3253 cm^{-1},corresponding to O–H stretching; the peaks near 2926 cm^{-1} and 2849 cm^{-1},representing C-H stretching, the peak near 1708 cm^{-1}, signifying C=O stretching; the peak near 1605.3 cm^{-1},indicating C=C

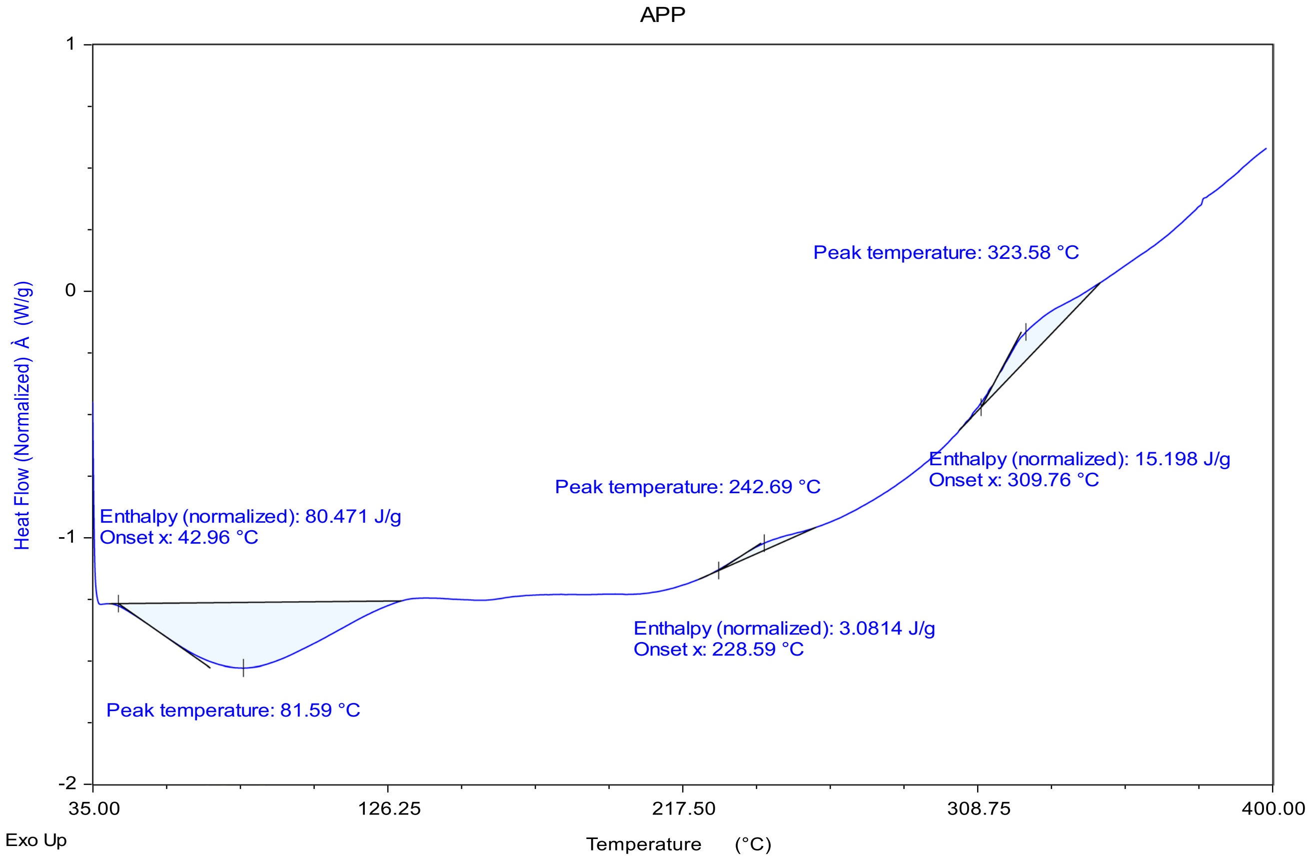

Fig. 6 DSC Analysis of *Punica granatum* Peel powder

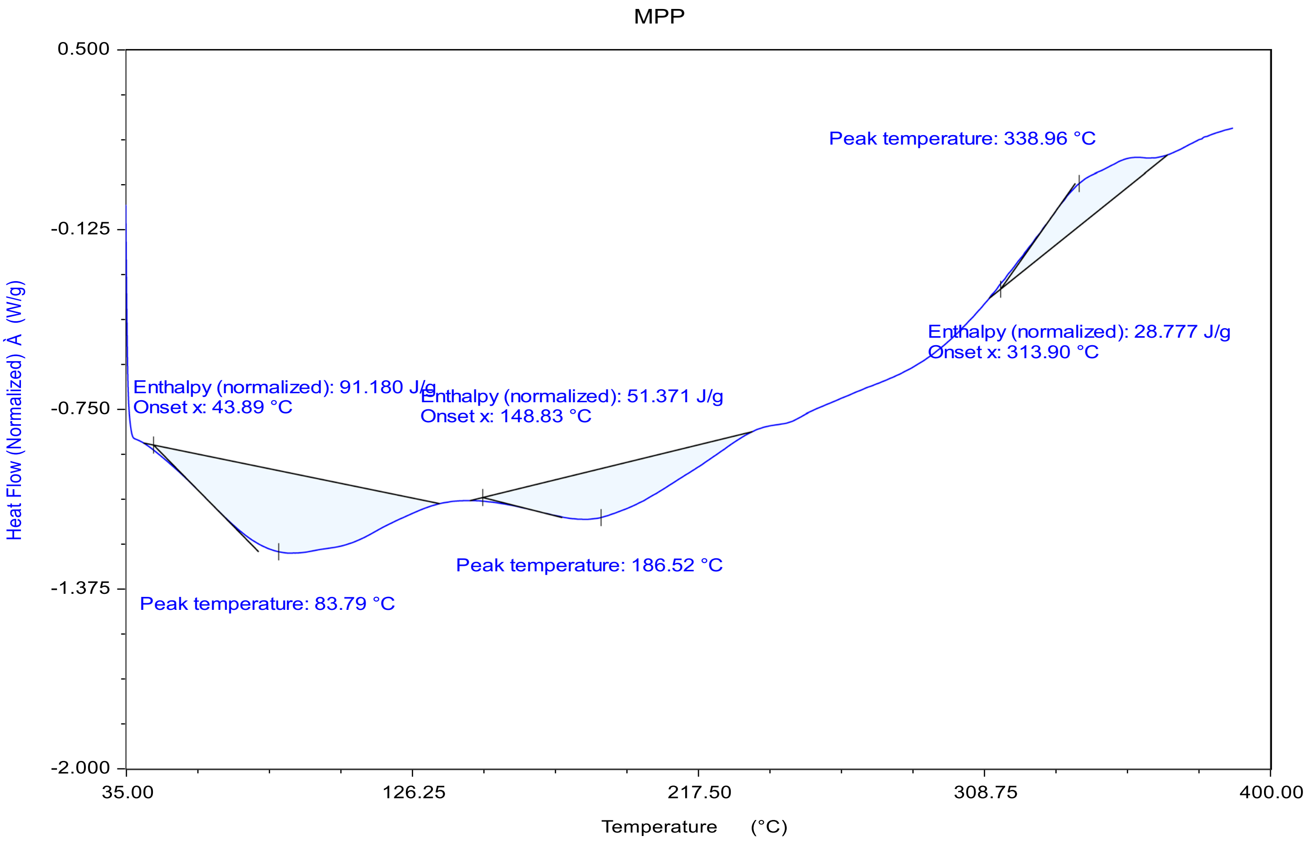

Fig. 7 DSC Analysis of *Citrus limetta* peel powder

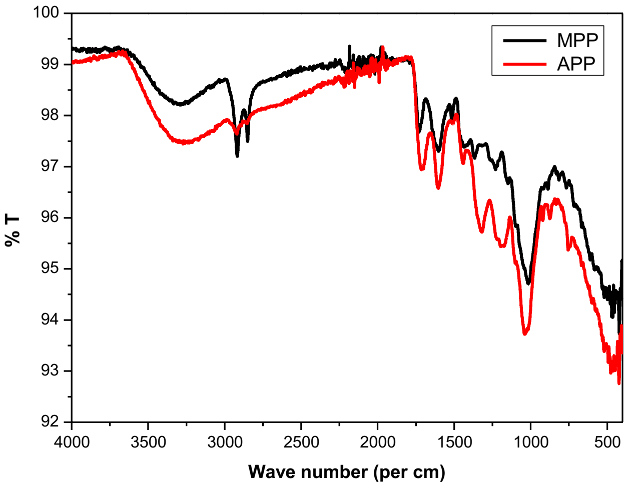

Fig. 8 FTIR Spectrum of *Punica granatum* and *Citrus limetta* peel powder

stretching, the peak near 1445 cm^{-1}, associated with O–H stretching; the peak near 1316.8 cm^{-1},representing O–H stretching; the peak near 1185.4 cm^{-1} denoting C-N stretching, the peak near 1037.43 cm^{-1}, representing C-O stretching; the peak near 919.32 cm^{-1},suggesting C = C stretching; and the peak near 871.24, representing C–Cl stretching. Other authors have also reported similar functional groups present in various biomasses, including *Punica granatum* peels. The FTIR results in literature showed the presence of O–H stretching (carboxylic acid), C-H stretching (aliphatic), C–C and C = C stretching (aromatic), C-O stretching(alcohol) [41]. Additionally, FTIR spectra indicated the presence of O–H stretching (carboxylic acid, phenol), C-H stretching, C-O stretching (carboxylic acid, ketone), C–C stretching, C = C stretching, and N–H stretching [42]. The peaks observed in the FTIR spectra suggested the presence of C-O stretching, C-H stretching, and C = C stretching, O–H stretching [43].

The FTIR spectrum of *Citrus limetta* peel is shown in Fig. 8. The analysis reveals distinctive peaks at corresponding to various molecular vibrations. Notably, the peak near 3282 cm^{-1} indicates the O–H stretching, while the peaks near 2916.5 cm^{-1} and 2852.4 cm^{-1} represent C-H stretching. The peak near 1720.7 cm^{-1} signifies C = O stretching, and the peak near 1599 cm^{-1} indicates N–H stretching. Furthermore, peaks near 1432.2 cm^{-1} and 1361 cm^{-1} suggest O–H bending, while the peak near 1230.3 cm^{-1} represents C-N stretching, and the peak near 1012.3 cm^{-1} denotes C-O stretching. Consistent functional groups have been reported by other authors for various biomasses, including *Citrus limetta* peels. The FTIR spectral analysis in literature indicated the presence O–H stretching (alcohols, phenols), N–H stretching, N–O stretching, C-O stretching (ethers) and C-O stretching (alcohols) [38]. In other studies, the FTIR results showed the presence of O–H stretching, C-H stretching, C-O stretching, C = O stretching, and C = C stretching [44].

4 Future prospects

The comprehensive characterization study of pomegranate and sweet lemon peels reveals exciting future possibilities in the realm of biomass valorization. Firstly, there is potential for optimizing the conversion processes of these peels into value-added products for diverse applications. This involves research into more efficient and eco-friendly methods. Moreover, exploring the synergies between pomegranate and sweet lemon peels and other biomass sources presents innovative opportunities for their sustainable utilization. Combining these peels with complementary feedstocks offers the potential to enhance both the yield and quality of derived products.

Additionally, there is an opportunity to produce valuable co-products. By-products or residues from the biomass processing can be utilized for various purposes, such as biogas, biochar, or even bio-based chemicals. This expanded use adds economic and environmental sustainability to the valorization process. Furthermore, integrating these peels into waste-to-energy systems could be a fruitful avenue. Collaborations with waste management facilities and energy companies may lead to the development of bioenergy generation units that utilize these biomass resources for heat and electricity production. Finally, scaling up and commercializing the production of valuable products from these peels is the logical next step. Partnerships with industries are required to bring these products to the market, making them accessible and significantly contributing to the global objectives of sustainable resource utilization.

5 Conclusion

This study has unveiled the valuable potential of pomegranate and sweet lemon peels as biomass resources for sustainable valorization. The comprehensive characterization of these materials, facilitated by a range of analytical techniques, has illuminated their inherent properties and suitability for deriving value-added products. The effective utilization of biomass waste paves the way for sustainable waste management and represents a significant step toward circular bioeconomy. Nevertheless, it is essential to acknowledge certain challenges and limitations of this study. A notable limitation is the need for optimization of the transformation process of biomass to maximize the yield of valuable products from these peels. Moreover, addressing issues related to scalability and the commercialization of production from these peels is a critical aspect that requires attention. To overcome these challenges, future research should focus on refining the conversion methods, exploring more efficient and eco-friendly approaches, and engaging in partnerships with relevant industries. These steps are crucial to ensure the successful transition from laboratory-scale studies to real-world applications. This research aligns with the United Nations sustainable development goals, particularly emphasizing sustainable production practices outlined in SDG 12. By exploring the potential of fruit peels as resources for deriving useful products, it contributes to the broader objectives of waste management, renewable energy generation, and environmental preservation. The significance of this work lies in its potential to lead to a more eco-conscious future. The insights gained from this study are poised to facilitate advancements in the utilization of waste biomass toward techno-economically viable and environmentally friendly production.

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Authors' contributions DBP performed the experiments and wrote the manuscript; AK helped in data analysis and edited the manuscript; AKA, RKA and AKT edited the manuscript.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this article.

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