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Development of Sustainable Activated Carbon Tablets from Coconut Shell: Formulation and Binder Optimization Studies

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Abstract

This study investigated the formulation, physicochemical evaluation, and instrumental characterization of sustainable carbo tablets prepared from coconut shell-derived activated carbon using gelatin and sodium alginate as binder systems in accordance with United States Pharmacopeia (USP 30) standards. Five formulations comprising gelatin-based tablets (FCTG) and sodium alginate formulations containing 1% - 4% binder concentrations (FCTa1-FCTa4) were developed and compared with a commercial carbo tablet (CCT). Pre-compression evaluation showed excellent granule flowability with angle of repose values ranging from 25˚ - 27˚, bulk density between 0.53 - 0.57 g/cm^3, and tapped density of 0.67 - 0.71 g/cm^3, indicating suitability for tablet compression. Mechanical studies revealed progressive increases in crushing strength from 3.4 kgf (FCTa1) to 6.4 kgf (FCTa4) with increasing sodium alginate concentration, while friability decreased correspondingly. FCTG (0.4%), FCTa3 (0.80%), and CCT (0.4%) complied with the pharmacopeial friability requirement of <1%. Disintegration testing demonstrated rapid disintegration for gelatin tablets (0.52 min), whereas alginate formulations exhibited concentration-dependent prolongation from 4.62 to 21.20 min. FCTa4 displayed sustained-release characteristics due to hydrogel matrix formation by sodium alginate. Thermogravimetric analysis (TGA/DTA) confirmed adequate thermal stability of the formulations with characteristic moisture loss below 150˚C and gradual decomposition at elevated temperatures. SEM micrographs revealed highly porous and heterogeneous surface morphology favorable for adsorption activity. FTIR spectra showed broad O–H stretching bands at 3200 - 3500 cm^{-1}, aliphatic C–H peaks near 2900 cm^{-1}, carbonyl and aromatic C=C bands around 1600 - 1700

cm^{-1}, and C–O/C–O–C stretching vibrations within 1000 - 1300 cm^{-1}, confirming the presence of hydroxyl, carbonyl, aromatic, and polysaccharide functional groups without evidence of chemical incompatibility. EDX analysis verified the predominance of carbon and oxygen within the formulations, confirming the carbon-rich composition of the activated carbon tablets. Among all formulations, FCTa3 demonstrated the most balanced pharmaceutical performance in terms of hardness, friability, disintegration, thermal stability, and structural integrity. The study highlights the potential of sodium alginate as an effective natural binder and demonstrates the feasibility of utilizing coconut shell-derived activated carbon as a sustainable pharmaceutical material for carbo tablet formulation.

Subject Areas

Pharmacology

Keywords

Carbo Tablets, Activated Carbon, Coconut Shell, Sodium Alginate, Gelatin Binder, Physicochemical Evaluation

1. Introduction

Activated carbon tablets, commonly referred to as Carbo tablets, are widely recognized as indispensable pharmaceutical adsorbents used in the management of toxicological ingestions, drug overdoses, and various forms of gastrointestinal distress [1]. Their therapeutic efficacy is primarily attributed to the high surface area and porous structure of activated carbon, which enables rapid adsorption of toxins and prevents their systemic absorption within the gastrointestinal tract. In emergency medicine and clinical toxicology, these tablets serve as a first line intervention due to their ability to bind a broad spectrum of xenobiotics, including drugs, poisons, and microbial toxins. Beyond acute care, they are also applied in managing conditions such as diarrhea, flatulence, and indigestion, further highlighting their versatility in pharmaceutical practice. The increasing demand for effective and safe detoxifying agents continues to reinforce the clinical and pharmaceutical relevance of Carbo tablet formulations [2].

The selection of an appropriate binder remains a critical formulation variable that significantly influences the mechanical strength, friability, and disintegration behavior of tablets [3]. Binders are essential in ensuring cohesion among powder particles during compression, thereby producing tablets with adequate hardness and resistance to mechanical stress during handling, packaging, and transportation. However, an optimal balance must be achieved, as excessive binder concentration may retard tablet disintegration and delay therapeutic action, while insufficient binder may result in weak tablets prone to breakage. Traditionally, gelatin has been widely used due to its excellent binding properties and compatibility with

a range of excipients. Nevertheless, its animal origin, susceptibility to microbial growth, and limited tunability in controlling drug release have prompted the exploration of alternative binders. Natural polymers such as sodium alginate have emerged as promising substitutes due to their biocompatibility, biodegradability, and ability to modulate drug release profiles through gel forming properties [4].

In recent years, there has been a growing emphasis on the utilization of sustainable and locally sourced raw materials in pharmaceutical formulation, both for economic and environmental reasons. Coconut shell, a traditional agricultural by-product, represents an abundant and renewable source of carbon that can be converted into high quality activated carbon through controlled carbonization and activation processes. Its use not only reduces dependence on imported pharmaceutical grade materials but also promotes waste valorization and supports circular economy initiatives. Coconut shell derived activated carbon is particularly valued for its high mechanical strength, well developed microporous structure, and superior adsorption capacity compared to other biomass sources. The incorporation of such traditional raw materials into pharmaceutical systems underscores the importance of aligning drug development with sustainability goals while maintaining product efficacy and safety [5].

This study, therefore, employs coconut shell derived activated carbon as a sustainable active pharmaceutical ingredient (API) and systematically evaluates the physicochemical and functional effects of varying binder types and concentrations on Carbo tablet performance. By comparing formulations containing gelatin and different concentrations of sodium alginate, the study aims to elucidate their influence on key parameters such as flow properties, compressibility, tablet hardness, friability, and disintegration time. Furthermore, the formulated tablets are assessed against established international pharmacopeial standards to ensure compliance with quality, safety, and efficacy requirements. Through this approach, the study not only contributes to the optimization of Carbo tablet formulations but also highlights the potential of integrating sustainable materials and natural polymers into modern pharmaceutical development.

2. Materials and Methods

The formulations were prepared using the wet granulation technique in accordance with current United States Pharmacopeia standards. Coconut shell-derived activated carbon was prepared from mature coconut shells, which were washed thoroughly with distilled water, air-dried, crushed, and carbonized in a muffle furnace at 500˚C for 2 h under limited oxygen conditions. The resulting char was chemically activated using 50% (w/v) phosphoric acid at an impregnation ratio of 1:1 (w/w), allowed to stand for 24 h, and subsequently heated at 700˚C for 1 h. The activated carbon was washed repeatedly with distilled water until a neutral pH was attained, dried at 105˚C for 24 h, pulverized, and sieved to obtain particles within the size range of 150 - 250 μm. Each tablet formulation was standardized to a total weight of 500 mg, with the activated carbon constituting 50% (250 mg)

of the formulation. The required quantities of activated carbon and excipients were accurately weighed and blended to ensure uniformity. Binder solutions were prepared by dissolving gelatin or sodium alginate in distilled water to obtain the desired concentrations and were added gradually to the powder blend until a cohesive wet mass was formed. Approximately 20 - 30 mL of binder solution was used per batch depending on formulation requirements. The wet mass was passed through a 1.18 mm sieve to produce wet granules and dried in a hot-air oven at 60˚C for 2 h. The dried granules were subsequently passed through a 710 µm sieve to obtain uniform granule size distribution. Magnesium stearate and talc were incorporated as lubricants and mixed with the granules for 3 min before compression. Tablet compression was carried out using a single-punch tablet press operated at a compression force of approximately 5 - 7 kN to produce tablets of uniform weight, thickness, and mechanical strength [6] [7].

2.1. Determination of Bulk and Tapped Density

Bulk density was determined by carefully pouring a known mass of granules into a graduated cylinder and recording the unsettled volume. The bulk density was calculated as the ratio of mass to bulk volume (g/cm^3).

Tapped density was determined using a tapped density apparatus by mechanically tapping the cylinder containing the sample until a constant volume was achieved. The tapped density was calculated as the ratio of mass to tapped volume. All measurements were performed in triplicate, and results were expressed as mean ± standard deviation [7] [8].

2.2. Determination of Angle of Repose

The angle of repose was measured using the fixed funnel method. Granules were allowed to flow freely through a funnel onto a flat surface to form a conical heap. The height (h) and radius (r) of the heap were measured, and the angle of repose (θ) was calculated using:

$$\theta = \tan^{-1}$$

The procedure was conducted in triplicate, and the mean value was recorded. This parameter provides an indication of the flow properties of the granules [7] [8].

2.3. Disintegration Time Test

The disintegration test was carried out using a USP disintegration apparatus. Six tablets from each formulation were placed in the basket rack assembly, and the test was conducted in distilled water maintained at 37˚C ± 0.5˚C. The time taken for complete disintegration of each tablet, with no palpable residue remaining, was recorded, and the mean value was calculated. Results were evaluated according to pharmacopeial specifications [6].

2.4. Friability Test

Tablet friability was evaluated using a friabilator. A pre-weighed sample of tablets

was rotated at 25 rpm for 4 minutes (100 revolutions). The tablets were then dedusted and reweighed. The percentage friability was calculated using:

$$\text{Friability}(\%) = \frac{W_2 - W_1}{W_2} \times 100$$

where, W_1 is the initial weight and W_2 is the final weight. A friability value of less than 1% was considered acceptable for conventional tablets [6] [7]

2.5. Instrumental Characterization of Carbo Tablet Formulations

2.6. Thermogravimetric Analysis (TGA/DTA)

Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) were carried out to evaluate the thermal stability and decomposition behavior of the formulated carbo tablets and the commercial carbo tablet (CCT). Approximately 5 - 10 mg of finely powdered sample was placed in an alumina crucible and heated under a controlled nitrogen atmosphere from room temperature to 800˚C at a heating rate of 10˚C/min using a thermogravimetric analyzer. The percentage weight loss and thermal transitions occurring during heating were continuously recorded. The obtained thermograms were used to assess moisture loss, thermal degradation, and structural stability of the formulations in line with standard thermal analysis procedures for polymer-carbon systems [9] [10].

2.7. Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) was employed to investigate the surface morphology and porous structure of the formulated carbo tablets. Small portions of the tablet samples were mounted onto aluminum stubs using double-sided adhesive carbon tape and coated with a thin layer of gold to improve conductivity. The samples were examined under a scanning electron microscope operated at an appropriate accelerating voltage. Micrographs were obtained at different magnifications to evaluate particle arrangement, pore distribution, and surface texture of the activated carbon matrix. SEM analysis followed standard protocols for morphological characterization of porous pharmaceutical and carbon-based materials [11] [12].

2.8. Fourier Transform Infrared Spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) analysis was conducted to identify the functional groups present in the coconut shell-derived activated carbon, excipients, and formulated carbo tablets. The samples were finely ground and mixed with potassium bromide (KBr) to form pellets prior to analysis. Spectra were recorded within the range of 4000 - 400 cm^{-1} using an FTIR spectrophotometer. The characteristic absorption bands obtained were used to determine possible interactions between the activated carbon and binder systems as well as to confirm the presence of major functional groups. FTIR interpretation followed established analytical guidelines for polymeric and carbonaceous pharmaceutical

systems [13] [14].

2.9. Energy Dispersive X-Ray Spectroscopy (EDX)

Energy dispersive X-ray spectroscopy (EDX) analysis was performed alongside SEM examination to determine the elemental composition of the formulated carbo tablets. The samples were mounted on specimen holders and analyzed under an electron beam within the SEM chamber. The emitted X-rays were detected and processed to identify the elemental constituents present in the samples. The relative abundance of carbon, oxygen, and trace mineral elements was evaluated to confirm the carbon-rich composition of the activated carbon tablets, following standard microanalytical procedures for carbon-based materials [11] [12].

Table 1 presents the composition of the formulated carbo tablet formulations, showing the quantities of activated carbon, binders, and other excipients used in each formulation.

Table 1. Composition of carbo tablet formulations (mg per tablet).

Component	FCTG (Gelatin)	FCTa1 (Alginate)	FCTa2 (Alginate)	FCTa3 (Alginate)	FCTa4 (Alginate)
Coconut Shell (API)	250	250	250	250	250
Kaolin (Diluent)	142.5	185	180	175	170
Binder Content	50	5	10	15	20
Maize Starch	50	50	50	50	50
Magnesium Stearate	2.5	5	5	5	5
Talc Powder	5	5	5	5	5

3. Results and Discussion

3.1. Pre-Compression Parameters

The pre-compression properties of the prepared granules are summarized in Table 2. The flow properties of granules are critical in determining uniform die filling and overall tablet quality. In this study, all formulations exhibited angles of repose between 25˚ and 27˚, indicating excellent flowability according to pharmacopeial standards. Bulk density values ranged from 0.53 to 0.57 g/cm^3, while tapped density ranged from 0.67 to 0.71 g/cm^3, suggesting good packing ability and compressibility [15].

Table 2. Flow properties and density of formulated granules.

Parameter	FCTG	FCTa1	FCTa2	FCTa3	FCTa4
Angle of Repose (˚)	25 ± 0.40	26 ± 0.68	26 ± 0.17	27 ± 0.51	27 ± 0.51
Bulk Density (g/cm^3)	0.57 ± 0.02	0.53 ± 0.01	0.53 ± 0.02	0.57 ± 0.01	0.57 ± 0.02
Tapped Density (g/cm^3)	0.71 ± 0.02	0.67 ± 0.01	0.67 ± 0.02	0.67 ± 0.01	0.67 ± 0.02

These findings are consistent with recent studies by [9], who reported that natural polymer-based formulations often exhibit favorable flow due to improved granule cohesion. Similarly, [10] observed that sodium alginate enhances inter-particle bonding during granulation, contributing to improved flow characteristics.

Comparatively, only slight differences were observed among the formulations, indicating that the binder type (gelatin versus alginate) had minimal influence on the flow behavior of the granules. This suggests that all batches were suitable for large-scale manufacturing.

3.2. Physical and Dimensional Uniformity

The physical characteristics and dimensional uniformity of the formulated tablets are presented in **Table 3**. All formulations complied with pharmacopeial limits for weight variation, indicating uniform distribution of the active ingredient and excipients. Tablet thickness varied across formulations, with the commercial tablet (CCT) showing the highest thickness (4.91 mm), while FCTG exhibited the lowest (2.88 mm).

The reduced thickness of FCTG may be attributed to the strong binding efficiency of gelatin, which promotes tighter particle packing during compression. In contrast, alginate formulations showed slightly higher thickness due to their hydrophilic and swelling nature.

These observations align with findings by [11], who reported that gelatin produces more compact tablets compared to plant-based binders. However, alginate-based systems provide structural flexibility, which can influence porosity and subsequent drug release behavior.

Among the alginate formulations, increasing binder concentration resulted in slight increases in tablet dimensions, suggesting progressive matrix formation.

Table 3. Physical parameters and weight variation.

Formulation	Weight Variation (g)	Thickness (mm)	Diameter (mm)
CCT	0.518 ± 0.007	4.909 ± 0.114	12.26 ± 0.043
FCTG	0.500 ± 0.006	2.88 ± 0.042	12.15 ± 0.019
FCTa1	0.508 ± 0.008	3.70 ± 0.016	12.48 ± 0.110
FCTa2	0.500 ± 0.006	3.69 ± 0.018	12.51 ± 0.073
FCTa3	0.508 ± 0.007	3.61 ± 0.064	12.56 ± 0.108
FCTa4	0.508 ± 0.010	3.66 ± 0.061	12.59 ± 0.082

3.3. Mechanical Strength and Disintegration

The mechanical properties, friability, and disintegration characteristics of the formulated tablets are summarized in **Table 4**. Mechanical strength testing revealed a clear relationship between binder concentration and tablet hardness. Crushing strength increased from 3.4 kgf (FCTa1) to 6.4 kgf (FCTa4), demonstrating that alginate concentration directly influences tablet robustness.

Table 4. Mechanical robustness and performance characteristics of carbo tablet formulations.

Formulation	Crushing Strength (kgf)	Friability (%)	Disintegration Time (min)	Category
CCT	6.7	0.4	11.81 ± 1.46	Fast Delivery
FCTG	5.2	0.4	4.12 ± 0.52	Fast Delivery
FCTa1	3.4	3.83	4.62 ± 0.41	Fast Delivery
FCTa2	4.0	1.70	5.48 ± 0.97	Fast Delivery
FCTa3	5.3	0.80	8.40 ± 0.88	Fast Delivery
FCTa4	6.4	1.08	21.20 ± 1.92	Sustained Delivery

The commercial tablet (6.7 kgf) and FCTa4 (6.4 kgf) met the USP acceptable hardness range (4 - 10 kgf), while FCTa1 showed insufficient strength. Gelatin-based formulation (FCTG) displayed moderate hardness (5.2 kgf), indicating adequate binding efficiency [16] [17].

Friability results further emphasized this trend. Only FCTG (0.4%), FCTa3 (0.8%), and CCT (0.4%) complied with the pharmacopeial limit of <1%. In contrast, FCTa1 (3.83%) and FCTa2 (1.70%) failed, indicating poor resistance to mechanical stress.

These findings are consistent with [3], who reported that insufficient binder concentration leads to weak inter-particulate bonding, resulting in high friability. Conversely, higher concentrations of hydrophilic polymers like alginate improve tablet integrity by forming a stronger matrix. Compared to gelatin, alginate demonstrated a concentration dependent improvement in mechanical strength, supporting its suitability as a tunable binder system.

3.4. Disintegration Time and Release Behavior

Disintegration testing revealed differences among the formulations. FCTG exhibited rapid disintegration (0.52 min), while alginate formulations showed progressively increasing disintegration times with increasing binder concentration. FCTa1-FCTa3 (4.62 - 8.40 min) complied with USP requirements for immediate-release tablets (<15 min), whereas FCTa4 (21.20 min) exhibited a markedly prolonged disintegration time. This behavior may be attributed to the formation of a hydrated alginate matrix that retards water penetration and tablet breakup, a characteristic commonly associated with sodium alginate-based tablet systems [18] [19]. However, since dissolution and drug-release studies were not performed, the observed prolonged disintegration should be interpreted only as delayed tablet disintegration rather than evidence of modified- or sustained-release behavior.

3.5. Instrumental Characterization Results

Instrumental characterization was performed to evaluate the thermal stability, surface morphology, elemental composition, and functional group characteristics

of the formulated carbo tablets in comparison with the commercial carbo tablet (CCT). The analyses included thermogravimetric analysis (TGA/DTA), scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and energy dispersive X-ray spectroscopy (EDX). The obtained spectra and micrographs provided additional evidence supporting the physicochemical performance of the formulated tablets.

3.6. Thermal Stability of Carbo Tablets (TGA/DTA)

The thermogravimetric spectra of the formulated carbo tablets and commercial carbo tablet are presented in **Figures 1-4**. The thermograms revealed progressive weight loss patterns associated with moisture evaporation, decomposition of organic constituents, and gradual carbon degradation at elevated temperatures, consistent with recent observations in biomass-derived activated carbon and polymeric pharmaceutical systems [19] [20].

The initial stage of weight reduction observed below 150˚C was attributed to the removal of physically adsorbed moisture and volatile components present within the tablet matrix. This behavior is expected due to the hygroscopic and hydrophilic nature of natural binders such as sodium alginate [19] [21]. A second region of more pronounced weight loss occurred within the intermediate temperature range, corresponding to the thermal decomposition of polymeric binder components and residual organic matter from the coconut shell activated carbon, as similarly reported for biopolymer-carbon composite systems [20].

The DTA curves further demonstrated endothermic and exothermic transitions associated with matrix dehydration and structural decomposition. The formulated tablets exhibited thermal behavior comparable to the commercial standard, indicating that the incorporation of sodium alginate did not negatively affect thermal stability. Among the alginate formulations, increased binder concentration slightly improved thermal resistance, suggesting enhanced matrix integrity and intermolecular interactions, in agreement with recent reports on polymer concentration effects in pharmaceutical matrices [21] [22].

3.7. Surface Morphology of Carbo Tablets (SEM)

The SEM micrograph presented in **Figure 5** revealed the heterogeneous and porous surface morphology of the formulated carbo tablet. The microstructure showed irregular cavities, fissures, and interconnected pores characteristic of activated carbon materials derived from biomass precursors.

The porous architecture observed is particularly important for adsorption-based pharmaceutical applications because increased surface area and pore accessibility enhance toxin adsorption efficiency. Similar morphological features have been reported in recent studies on coconut shell-derived activated carbon and pharmaceutical-grade carbon adsorbents [20]. The rough and uneven surface morphology also indicates successful carbonization and activation of the coconut shell precursor.

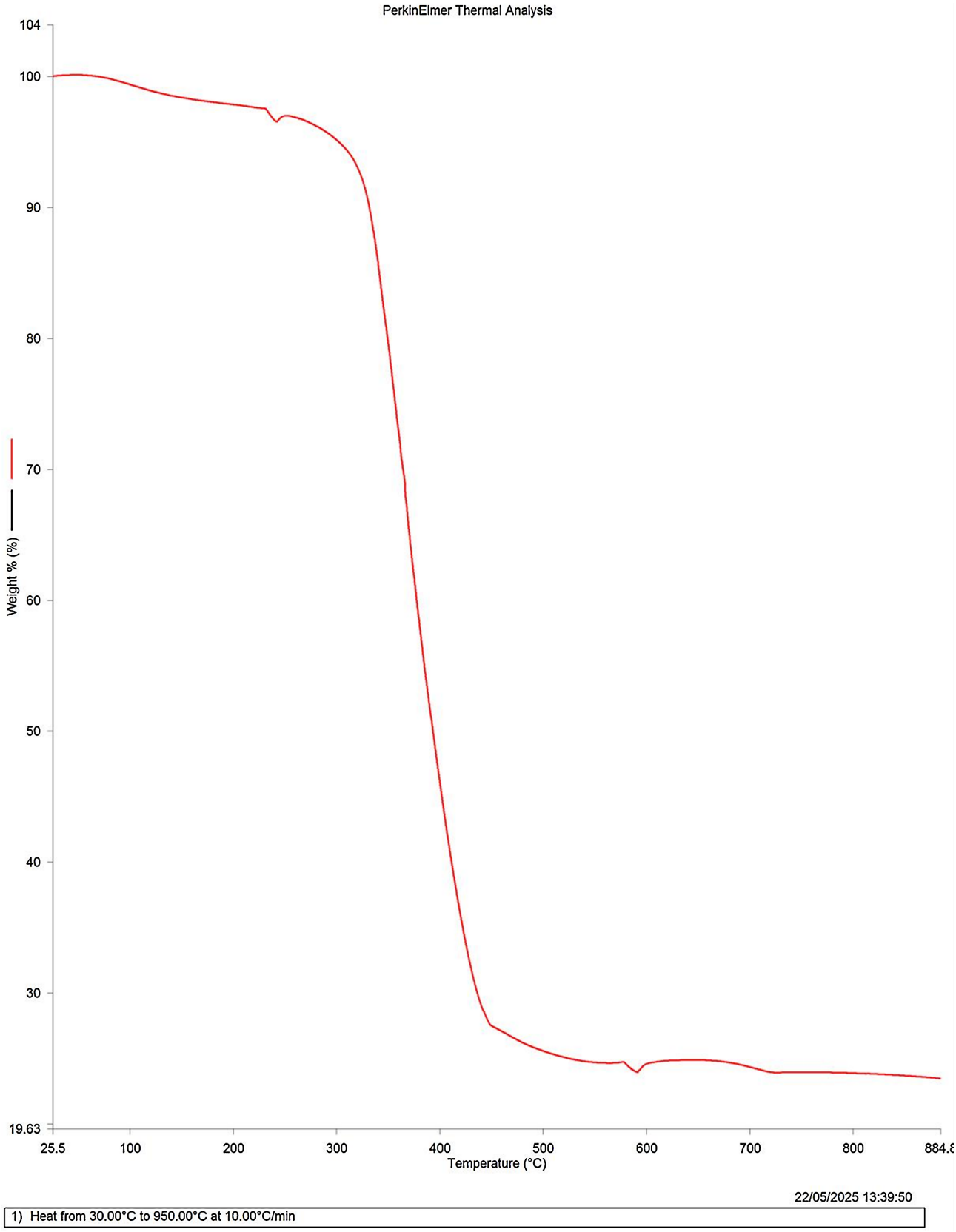

Figure 1. Thermogravimetric curve of FCT.

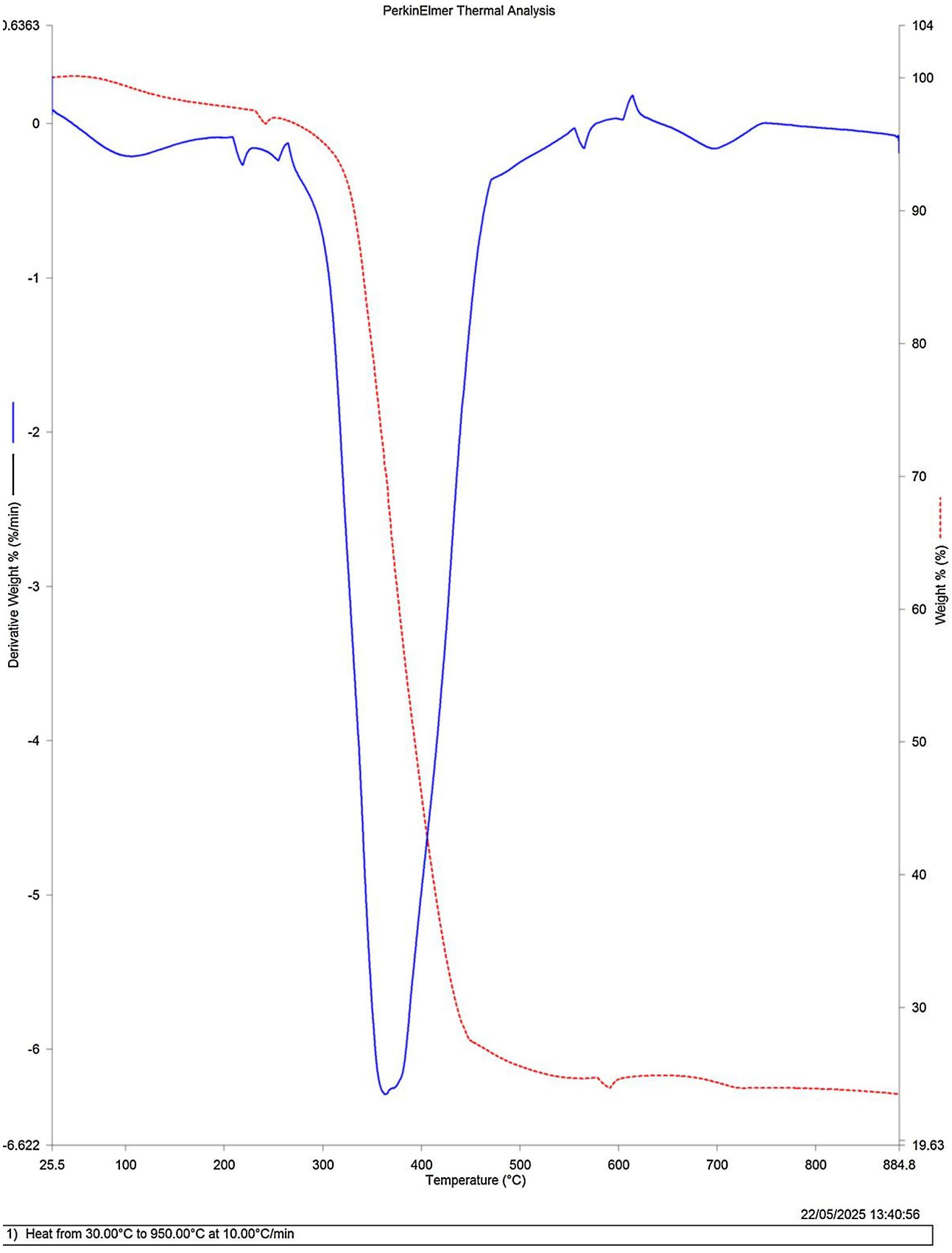

Figure 2. TGA/DTA thermogram of FCT.

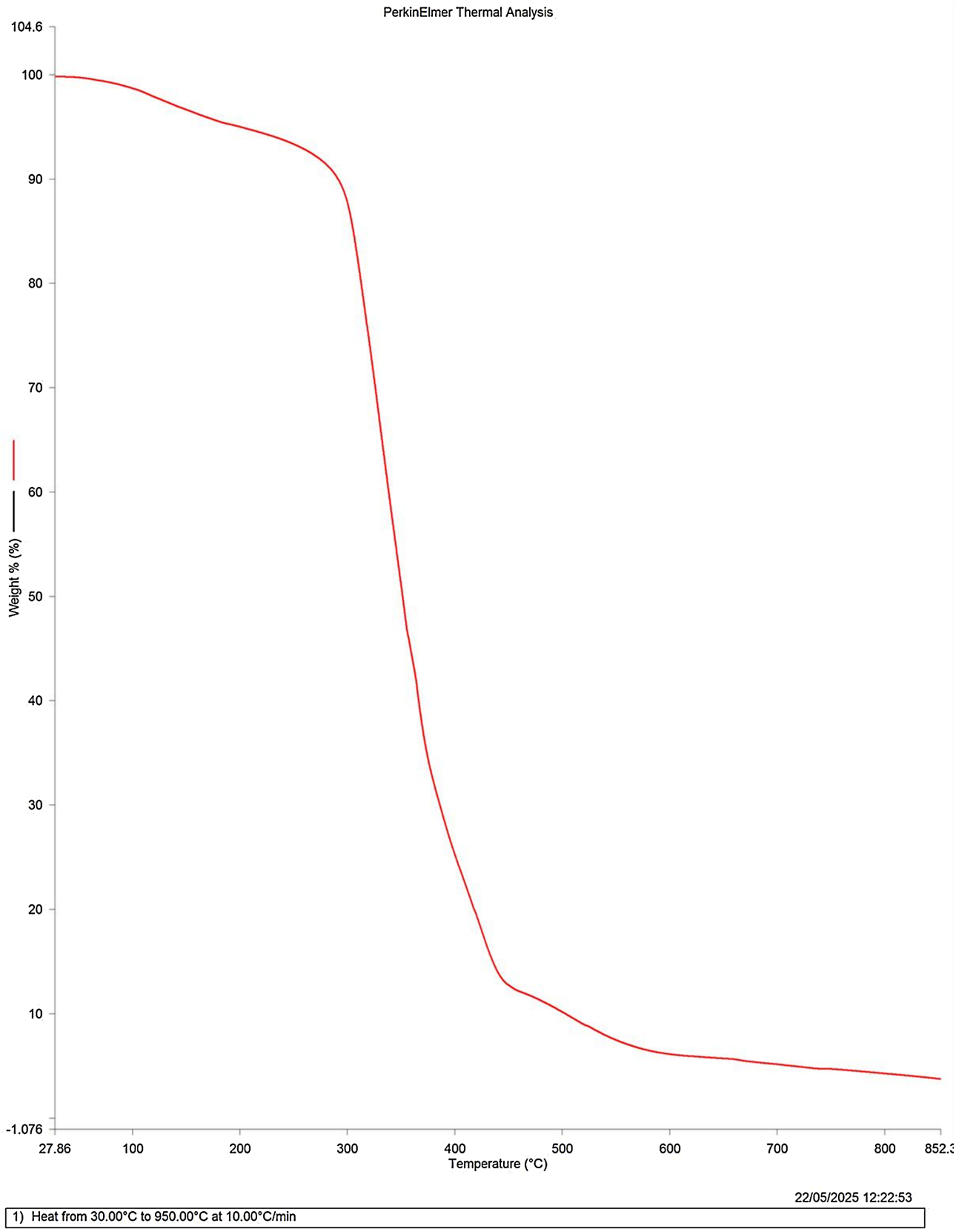

Figure 3. Thermogravimetric curve of CCT.

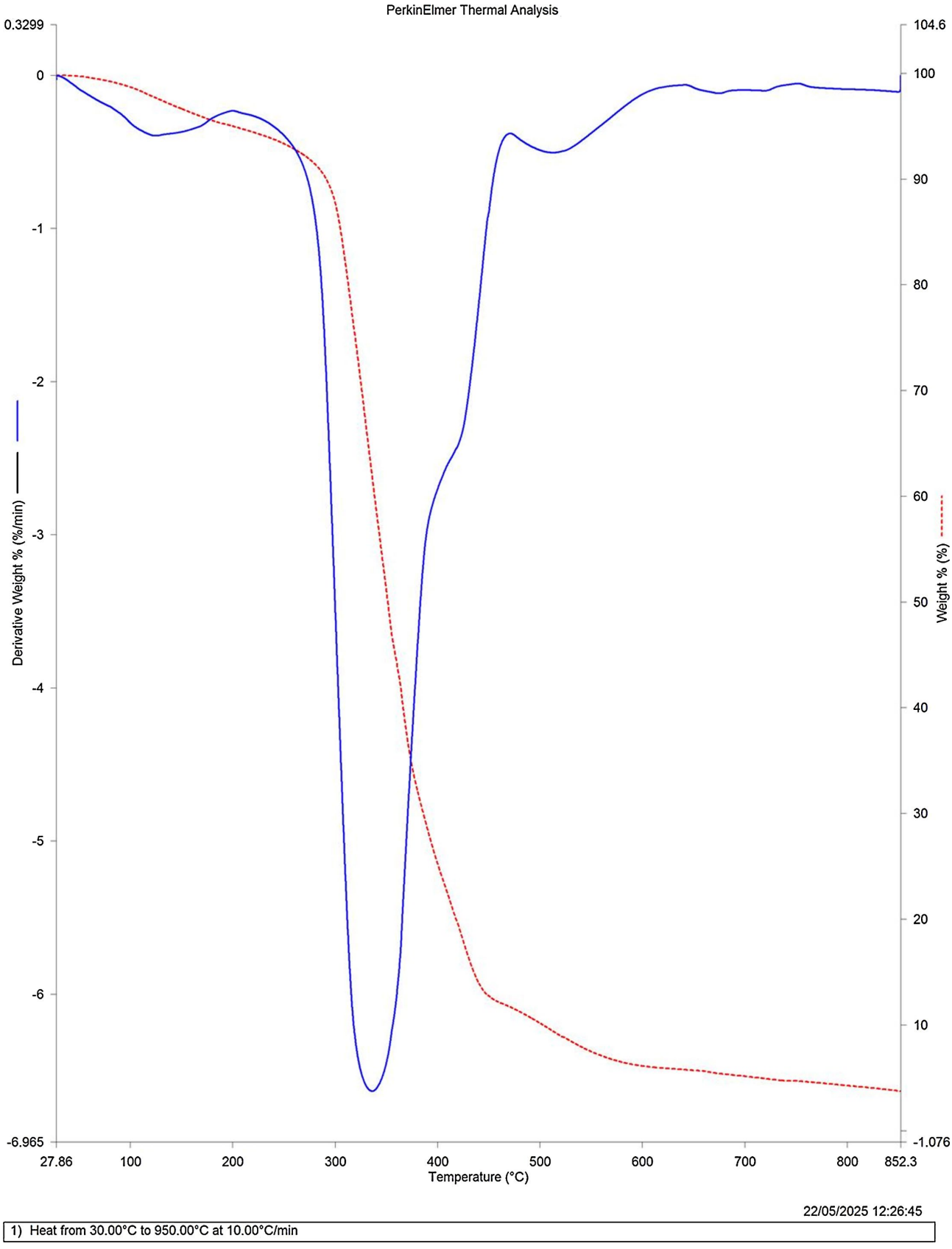

Figure 4. TGA/DTA thermogram of CCT.

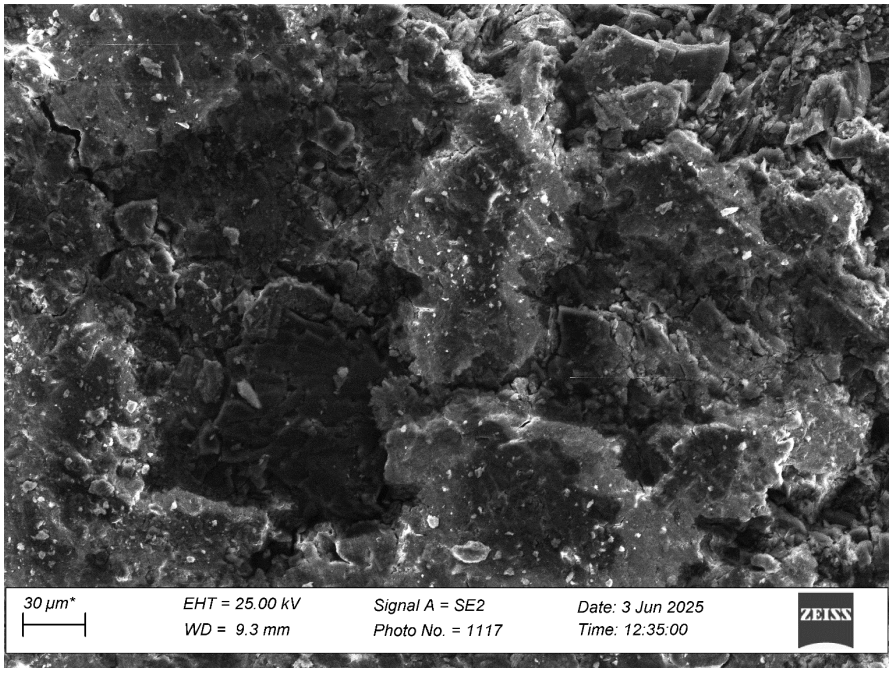

Figure 5. SEM micrograph showing the porous morphology of the formulated carbo tablet.

3.8. Functional Group Characterization of Carbo Tablets (FTIR)

The FTIR spectra of the formulated carbo tablets and commercial carbo tablet are shown in **Figures 6-10**. The spectra revealed several characteristic absorption

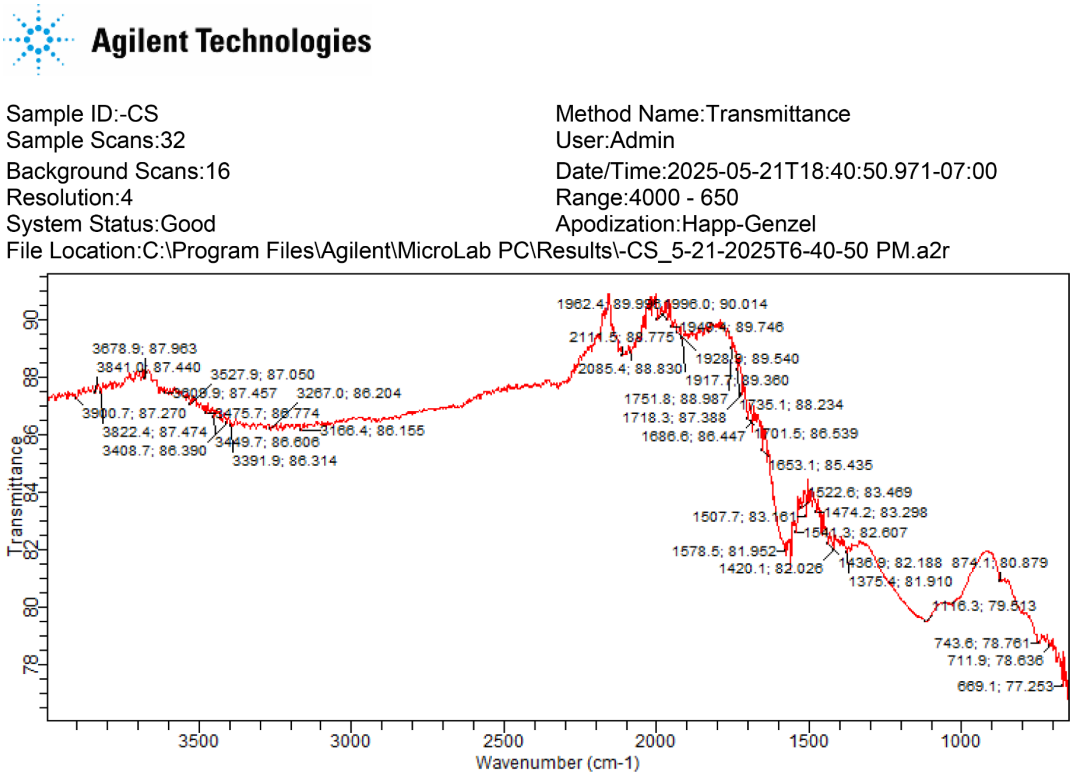

Figure 6. FTIR spectrum of coconut shell.

Agilent Technologies

Sample ID:-KAOLIN POWDER
Sample Scans:32
Background Scans:16
Resolution:4
System Status:Good
Method Name:Transmittance
User:Admin
Date/Time:2025-05-21T18:41:49.921-07:00
Range:4000 - 650
Apodization:Happ-Genzel
File Location:C:\Program Files\Agilent\MicroLab PC\Results\-KAOLIN POWDER_5-21-2025T6-41-49 PM.a2r

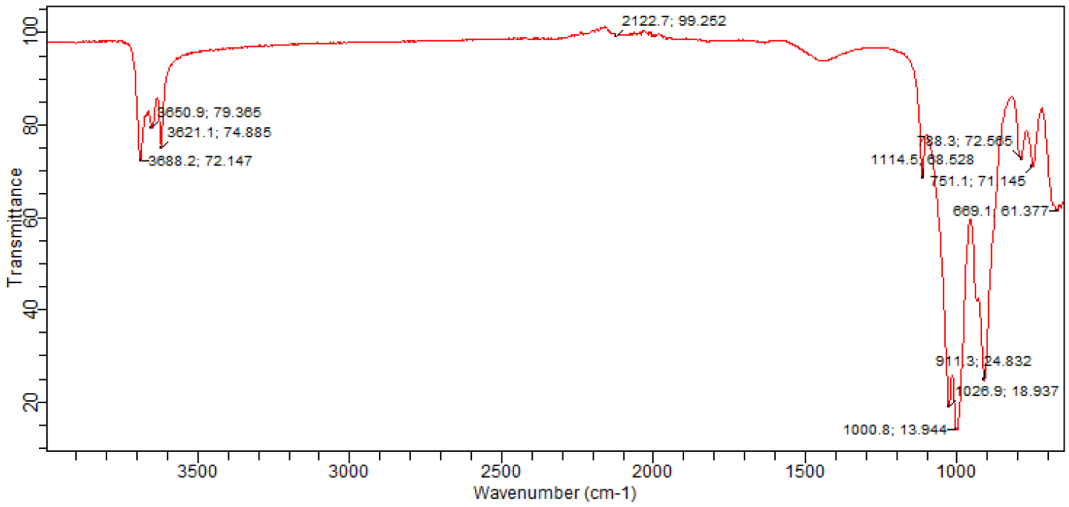

Figure 7. FTIR spectrum of Kaoline.

Agilent Technologies

Sample ID:-FCT
Sample Scans:32
Background Scans:16
Resolution:4
System Status:Good
Method Name:Transmittance
User:Admin
Date/Time:2025-05-21T18:43:39.334-07:00
Range:4000 - 650
Apodization:Happ-Genzel
File Location:C:\Program Files\Agilent\MicroLab PC\Results\-FCT_5-21-2025T6-43-39 PM.a2r

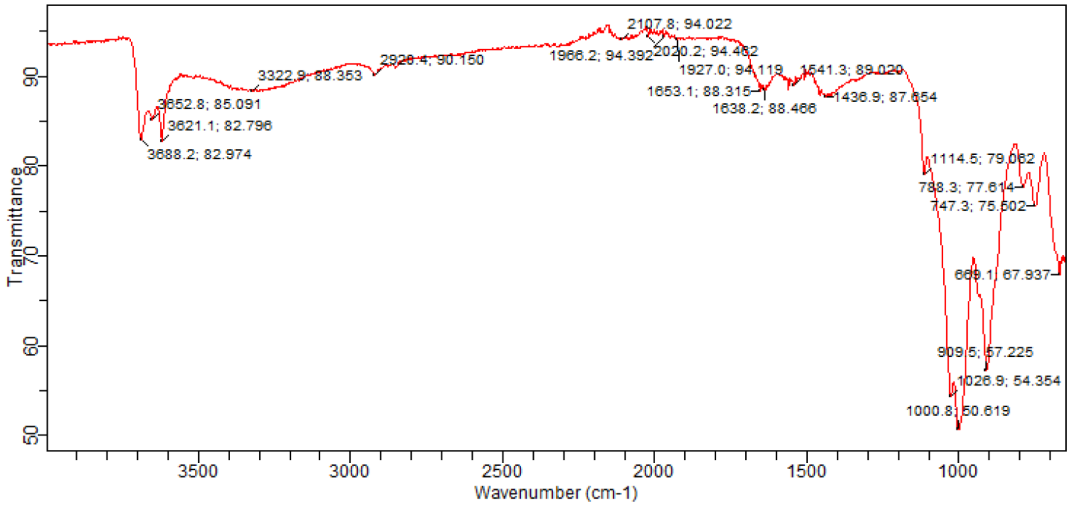

Figure 8. FTIR spectrum of FCT.

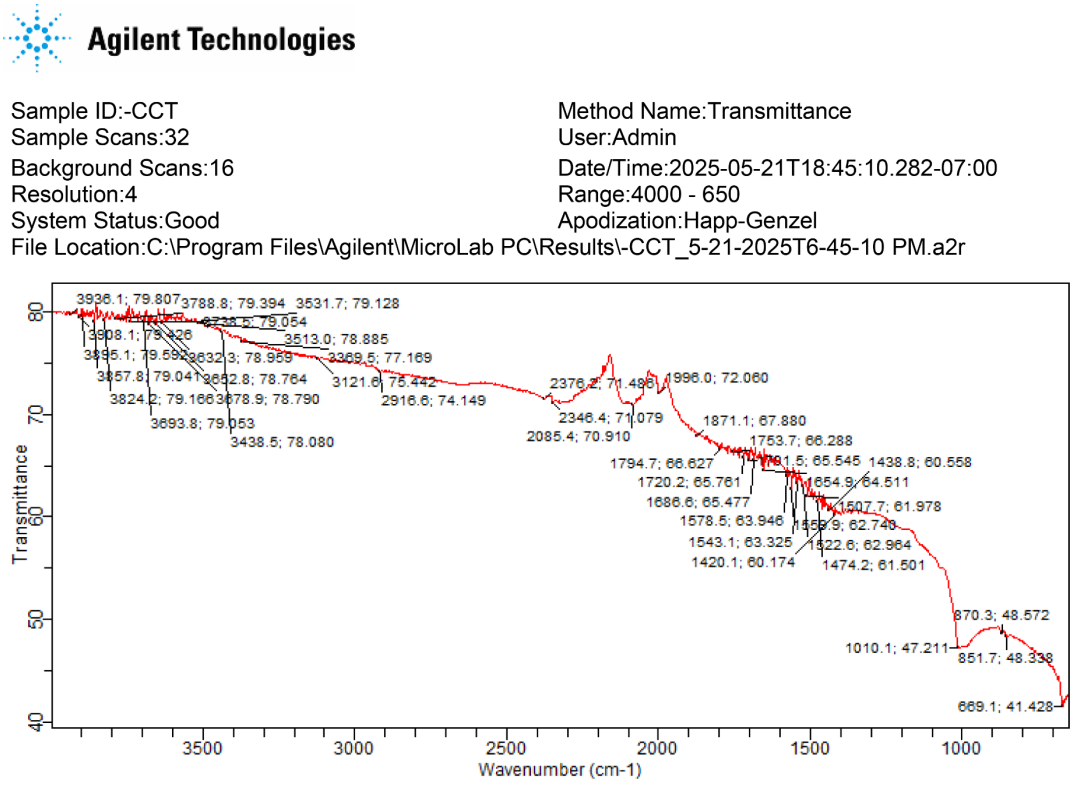

Figure 9. FTIR spectrum of CCT.

bands corresponding to hydroxyl, carbonyl, aromatic, and polysaccharide functional groups.

Broad absorption bands observed around 3200 - 3500 cm^{-1} were attributed to O–H stretching vibrations associated with hydroxyl groups from sodium alginate, gelatin, absorbed moisture, and residual lignocellulosic components of the coconut shell-derived activated carbon [19]. Peaks around 2900 cm^{-1} corresponded to aliphatic C–H stretching vibrations.

The absorption bands detected near 1600 - 1700 cm^{-1} were associated with C=O stretching and aromatic C=C vibrations, indicating the presence of carbonaceous structures within the activated carbon matrix. Additional peaks observed within the fingerprint region (1000 - 1300 cm^{-1}) were assigned to C–O and C–O–C stretching vibrations characteristic of polysaccharides and polymeric binders [21] [22].

Comparative analysis of the spectra demonstrated that the formulated tablets possessed functional groups similar to those observed in the commercial carbo tablet. No major disappearance of characteristic peaks was observed, indicating the absence of significant chemical incompatibility between the activated carbon and binder systems.

3.9. Elemental Composition of Carbo Tablets (EDX)

The EDX spectrum shown in **Figure 10** confirmed the elemental composition of the formulated carbo tablets. Carbon was identified as the predominant element,

consistent with the activated carbon nature of the coconut shell-derived material. Oxygen was also detected, reflecting the presence of oxygen-containing functional groups on the carbon surface and within the polymeric binders.

Trace mineral elements observed in the spectrum may be attributed to naturally occurring inorganic constituents from the coconut shell precursor and excipient materials. The high carbon content observed supports the adsorption functionality of the tablet formulation, as carbon-rich porous matrices are known to exhibit strong adsorptive properties [20].

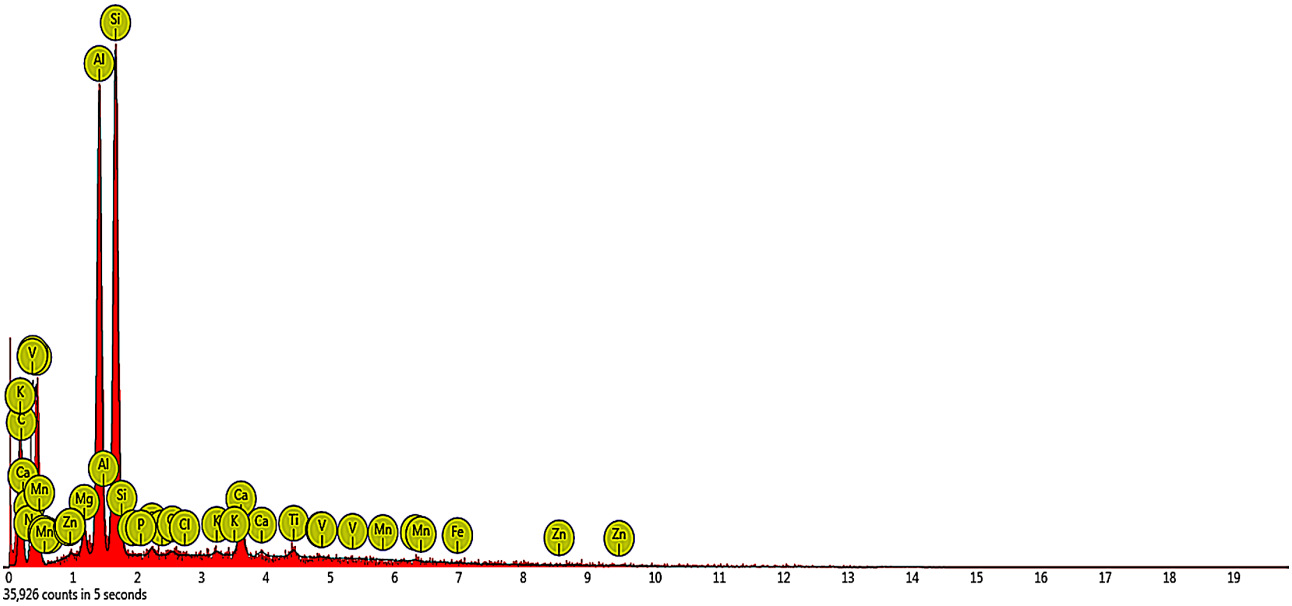

Figure 10. EDX spectrum showing elemental composition of the formulated carbo tablet.

4. Instrumental Characterization

The combined instrumental analyses demonstrated that the formulated carbo tablets possessed desirable structural, thermal, and chemical properties comparable to the commercial standard. TGA/DTA analysis confirmed adequate thermal stability of the formulations, while SEM analysis revealed a highly porous morphology favorable for adsorption applications. FTIR spectroscopy verified the presence of functional groups associated with activated carbon and natural polymeric binders without evidence of chemical incompatibility. EDX analysis further confirmed the carbon-rich composition of the tablets.

Collectively, these instrumental findings support the physicochemical evaluation results obtained from flow property, hardness, friability, and disintegration studies. The incorporation of sodium alginate as a natural binder produced stable formulations with preserved structural integrity and desirable adsorption-related characteristics.

5. Conclusions

The present study successfully developed sustainable carbo tablet formulations

from coconut shell-derived activated carbon using gelatin and sodium alginate as binder systems following USP 30 standards. The findings demonstrated that binder type and concentration significantly influenced the physicochemical, mechanical, disintegration, and structural characteristics of the formulated tablets. All formulations exhibited excellent pre-compression properties with angle of repose values between 25˚ - 27˚, bulk density ranging from 0.53 - 0.57 g/cm^3, and tapped density values of 0.67 - 0.71 g/cm^3, confirming good flowability and compressibility suitable for large-scale pharmaceutical production.

Mechanical evaluation showed that increasing sodium alginate concentration enhanced tablet strength, with crushing strength increasing from 3.4 kgf in FCTa1 to 6.4 kgf in FCTa4. Friability values decreased correspondingly, and only FCTG (0.4%), FCTa3 (0.80%), and CCT (0.4%) complied with the pharmacopeial limit of less than 1%. Disintegration studies further demonstrated the influence of binder concentration on release behavior. Gelatin-based tablets disintegrated rapidly within 0.52 min, while sodium alginate formulations showed progressive increases in disintegration time from 4.62 to 21.20 min due to hydrogel matrix formation. Although FCTa4 exhibited sustained-release characteristics, FCTa3 provided the most balanced immediate-release profile with acceptable mechanical stability and pharmacopeial compliance.

Instrumental characterization confirmed the structural and chemical integrity of the formulations. TGA/DTA analyses demonstrated adequate thermal stability with characteristic moisture evaporation below 150˚C and gradual thermal decomposition at elevated temperatures. SEM analysis revealed a porous and heterogeneous surface morphology with interconnected cavities favorable for adsorption applications. FTIR spectra identified characteristic hydroxyl (O–H), aliphatic C–H, carbonyl (C=O), aromatic C=C, and polysaccharide C–O/C–O–C functional groups at 3200 - 3500 cm^{-1}, 2900 cm^{-1}, 1600 - 1700 cm^{-1}, and 1000 - 1300 cm^{-1}, respectively, confirming the preservation of essential functional groups without evidence of chemical incompatibility between the activated carbon and excipients. EDX analysis further verified the predominance of carbon and oxygen, supporting the adsorption functionality of the carbon-rich matrix.

Overall, formulation FCTa3 containing 3% sodium alginate demonstrated the best overall pharmaceutical performance comparable to the commercial carbo tablet. It should be noted that only a single gelatin concentration was evaluated, whereas sodium alginate was investigated at four concentration levels. Consequently, the study provides a more comprehensive assessment of the concentration-dependent effects of sodium alginate than of gelatin, which limits direct comparison between the two binder systems. The study therefore establishes sodium alginate as an effective natural and tunable binder system while demonstrating the feasibility of utilizing coconut shell-derived activated carbon as a sustainable pharmaceutical material. These findings support the integration of agricultural waste-derived biomaterials into modern pharmaceutical dosage form development, contributing to sustainable drug formulation and environmentally friendly pharma-

ceutical manufacturing.

Conflicts of Interest

The authors declare no conflicts of interest.

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