

Proof-of-Concept Formulation of Manuka Honey into Powdered and Electrospun Bioactive Systems: Physicochemical Characterization and Antibacterial Screening

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Research Article

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Abstract

Manuka honey is a bioactive natural product with considerable formulation potential, but its direct use can be limited by viscosity, stickiness, and handling difficulties. In this study, a commercially sourced monofloral Manuka honey labelled as methylglyoxal (MGO) 100 + was processed into two alternative formats: a powdered formulation prepared with microcrystalline cellulose (MCC) under ambient conditions and an electrospun formulation produced with polyvinyl alcohol (PVA). The liquid honey and the two processed formulations were compared in terms of morphology, thermal behavior, spectral characteristics, and antibacterial screening performance. Scanning electron microscopy showed that MCC-assisted powdering produced irregular particulate aggregates, whereas electrospinning formed a continuous fibrous network. Thermogravimetric and Fourier transform infrared analyses showed that the two formulations had different thermal and spectral profiles, while major honey-associated spectral features remained detectable after processing. Antibacterial responses were evaluated against six bacterial strains using a disc/pellet diffusion assay with gentamicin as the positive control. The electrospun formulation showed the broadest inhibition profile, with the largest inhibition zone observed against *Staphylococcus aureus* (26 mm). Overall, the findings present a practical proof-of-concept for converting Manuka honey into process-dependent bioactive formulations with distinct physicochemical and antibacterial screening profiles.

1. Introduction

Honey is a chemically complex bee-derived product whose scientific value is no longer limited to its nutritional use. Its natural composition includes sugars, organic acids, enzymes, phenolic constituents, and several minor compounds that have been associated with antioxidant, antimicrobial, antiviral, anti-inflammatory, and immunomodulatory effects [1, 2]. This broad bioactive profile has encouraged the use of honey and other bee products in food technology, biomaterial design, and functional ingredient research [3]. However, honey is also a difficult material to formulate. Its viscosity, stickiness, hygroscopic nature, and high sugar content can restrict direct incorporation into applied product systems. Transforming honey into more manageable solid or fibrous forms is therefore not only a processing issue, but also a practical formulation problem with biotechnological relevance.

Manuka honey is particularly suitable for this type of formulation work because it is one of the most widely studied bioactive honeys and is well known for its antibacterial properties [4]. Previous studies have also considered Manuka honey and other regional honeys as natural antimicrobial ingredients for food-related and formulation-oriented applications [5]. Even so, honey-based systems cannot be evaluated as if all honeys behave in the same way. Botanical origin, geographical source, and compositional background may influence both biochemical properties and functional response [5, 6]. For this reason, studies on reformulated honey products should be linked to a clearly defined starting material.

Recent developments in honey-containing films, hydrogels, composite matrices, and other bee-product-based systems show that honey can be incorporated into different platforms with technological and biological relevance [3, 7]. Similar interest has been reported for antimicrobial composite films and bee-product-based gel systems, where apicultural products are used as functional ingredients in bioproduct and material development [8–10]. These studies suggest that an appropriate carrier or processing strategy may help translate the biological potential of honey into a more usable formulation format.

Two approaches are relevant in this regard. Carrier-assisted powdering offers a simple way to convert viscous honey into a dry particulate product. Electrospinning, on the other hand, can produce fibrous mats from polymer-based solutions containing bioactive ingredients. Electrospun systems are useful because active compounds can be physically entrapped within a polymeric fiber network, producing a solid format from materials that are difficult to use in liquid form [11]. Honey-containing fibrous meshes and Manuka-honey-loaded matrices reported in previous studies further support the feasibility of incorporating honey into structured carrier systems [12, 13].

For powdered honey, previous reports have shown that the drying strategy, carrier material, and processing conditions can influence the quality and functional properties of the final powder [14, 15]. In the present approach, microcrystalline cellulose is not used as a water-soluble drying agent. Rather, it serves as an insoluble solid carrier that can physically support, disperse, and organize honey within a particulate matrix. This differs from conventional thermal drying and may provide a low-energy route for producing a manageable honey-containing powder. By contrast, electrospinning is a more process-intensive route, but it offers a fibrous formulation format with a different morphology and surface organization.

Although powdered honey and electrospun honey-containing systems have been studied separately, direct comparison of these two formulation routes using the same authenticated Manuka honey source remains limited. Such a comparison is useful because the two methods differ in process complexity, product morphology, and potential scalability. The present study was designed as a proof-of-concept formulation study comparing microcrystalline cellulose-assisted non-thermal powdering and polyvinyl alcohol-assisted electrospinning for converting Manuka honey into alternative bioactive formats. The working hypothesis was that these two processing routes would generate different physicochemical profiles and formulation-level antibacterial screening responses. To test this hypothesis, liquid Manuka honey, powdered Manuka honey, and electrospun Manuka honey formulations were evaluated using morphological imaging, thermogravimetric analysis, Fourier transform infrared spectroscopy, and disc/pellet diffusion-based antibacterial screening.

2. Materials and Methods

2.1. Materials, chemicals, and culture media

Commercial monofloral Manuka honey labelled as methylglyoxal (MGO) 100 + was used as the bioactive starting material. Microcrystalline cellulose (MCC; Smart Kimya, Turkey; TR-35-K-047442) was used as the solid carrier for the powdered formulation. Polyvinyl alcohol (PVA; 87.0–89.0% hydrolyzed, molecular weight approximately 31,000–50,000, Thermo Scientific, Cat. No. 183141000) was used as the fiber-forming polymer for electrospinning. Gentamicin sulfate (Sigma-Aldrich, USA, MW: ~575.59 g/mol, CAS: 1405-41-0) was used as the positive antibacterial control. Nutrient broth (Merck 1.05443) and Nutrient agar (Merck 1.05450) were used for bacterial cultivation and diffusion-based antibacterial screening. Distilled water was used for preparation of the PVA solution and other aqueous preparations.

2.2. Honey sample

A commercially purchased monofloral Manuka honey sample labelled as methylglyoxal (MGO) 100 + was used as the starting material. The label value “MGO 100+” refers to the commercial methylglyoxal rating of the honey, while the supplier-provided certificate of analysis reported an MGO content of 180 mg/kg for the batch used in this study. Selected physicochemical, authenticity-related, and microbiological characteristics reported in the certificate of analysis are summarized in Table 1 to define the starting material used for formulation. These certificate-based values were used only for sample description and were not treated as experimentally generated post-processing data. Before use, the honey was stored at room temperature in a dry environment and protected from direct light.

Table 1
Supplier-reported quality characteristics of the honey sample used in the study

Parameter	Specification	Result	Unit
Honey type	Monofloral	Monofloral	–
Moisture content	≤ 20	18	%
Hydroxymethylfurfural (HMF)	≤ 40	10.6	mg/kg
Methylglyoxal (MGO)	≥ label claim (100+)	180	mg/kg
Tutin	≤ 0.70	< 0.01	mg/kg
3-Phenyllactic acid (3-PLA)	≥ 400 (monofloral)	460	mg/kg
2-Methoxyacetophenone (2-MAP)	≥ 5 (monofloral)	6.7	mg/kg
2-Methoxybenzoic acid (2-MB)	≥ 1	5.2	mg/kg
4-Hydroxyphenyllactic acid (4-HPA)	≥ 1	4.5	mg/kg
Manuka pollen DNA	< Cq 36	22.07	Cq
Mould	< 1000	< 10	cfu/g
Yeast	< 2500	2300	cfu/g

2.3. Preparation of powdered Manuka honey

To obtain Manuka honey in powdered form under ambient conditions, a microcrystalline cellulose (MCC)-based non-thermal approach was used. In this formulation, water-insoluble MCC served as the carrier matrix, providing a surface for adsorption and physical incorporation of honey components. Liquid Manuka honey (10 g) was mixed with microcrystalline cellulose (MCC, 4 g) until a homogeneous blend was obtained. This proportion was selected to provide sufficient powder formation, acceptable flow behavior, and handling stability while maintaining a relatively high honey content. The resulting material was then placed in open glass containers and kept under ambient laboratory conditions (22–25°C and 35–40% relative humidity) in a dry environment protected from direct light. To support gradual incorporation of honey into the cellulose matrix and to promote uniform drying, the mixture was mechanically stirred 3–4 times per day. Drying was carried out under room-temperature conditions without thermal treatment, forced air, or auxiliary drying equipment, and the process continued for approximately two weeks until a free-flowing powdered structure without visible agglomeration was obtained, consistent with the previously described non-thermal powdering approach [16]. For antimicrobial testing, the powdered honey formulation was shaped into pellets with a diameter of 5 mm. The powdered Manuka honey was subsequently kept under dry laboratory conditions at ambient temperature until further analysis.

2.4. Preparation of electrospun Manuka honey formulation

The electrospun Manuka honey formulation was produced by PVA-assisted electrospinning. A 12% polyvinyl alcohol (PVA) solution was first prepared in pure water at 75°C for 3 h under magnetic stirring at 250 rpm, and the Manuka honey sample was then incorporated into the polymer solution to obtain the electrospinning mixture. The final electrospinning mixture contained honey at 70% (w/v) and was homogenized at 300 rpm for 4 h. The prepared solution was electrospun at a flow rate of 0.300 mL/h, under an applied voltage of 13.5 kV, with a 9.5 cm tip-to-collector distance. The nanofibrous material was collected on oiled paper placed on the collector surface. An electrospinning device (0–30 kV, 0–1.0 mA; Faraday Electric and Electronics Ltd., Erzurum, Türkiye) and an injection pump (Harvard Apparatus 11 Plus, Holliston, MA, USA) were used. For antibacterial testing, the electrospun nano Manuka honey formulation was cut into 5 mm discs.

2.5. Morphological and physicochemical characterization

2.5.1. Light microscopy

The powdered Manuka honey formulation was examined using a trinocular light microscope imaging system (Olympus BX43 equipped with an SC180 camera system, Japan) to document its macro- to micro-scale particulate appearance after non-thermal powdering. Representative images were recorded to support visual assessment of particle aggregation, heterogeneity, and powder-like structural organization.

2.5.2. Scanning electron microscopy (SEM)

The morphology of the electrospun nano and powdered Manuka honey formulations was examined by scanning electron microscopy (SEM). SEM analyses were performed using a JEOL JSM 6510 instrument at Bingöl University Application and Research Center. Electrospun samples were observed under low-vacuum conditions at an approximate working distance of 12 mm and an accelerating voltage of 7 kV. SEM micrographs were examined using the ImageJ software for qualitative morphological assessment.

2.5.3. Thermogravimetric analysis (TGA)

Thermal behavior of the samples was evaluated by thermogravimetric analysis (TGA) using a STA6000/8000 thermogravimetric analyzer (PerkinElmer, USA). Measurements were carried out over the temperature range of 30–600°C at a heating rate of 10°C/min under a nitrogen atmosphere.

2.5.4. Fourier transform infrared spectroscopy (FTIR)

Functional group analysis was performed by Fourier transform infrared spectroscopy (FTIR) using a PerkinElmer Spectrum 100 FT-IR spectrometer. Spectra were recorded in the range of 450–4000 cm⁻¹ at a resolution of 4 cm⁻¹. The instrument was equipped with an MCT detector and a CSI optics/TGS system.

2.6. Microorganisms and diffusion-based antibacterial response assay

Antibacterial responses were assessed against six bacterial strains, comprising three Gram-positive species (*Staphylococcus aureus*, *Streptococcus pneumoniae*, and *Enterococcus faecium*) and three Gram-negative species (*Escherichia coli*, *Salmonella typhimurium*, and *Serratia marcescens*). These reference strains were obtained from the culture collection of Atatürk University. The strains were first revived in Nutrient broth (Merck 1.05443) and then adjusted to a final concentration of 10⁶ CFU/mL (OD600 = 0.02 Abs). The resulting suspensions were spread onto Nutrient agar plates (Merck 1.05450). For antimicrobial comparisons, the applied amount of Manuka honey was standardized across formulations on a mass basis. Liquid honey was applied at 10 µL per plate, corresponding to approximately 14 mg of honey. Since the powdered formulation contained 71.4% (w/w) honey (10 g honey in 14 g total formulation), each 5 mm powdered pellet was adjusted to a total mass of 19.6 mg to provide approximately 14 mg of honey. Electrospun nano Manuka honey discs were prepared in 5 mm diameter and used on an approximately equivalent honey-loading basis relative to the other tested formulations. For antibacterial testing, liquid Manuka honey was applied directly to the inoculated Petri dishes as a single drop. Powdered honey was evaluated in pellet form (5 mm diameter), whereas electrospun nano Manuka honey was tested as disc-shaped material of the same diameter obtained on oiled paper. Gentamicin solution served as the positive control and was applied using the disc diffusion method under the same assay conditions. After application of the test materials, after application of the test materials, the inoculated plates were incubated at 37°C for 24 h. All assays were carried out in triplicate using three parallel applications prepared from the same batch, and inhibition zone diameters were measured in millimeters. Although the applied honey amount was standardized across formulations on a mass basis, the tested materials differed in physical presentation, namely a liquid drop, a powdered

pellet, and an electrospun disc. Therefore, the disc/pellet diffusion assay was used as a comparative screening method for formulation-level antibacterial response under diffusion-based conditions. Inhibition-zone diameter was not interpreted as a direct measure of intrinsic antibacterial potency, because it may also be affected by matrix architecture, surface exposure, hydration, and diffusion behavior.

2.7. Statistical analysis

All antibacterial screening assays were performed in triplicate using parallel applications prepared from the same formulation batch. Inhibition-zone diameters were recorded in millimeters and evaluated within a comparative formulation-screening framework. The analytical focus of the assay was to compare the observable antibacterial response profiles of liquid Manuka honey, powdered Manuka honey pellets, and electrospun Manuka honey discs under the same diffusion-based test conditions.

Because the study was designed as a proof-of-concept formulation screening study, the antibacterial data were interpreted descriptively according to formulation type and bacterial strain. This approach was selected to match the experimental design, in which the tested preparations differed not only in honey-containing composition but also in physical presentation, agar-contact geometry, hydration behavior, and diffusion mode. Therefore, inhibition-zone diameters were used as formulation-level screening endpoints rather than as direct quantitative rankings of intrinsic antibacterial potency.

The resulting response patterns were compared across the tested bacterial strains to determine whether processing the same Manuka honey source into powdered and electrospun formats produced distinct antibacterial screening profiles. This comparative framework allowed the antibacterial outcome to be interpreted together with the morphological, thermal, and spectral characterization data.

3. RESULTS

3.1. Morphological characterization

Macro- and micro-scale morphological examination showed that MCC-assisted non-thermal powdering converted liquid Manuka honey into a dry, particulate, and structurally heterogeneous material (Fig. 1). The powdered formulation displayed irregular particle aggregates with a broad size distribution, indicating that the MCC matrix provided a solid carrier framework for organizing honey into a powder-like architecture. SEM analysis further demonstrated that the two reformulation strategies produced clearly distinct material organizations from the same Manuka honey source (Fig. 2). The electrospun formulation formed a continuous fibrous network across the observed area, whereas the powdered formulation exhibited irregular, discontinuous, agglomerated, and plate-like particulate structures. These morphological differences show that powdering and electrospinning did not merely change the physical appearance of honey; rather, they generated two different material architectures with distinct surface organization and structural hierarchy.

3.2. Thermal characterization

The thermal profiles of the powdered and electrospun Manuka honey formulations demonstrated formulation-dependent mass-loss behavior over the 30–600°C range (Fig. 3). Both samples showed progressive thermal decomposition, with the main mass-loss region occurring approximately between 220 and 380°C. The electrospun formulation decreased from nearly 100% to approximately 19% residual mass at 600°C, whereas the powdered formulation decreased from about 89–90% to approximately 22–23%. Differences in initial mass level, curve trajectory, main degradation behavior, and final residue indicate that the two formulations had distinct thermal responses. The convergence and crossing of the curves around 270–280°C further supports the presence of formulation-specific thermal behavior. These findings show that the material architectures generated by MCC-assisted powdering and PVA-assisted electrospinning were reflected not only in morphology but also in thermal mass-loss characteristics.

3.3. FTIR spectral characterization

FTIR spectral characterization confirmed that both reformulated Manuka honey systems retained major honey-associated spectral features while displaying formulation-dependent spectral differences (Fig. 4). The powdered formulation showed a broad absorption band around 3271 cm^{-1} , together with bands near 2935 and 1643 cm^{-1} . The electrospun formulation exhibited a distinct band near 2988 cm^{-1} . In the fingerprint region, strong bands were observed around 1010 cm^{-1} for the powdered formulation and around 1008 cm^{-1} for the electrospun formulation, consistent with carbohydrate-rich honey matrices. The preservation of these spectral features indicates that the principal honey-related functional group profile remained detectable after reformulation. At the same time, differences in band position and intensity show that MCC-assisted powdering and PVA-assisted electrospinning created different molecular environments within the final material structures.

3.4. Antibacterial responses

The diffusion-based antibacterial response profiles of liquid, powdered, and electrospun Manuka honey formulations are presented in Table 2 and Fig. 5. The tested preparations produced formulation- and strain-dependent inhibition patterns. Among Gram-positive bacteria, the electrospun formulation showed its highest response against *Staphylococcus aureus*, with an inhibition zone of 26 mm, compared with 15 mm for liquid honey, 9 mm for powdered honey, and 17 mm for gentamicin. Against *Streptococcus pneumoniae*, liquid and electrospun Manuka honey produced equal inhibition zones of 14 mm, whereas powdered honey produced an 8 mm zone and gentamicin produced a 16 mm zone. For *Enterococcus faecium*, the inhibition zones were 11 mm for both liquid and powdered honey, 16 mm for the electrospun formulation, and 22 mm for gentamicin.

Among Gram-negative bacteria, *Escherichia coli* showed inhibition zones of 9, 6, 12, and 13 mm for liquid honey, powdered honey, electrospun honey, and gentamicin, respectively. A similar pattern was observed for *Salmonella typhimurium*, with inhibition zones of 10, 6, 11, and 22 mm. *Serratia marcescens* showed a

more limited response to honey-based formulations; liquid and electrospun Manuka honey produced inhibition zones of 9 and 7 mm, respectively, whereas powdered honey produced no detectable inhibition zone and gentamicin produced a 24 mm zone. Overall, the electrospun formulation displayed the broadest measurable inhibition profile under the applied diffusion assay conditions. These results demonstrate that reformulation of the same Manuka honey source into distinct physical architectures produced different antibacterial response profiles across the tested bacterial strains.

Table 2 Formulation-dependent diffusion-based antibacterial response profiles of liquid, powdered, and electrospun Manuka honey against selected bacterial strains				
Bacterial Strains	Liquid Manuka honey	Powdered Manuka honey	Electrospun Manuka honey	Gentamicin
Gram-positive				
<i>Staphylococcus aureus</i>	15	9	26	17
<i>Streptococcus pneumoniae</i>	14	8	14	16
<i>Enterococcus faecium</i>	11	11	16	22
Gram-negative				
<i>Escherichia coli</i>	9	6	12	13
<i>Salmonella typhimurium</i>	10	6	11	22
<i>Serratia marcescens</i>	9	–	7	24

Values represent inhibition-zone diameters recorded in triplicate formulation-screening assays and are reported in millimeters. The data were evaluated descriptively within the proof-of-concept comparative design. “–” indicates that no detectable inhibition zone was observed.

4. Discussion

The present study positions Manuka honey reformulation as a proof-of-concept applied formulation study rather than treating it only as a conventional antibacterial screening model. Manuka honey is widely regarded as a distinctive antibacterial honey, and recent literature has continued to emphasize its relevance particularly against problematic *Staphylococcus* species [17]. At the same time, honey bioactivity is not attributed to a single determinant, because its antibacterial profile is shaped by physicochemical characteristics, floral origin, and overall bioactive composition [18]. This broader compositional framework remains important when interpreting the present findings, as region-based

analytical work has shown that honey composition can vary substantially according to production area [19], while studies from other geographical settings have likewise demonstrated close links between physicochemical profile, microbiological quality, and antibacterial performance in natural honeys [20]. A similar composition-dependent pattern has also been documented in other bee-derived products, where biological response varies according to matrix properties and experimental context [21]. In the present study, however, the main contribution is not another compositional comparison of honey sources, but the demonstration that the same monofloral Manuka honey can be converted into two process-dependent formulation formats with distinct morphological, thermal, spectral, and antibacterial screening profiles. The morphological, thermal, and spectral findings collectively show that MCC-assisted powdering and PVA-assisted electrospinning generated distinct process-dependent formulation systems from the same honey matrix. As shown in Fig. 2, SEM images revealed a fibrous, interconnected morphology in the electrospun formulation, whereas powdered Manuka honey showed irregular, agglomerated, non-fibrous, plate-like, and particulate structures. These differences were also reflected in the TGA and FTIR profiles shown in Figs. 3 and 4, indicating that the two processing routes affected not only the external form of the material but also its measurable thermal and spectral behavior. This interpretation agrees with recent studies indicating that both drying method and botanical origin can affect the physicochemical and potentially bioactive properties of honey powders [22]. Other reports have shown that antioxidant, antimicrobial, and anti-inflammatory properties may vary with the powdering method and carrier system used [23], while carrier selection itself can influence the development and final properties of freeze-dried honey powders [24]. Likewise, freeze-drying, vacuum-drying, foam-mat drying, and spray-drying have been shown to produce honey powders with different structural and technological characteristics, leading to different functional outcomes [25–27]. Mixture-design studies have further shown that both botanical origin and processing strategy influence hydration-related behavior in honey-based powder ingredients [28]. The present study extends this discussion by comparing two fundamentally different formulation routes, carrier-assisted powdering and electrospinning, within the same authenticated Manuka honey source.

The electrospun formulation represents the fiber-based biotechnological formulation route within this comparative design. Fibrous honey-containing materials have been reported to show organized structural features in mesh-like formats [29], while Manuka-honey-loaded matrices have also been described as carrier systems with retained antibacterial activity [13]. In the present study, electrospinning converted Manuka honey into a continuous fibrous material architecture that was clearly different from the particulate MCC-supported powder structure. This distinction is central to the novelty of the study because it links a monofloral honey matrix with two different material organizations and evaluates their corresponding thermal, spectral, and antibacterial response profiles. The combination of fibrous morphology, retained honey-associated FTIR features, distinct thermal behavior, and broad measurable antibacterial response identifies the electrospun formulation as a differentiated bioactive honey-derived formulation system.

Within this applied formulation framework, the antibacterial results presented in Table 2 provide the functional screening dimension of the study. Manuka honey retained measurable antibacterial activity

after conversion into powdered and electrospun forms, although the extent of inhibition varied according to formulation type and bacterial strain. The electrospun formulation produced the largest inhibition zone against *Staphylococcus aureus*, whereas powdered Manuka honey generally showed lower inhibition values and no visible zone against *Serratia marcescens*. This strain-dependent variation is consistent with previous reports showing that the antibacterial activity of varietal and unifloral honeys can differ substantially among target microorganisms, including chronic wound isolates, respiratory pathogens, and biofilm-associated bacteria [30–32]. Similar observations have also been reported for multidrug-resistant pathogens, where some honeys remain active against clinically challenging organisms while still showing organism-specific response patterns [33]. In the present study, the use of the same Manuka honey source across liquid, powdered, and electrospun formats emphasizes that the observed antibacterial screening profiles are closely associated with the formulation format created by processing.

The diffusion assay is particularly informative for this study because it captures how differently structured formulations express antibacterial responses at the agar interface. Reviews of honey antibacterial testing have shown that agar diffusion assays are valuable for comparative screening, while inhibition-zone diameter may also reflect diffusion-related behavior, especially when physically different materials are compared [34]. This point is directly relevant here because liquid honey, powdered honey pellets, and electrospun discs represent different material formats produced from the same Manuka honey source. For the powdered formulation, microcrystalline cellulose was incorporated as a carrier to obtain a solid honey matrix [35]. For the electrospun formulation, the fibrous architecture provides a distinct surface organization compared with the compressed particulate pellet. Electrospun medicated nanofibers have been reviewed as structured fibrous systems relevant to material-based delivery applications [11]. Therefore, the inhibition zones observed in this study are best understood as formulation-level screening responses shaped by honey-derived antibacterial activity, carrier matrix, surface organization, hydration behavior, and diffusion pathways.

Taken together, the study provides a comparative applied biotechnology framework for evaluating the conversion of Manuka honey into powdered and electrospun bioactive formulation formats. The originality of the work lies in evaluating the same monofloral Manuka honey source across three physical presentations and comparing the resulting morphological, thermal, spectral, and antibacterial screening profiles within a single proof-of-concept design. The findings show that processing route is a determining factor in the final physicochemical and functional screening behavior of honey-derived formulations. This is relevant not only for powdered and electrospun honey development but also for the broader design of bioactive natural product formulations in which processing strategy and carrier format influence measurable performance.

5. Conclusion

This study demonstrated that the same monofloral Manuka honey source can be converted into distinct bioactive formulation formats through MCC-assisted non-thermal powdering and PVA-assisted

electrospinning. The powdered formulation exhibited a dry, particulate, agglomerated, and plate-like architecture, whereas the electrospun formulation formed a continuous fibrous network. These morphological differences were accompanied by formulation-dependent thermal mass-loss behavior and FTIR spectral variation, while major honey-associated spectral features remained detectable after processing.

The diffusion-based antibacterial screening assay further showed that reformulation altered the observable antibacterial response profile across bacterial strains. The electrospun formulation produced the broadest measurable inhibition profile, with the highest response against *Staphylococcus aureus*, whereas the powdered formulation showed a different and generally lower inhibition pattern. These differences indicate that the physical architecture of the formulation contributes to how Manuka honey expresses antibacterial functionality under diffusion-based conditions.

Overall, the findings support a proof-of-concept applied formulation framework for powdered and electrospun Manuka honey systems. By comparing processing-induced morphology with thermal, spectral, and antibacterial screening profiles, the study highlights formulation format as an important determinant of the measurable performance of honey-derived bioactive systems. This provides an applied biotechnology-oriented basis for the further development of structured honey formulations with defined physicochemical and functional screening properties.

Declarations

Competing interests

The author declares that there are no competing interests.

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Author contribution

E.K. contributed to the study conception and design, material preparation, experimental work, data interpretation, manuscript drafting, and final approval of the manuscript.

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Data availability

The data generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Figures

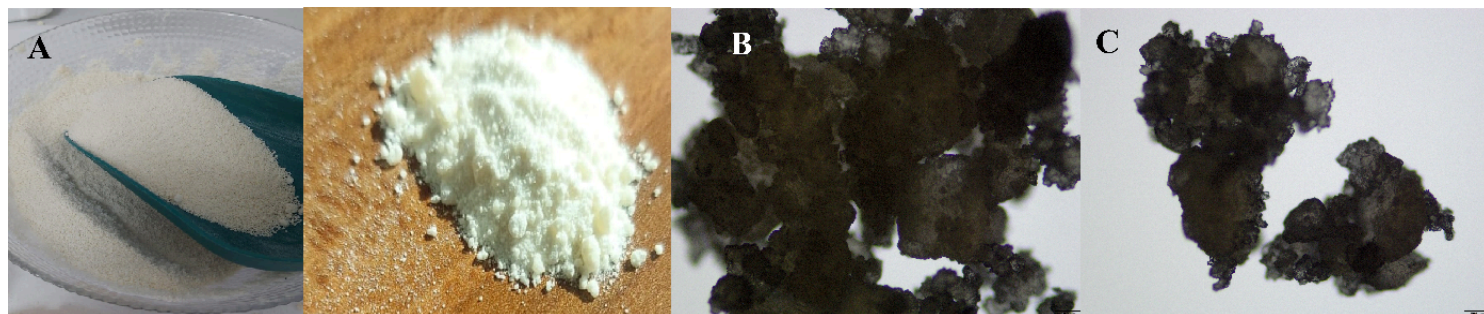


Figure 1

Macro- and micro-scale morphology of powdered Manuka honey obtained by MCC-assisted non-thermal powdering. (A) Macroscopic appearance showing the dry and powder-like structure of the formulation. (B–C) Light microscopic images showing irregular particle aggregates and heterogeneous particulate organization.

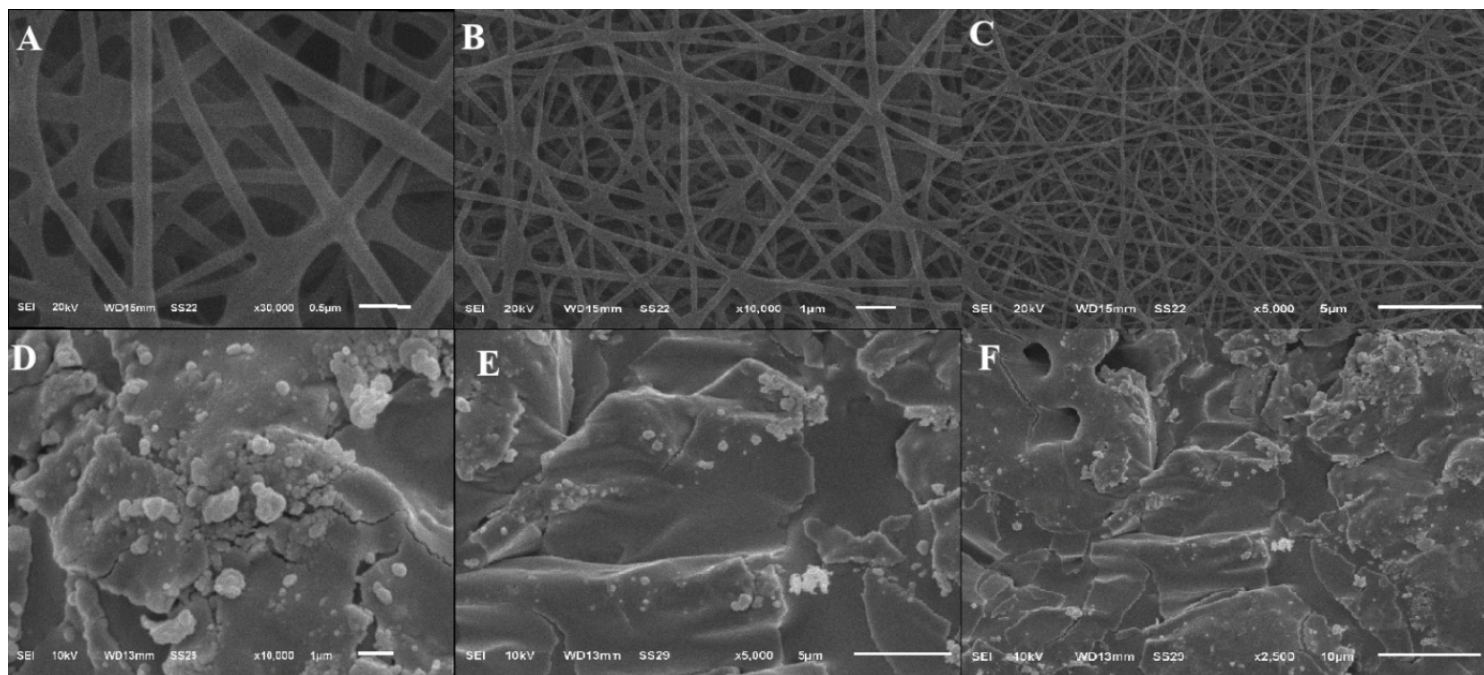


Figure 2

SEM micrographs showing the distinct microstructural architectures of electrospun and powdered Manuka honey formulations. (A–C) Electrospun formulation showing a continuous fibrous network. (D–F) Powdered formulation showing irregular, agglomerated, plate-like, and particulate structures.

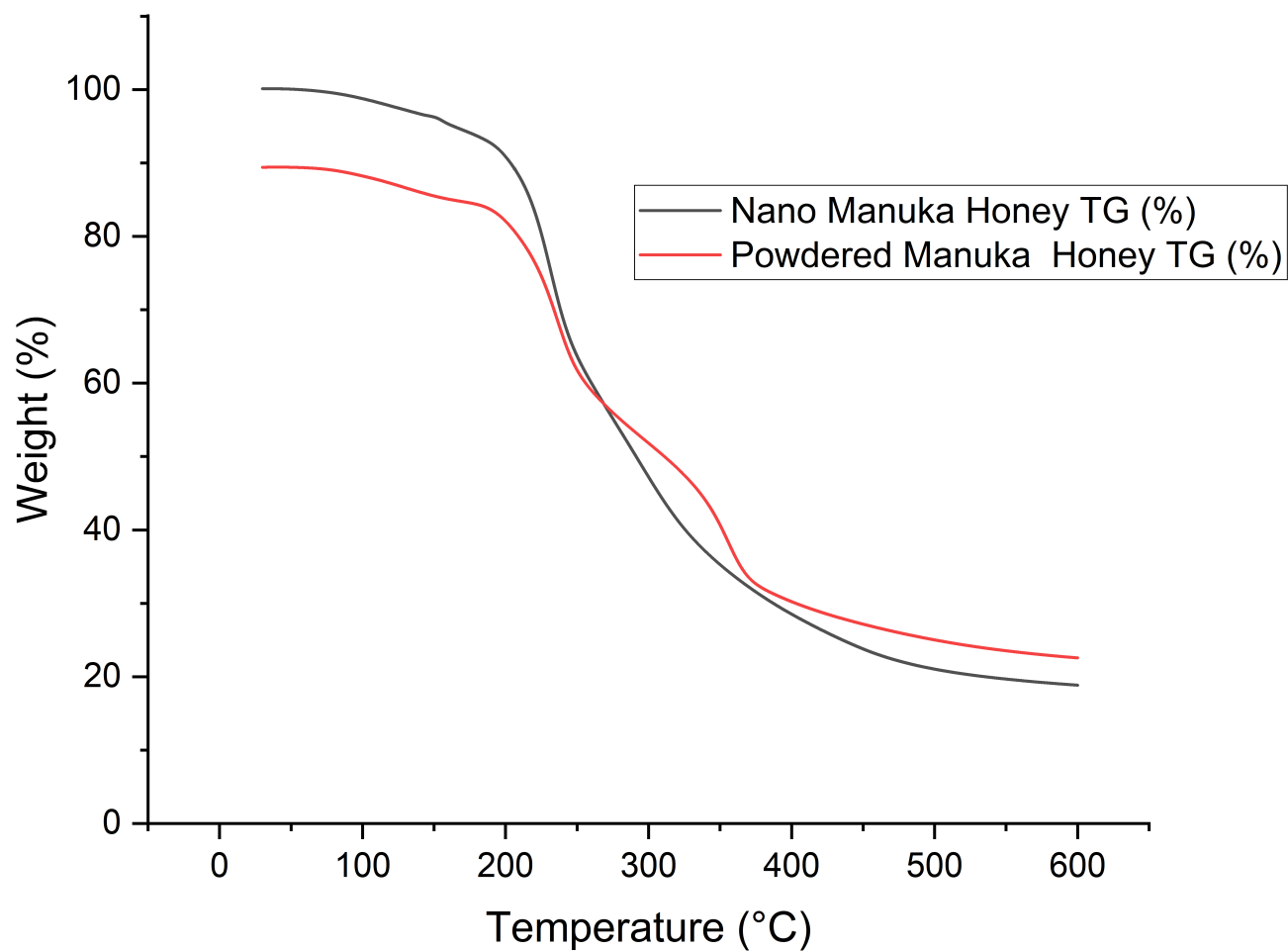


Figure 3

Thermogravimetric profiles of powdered and electrospun Manuka honey formulations, showing formulation-dependent thermal mass-loss behavior between 30 and 600 °C.

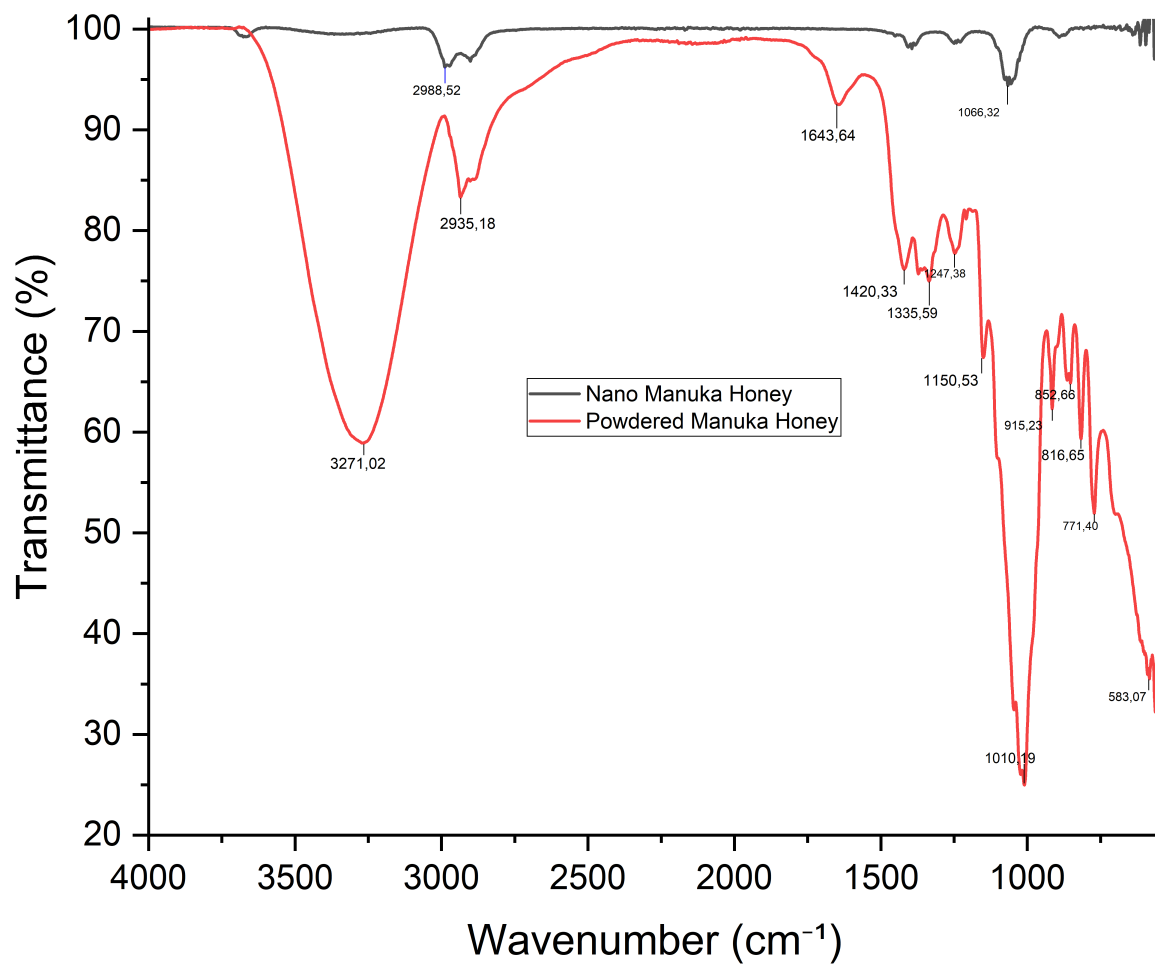


Figure 4

FTIR spectra of powdered and electrospun Manuka honey formulations, showing retained honey-associated spectral features and formulation-dependent spectral differences.

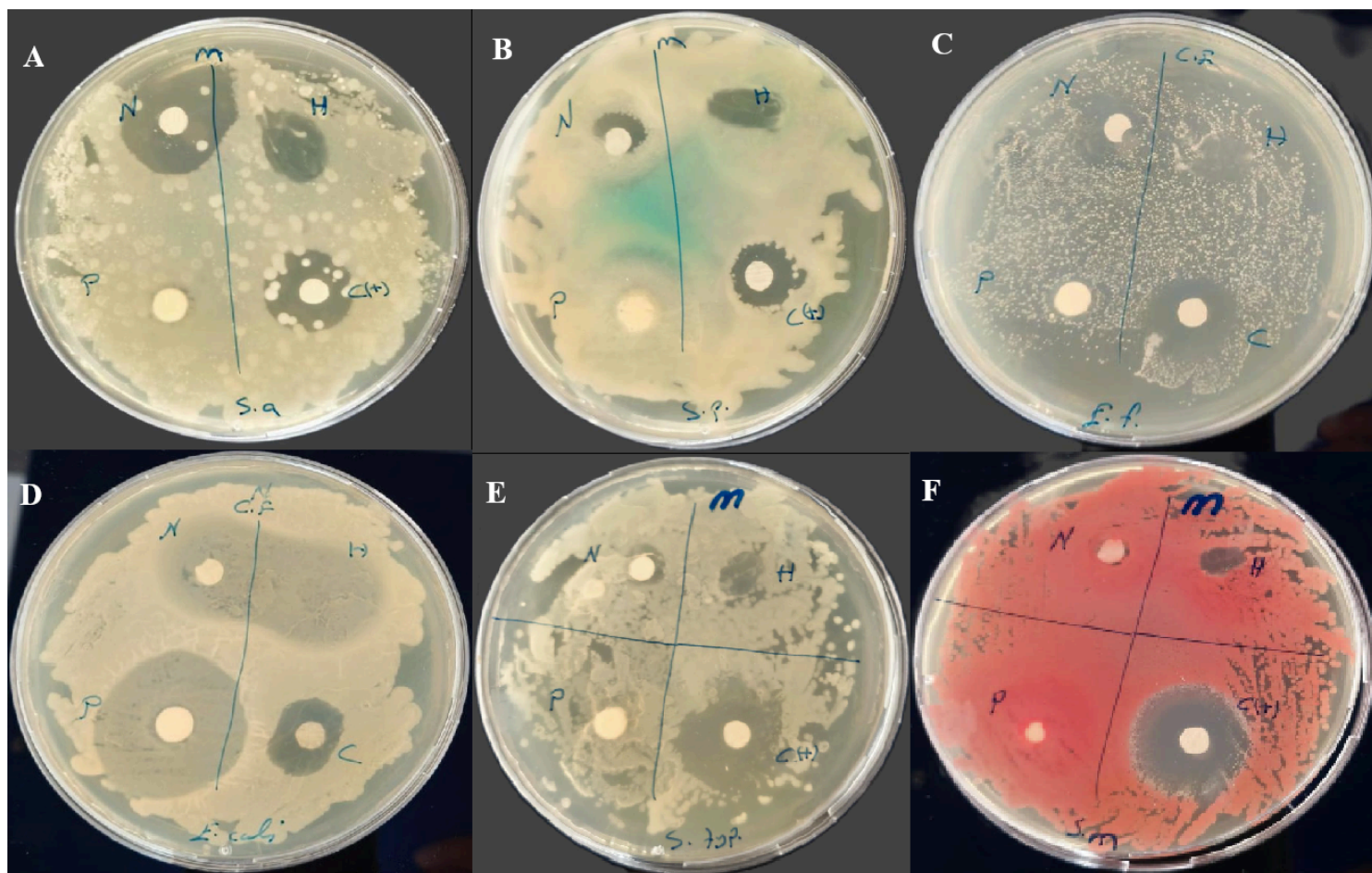


Figure 5

Diffusion-based antibacterial response profiles of liquid, powdered, and electrospun Manuka honey formulations compared with gentamicin against selected Gram-positive and Gram-negative bacterial strains.

Supplementary Files

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