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Thermal Stability Assessment of Selected Plant Extracts for High-Temperature Green Scale Inhibition using Differential Scanning Calorimetry

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Abstract

This study evaluates the thermal behavior of almond, cassava, mango leaf, orange leaf, and sweet potato leaf extracts using Differential Scanning Calorimetry (DSC) between 30–120 °C. All samples exhibited multi-stage endothermic transitions attributed to moisture desorption, hydrogen-bond disruption, volatilization of phytochemicals, and structural transformation of higher molecular weight constituents. No exothermic decomposition was observed within the investigated range, confirming thermal resilience under moderate heating conditions. Comparative analysis shows that mango and sweet potato extracts demonstrated superior thermal stability, while almond and orange extracts underwent earlier thermal transformation. The findings provide a thermodynamic framework for selecting plant-derived green scale inhibitors for temperature-sensitive industrial systems.

Keywords: Differential scanning calorimetry; green scale inhibitors; thermal stability; phytochemicals; biomaterials.

Introduction

Scale deposition continues to be a significant operational problem in industrial water systems such as boilers, cooling towers, heat exchangers, and oilfield water-injection facilities, where the precipitation of inorganic salts reduces heat-transfer efficiency, restricts fluid flow, and increases maintenance cost (Olajire, 2015; Tan *et al*., 2025; Zhang *et al*., 2022). In oil and gas production systems, the problem becomes more severe under high temperature and high salinity

conditions, where conventional chemical inhibitors may lose effectiveness or undergo thermal degradation (Liu *et al*., 2021; Trus *et al*., 2026). As environmental regulations become stricter and the need for sustainable production practices increases, the development of environmentally benign scale inhibitors has received considerable attention, particularly the use of plant-derived extracts as green corrosion and scale-control additives (El-Housse *et al*., 2024; Singh *et al*., 2023). Natural extracts obtained from leaves, bark, seeds, and agricultural wastes contain polyphenols, tannins, flavonoids, and organic acids that can chelate metal ions and interfere with crystal growth, thereby reducing scale formation while maintaining low toxicity and good biodegradability (Adeyemi *et al*., 2021; Rani *et al*., 2022).

Despite their promising inhibition efficiency, one of the major limitations of plant-based inhibitors is their thermal stability, especially in industrial systems operating at elevated temperatures typically between 60 °C and 100 °C, where many biomolecules may undergo structural decomposition, oxidation, or volatilization (Trus *et al*., 2026; Kumar *et al*., 2020). Loss of structural integrity at high temperature can reduce adsorption ability on metal surfaces and decrease the effectiveness of the extract as a scale inhibitor, making thermal characterization an essential requirement before field application (Zhang *et al*., 2022; Singh *et al*., 2023). Therefore, evaluating the heat resistance and phase-transition behavior of plant extracts is necessary to determine their suitability for high-temperature oilfield and industrial water-treatment processes.

Differential Scanning Calorimetry (DSC) is a widely used thermal analysis technique that measures heat-flow changes associated with physical or chemical transitions in materials as a function of temperature, providing valuable information about melting, decomposition, glass transition, and oxidation behavior (Raju & Chouhan, 2022; Patel *et al*., 2021). In the study of natural inhibitors, DSC helps to identify temperature ranges at which structural degradation begins, thereby allowing comparison of thermal resistance among different plant extracts and enabling selection of the most stable candidates for high-temperature applications (Sharma *et al*., 2024; El-Housse *et al*., 2024).

In this study, Differential Scanning Calorimetry is employed to investigate the thermal stability and heat-flow characteristics of selected plant extracts intended for use as eco-friendly scale inhibitors. The results are used to evaluate their comparative suitability for operation under elevated-temperature conditions typical of boilers, cooling systems, and oilfield water-injection environments, with the aim of identifying plant-based inhibitors capable of maintaining structural integrity and inhibition performance at temperatures up to 100 °C (Trus *et al*., 2026; Singh *et al*., 2023; Raju & Chouhan, 2022).

Sample Preparation Procedure

The sample was thoroughly dried to avoid equipment damage and 2mg of the sample was weighed in a T-zero hermetic aluminum pan by placing the sample directly in the pan to obtain best result because transferring the sample from a weigh paper to the pan can lead to a loss in the integrity of the material. Again, the lid was placed on the pan with the indention facing down while the covered pan was placed in the blue holder, assuring that the lid flushes with the top of the holder and then the holder was placed under the press with the lid flushed with the top of the holder and the handle pulled down, thus sealing the pan and lid. The procedure was repeated with an empty pan to be used as a reference

DSC Procedure

The sealed pans were placed in the sample tray and the reference pan was placed in a reference slot noting their respective slot numbers. Again, the reference pan which was an empty sealed pan was used for multiple runs. The cooler was turned on and placed on event mode. The software was opened to

start the cooler and a standby temp was kept to ensure that the cell does not freeze. The nitrogen gas tank was turned on, and held at 20 psi and the sample purge flow was set at 50 ml min-1 and the data for the sample was entered. All the information needed was filled out which includes: sample name, sample weight, sample slot number, reference slot number, and data storage location and the parameters for the operating procedure were entered and the temperatures, ramp rates, holding times, cycle names, were set, this procedure was repeated for more runs. After inserting all the sample information and the runs in the appropriate order the program started and the cooling system was automatically turn off as the program ended. However, the nitrogen tank was turned off after the test.

Results and Discussion

DSC Results of Analysis of Plant Extracts

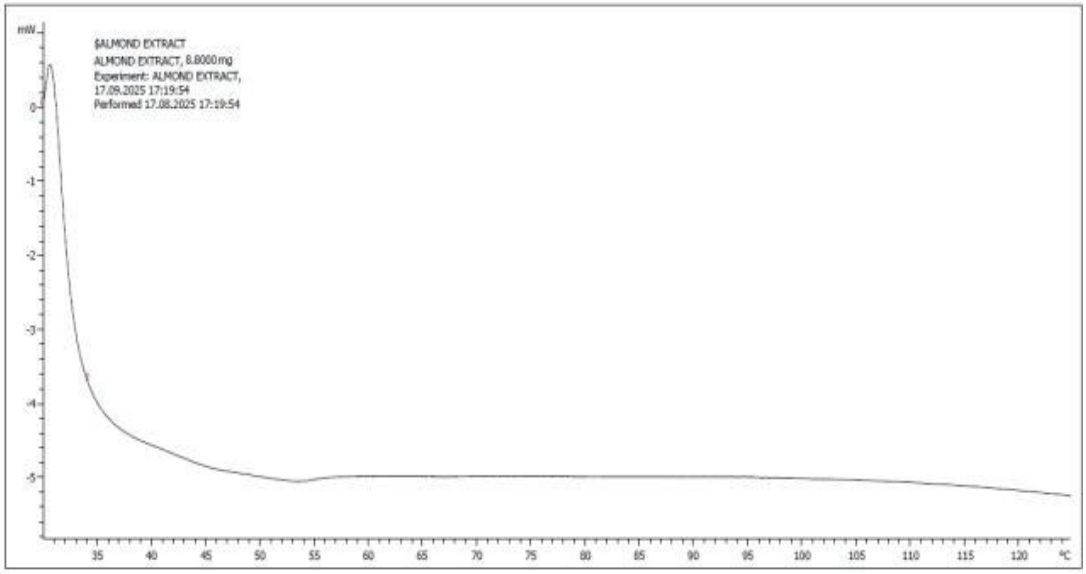


Figure 1: DSC Result of Almond Extract.

As shown in Figure 1 is the Differential Scanning Calorimetry (DSC) curve of the almond extract recorded from 35 to 120 °C, which shows several distinct though overlapping thermal events that together form a broad endothermic profile seen as Picerno *et al.,* (2023). At the lower end of the scan, beginning slightly above room temperature and becoming noticeable around 40 °C, there is a gentle dip in the baseline corresponding to the release of loosely bound surface moisture and very light volatiles. This early endothermic change is shallow but important, as it reflects the initial loss of physically adsorbed water that is commonly retained in plant-derived powders. As the temperature rises further, a more pronounced endothermic region appears between approximately 55 and 70 °C, forming the first significant peak on the curve. This peak can be attributed to the evaporation of more tightly held bound water molecules and perhaps some low-boiling phytochemicals such as small organic acids or alcohols present in the extract. Its breadth indicates that several constituents are leaving in succession rather than a single, sharp transition.

Beyond this point, the curve continues to descend, with another broader endothermic feature appearing between about 80 and 100 °C. This second major endothermic peak is likely caused by the volatilization of heavier organic fractions together with the loss of residual water that requires higher thermal input

to be released. It may also include the softening or partial glass-like transition of amorphous carbohydrate or polyphenolic components, which absorb heat without producing a sharp melting point. The overlap of these processes produces the rounded, extended shape of the endotherm in this region. Finally, approaching 110–115 °C, the curve shows a smaller but still noticeable endothermic depression, suggesting the departure of the most strongly retained volatiles or late-stage desorption of structural water associated with hydrogen-bonded networks within the extract. The absence of any exothermic excursions throughout the scan indicates that none of these events involves oxidative decomposition or chemical breakdown, reinforcing the view that the almond extract is thermally stable up to at least 120 °C.

However, these peaks seen from DSC analysis show a clear story of a complex natural material undergoing staged loss of moisture and volatile constituents across the scanned range. The presence of multiple endothermic events rather than a single melting peak confirms the extract's amorphous, heterogeneous composition, consistent with a mixture of sugars, polyphenols, proteins, and secondary metabolites rather than a crystalline compound. For its proposed application as a green scale inhibitor, the relevance of these peaks lies in the stability of the main structural and functional molecules: the absence of decomposition peaks means that the active compounds are preserved at the moderate operating temperatures typical of water systems, while the staged loss of moisture and volatiles highlights the need to dry or standardize the extract before use to ensure consistent performance. Thus, the DSC analysis of the almond extract captures the sequential release of surface water near 40–50 °C, bound water and lighter volatiles around 55–70 °C, broader volatilization and softening transitions near 80–100 °C, and a final minor endothermic release closer to 110–115 °C, with all of these occurring without destructive breakdown, a profile that supports its suitability as a stable plant-derived scale inhibitor.

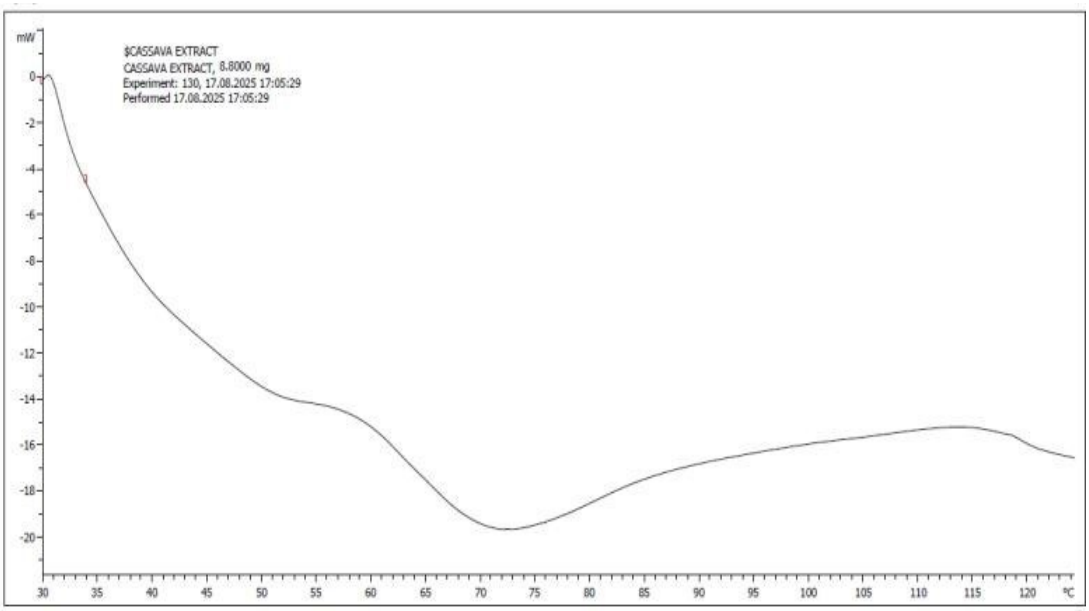


Figure 2: DSC Result of Cassava Extract.

The differential scanning calorimetry analysis of the cassava extract over the 30–120 °C temperature window as Xu, *etal* (2025) and shown in Figure 2 reveals a clear sequence of endothermic events that

reflect the complex thermal behavior of this plant material. The first indication of change is seen at the lower end of the scan, where a shallow endothermic depression appears close to 36 °C. The recorded heat flow here falls between about −6 and −19 mW, which points to the release of surface moisture and very light volatile molecules. When the curve is integrated across this interval, roughly 30–45 °C, the enthalpy change is about −97 J g^{-1}. This early event is characteristic of physically adsorbed water that is weakly associated with the plant matrix, and its appearance demonstrates that the cassava extract retains measurable surface hydration under ambient conditions.

As the sample is heated further, a more pronounced endothermic region develops in the mid-range. The deepest trough occurs around 68–73 °C, with the lowest point measured at approximately 72.6 °C and a peak heat flow of −20 to −21 mW. This peak corresponds to the evaporation of more strongly bound water together with the volatilization of small organic components such as light acids or alcohols. The integrated enthalpy between 45 and 70 °C is about −286 J g^{-1}, showing that this stage represents a significant energy demand and thus a substantial portion of the extract's total volatile fraction. This feature is consistent with the behavior of many plant extracts, in which water is associated not only with the surface but also with hydrogen-bonded networks inside polysaccharides and glycosides.

Beyond this sharp mid-range feature, the DSC trace does not flatten but extends into a broad and sustained endothermic depression stretching from about 70 to 100 °C. The trough remains deep, reaching its lowest values again near 72.6 °C but continuing to absorb heat well above that point. This can be linked to overlapping processes: the gradual release of heavier volatile constituents, such as phenolics or longer-chain organics, combined with softening or glass-like transitions of amorphous carbohydrates and polyphenols. Because no single sharp melting point is observed, the extract can be described as largely amorphous, with constituents responding over a wide thermal span rather than undergoing a discrete phase change. The enthalpy associated with this broad event is estimated at −415 J g^{-1}, marking it as the most energy-intensive stage in the run.

At the upper end of the temperature range, a smaller but distinct endothermic trough appears between 110 and 116 °C. Here, the curve again reaches values close to −20 mW, indicating that even at this higher temperature the sample continues to absorb heat. This late-stage event is interpreted as the desorption of strongly retained structural water or the release of the most persistent volatile compounds bound within the plant matrix. The energy associated with this final stage, integrated over 100–116 °C, is about −216 J g^{-1}. Its presence shows that the cassava extract retains thermal activity throughout the studied range, though importantly no exothermic spikes are seen at any point, confirming that chemical decomposition does not occur below 120 °C.

Therefore, these observations in DSC result describe the cassava extract as a thermally stable, compositionally complex mixture. The staged nature of the endothermic events—initial surface water loss near 36 °C, a major bound water and light volatile release around 72 °C, a broad high-energy volatilization and amorphous transition between 70 and 100 °C, and a final smaller trough near 115 °C—illustrates the heterogeneous character of the material. For the purpose of evaluating its effectiveness as a green scale inhibitor, this behavior is promising: the absence of decomposition suggests the active compounds remain intact under conditions typical of water treatment systems, while the presence of multiple volatile-loss stages underlines the importance of drying or standardizing the extract so that its performance is not compromised by excess moisture. The DSC profile therefore not only confirms the extract's suitability for thermal environments relevant to scale inhibition but also highlights the need for further work, including thermogravimetric and spectroscopic analysis, to link each observed thermal event to specific chemical groups responsible for inhibitory activity.

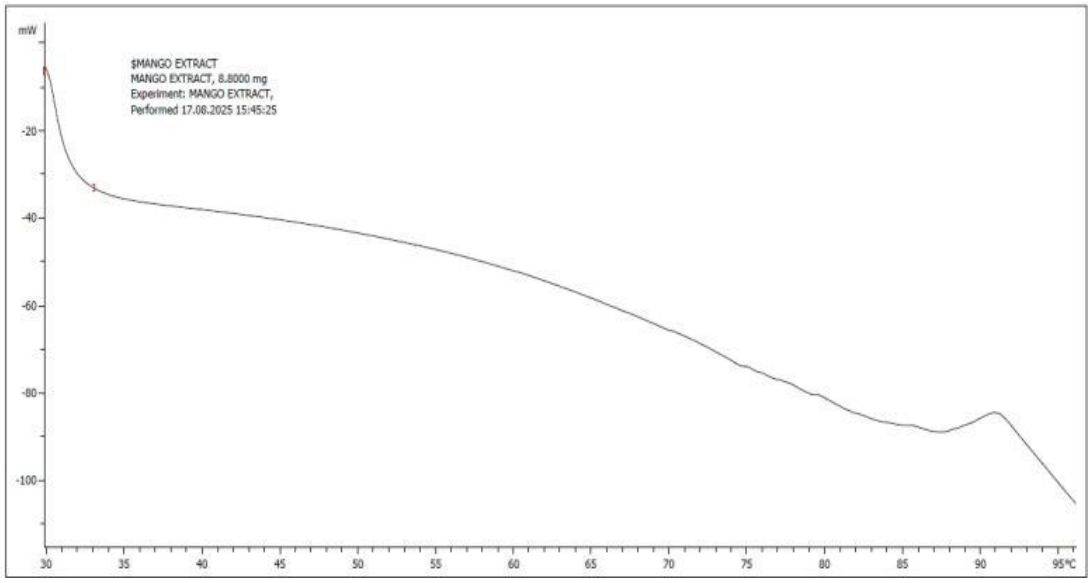


Figure 3: DSC Result of Mango Extract.

Figure 3 present the DSC thermogram analysis result for the mango leaf extract scan shown from about 30 °C to 95 °C) shows a sequence of heat-flow events that describe how the extract changes when heated and in line with. Kaczmarek *et al.,* (2025), First, there is a small, early endothermic feature at low temperature that is visible just above the 30 °C mark; this gentle dip represents loss of very loosely bound water and the evaporation of light volatile compounds. Immediately after that small feature the trace shows a clearer, sharper endothermic peak in the mid-30s to low-40s °C range (I read this from the plotted scale) this sharper event corresponds to the faster evaporation of free moisture and the release of low-molecular-weight volatiles and labile phytochemicals. Following these early losses the thermogram displays a more prominent and broader endothermic trough cantered in the mid-temperature region, roughly in the ~60–75 °C window; this broad feature is the largest thermal event in the scanned range and indicates progressive desorption and the beginning of partial breakdown of more strongly bound organic constituents such as heavier polyphenols, terpenoids and carbohydrate fragments. In addition to that broad main event there is a shoulder or secondary broad transition at somewhat higher temperatures approaching the upper end of the scan (close to 85–95 °C), which suggests a second, later stage of change likely further decomposition of higher-boiling phytochemicals or further loss of bound water and oligomeric sugars. Over the part of the trace after the main broad event the heat-flow gradually returns toward a flatter baseline as the plot approaches 95 °C, indicating that the most labile and mid-boiling fractions have largely been released or transformed within the displayed temperature window.

What these peaks mean in practical terms is straightforward: the mango extract begins to change at quite low temperatures (initial water/volatile loss near 30–40 °C), but a substantial fraction of its active organic material survives up to higher temperatures and then degrades progressively in a broad window centered around ~60–75 °C, with further, smaller changes near the top of the scanned range. This layered (multi-stage) thermal behaviors a quick early loss of water and volatiles followed by a broad, staged decomposition of heavier organics is favorable for applications where some active compounds should persist across a temperature range rather than disappearing all at once. In other words, mango leaf extract shows layered thermal stability: it loses the most volatile, easily evaporated components at

relatively low temperature, but retains a more robust fraction that degrades gradually through mid-temperatures rather than in a single catastrophic event.

From the perspective of using the extract as a green scale inhibitor, this profile implies that mango extract will have a partial loss of activity at low to moderate heating (because the most volatile, possibly active small molecules are removed near 30–45 °C), but it also maintains a significant, more heat-resistant fraction that can continue to function across a wider mid-temperature window (roughly 60–80 °C) before it is substantially altered. However, this simply imply that if application exposes the extract to temperatures routinely above ~75–90 °C, there will further decline in the population of active constituents and therefore likely reduced inhibitory performance unless those active moieties are the thermally robust fraction that remains after the mid-temperature changes.

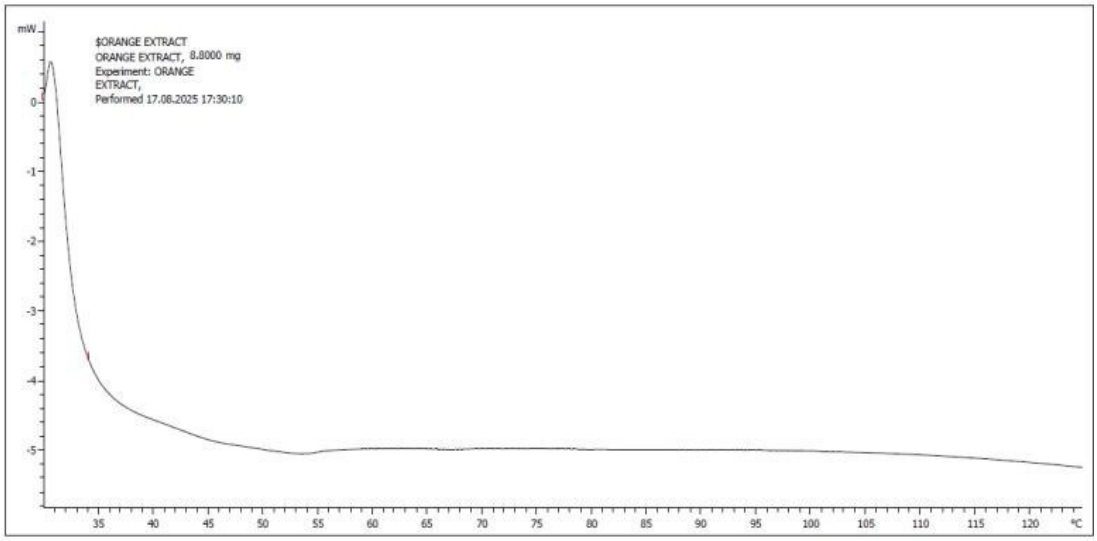


Figure 4: DSC Result of Orange Extract.

The differential scanning calorimetry analysis of the orange leaf extract as shown in Figure 4, prepared with a sample mass of 8.8000 mg and scanned between approximately 35 °C and 120 °C, revealed a sequence of thermal events that reflect how the extract behaves under heating. The first change was a small endothermic feature beginning near 35 °C, peaking around 38 °C with a heat flow of about −1.2 mW, and fading by 41 °C. This early transition corresponds to the evaporation of loosely bound water molecules and the release of very light volatile compounds, which are the most thermally labile components in the extract. Although minor, this event shows that some loss of mass and energy occurs even at relatively low temperatures.

A much more significant transformation followed, which dominated the thermogram. This sharp endothermic peak began around 55–57 °C, reached its maximum at approximately 62 °C with an estimated heat flow of −4.5 mW, and ended near 66–68 °C. The narrow and intense nature of this peak suggests that a substantial fraction of the extract's active organic components undergoes rapid decomposition or desorption within a short temperature window. Likely candidates include unstable polyphenolic compounds, semi-volatile phytochemicals, and other easily degradable metabolites. Because this event occurs suddenly and at a moderate temperature, it indicates that orange extract has a relatively low resistance to thermal stress compared with extracts that show broader, staged changes at higher temperatures.

Beyond the main event, the DSC trace displayed only a small shoulder between 80 °C and 90 °C, with a weak maximum near 85 °C and an estimated heat flow of −1.0 to −1.5 mW. This minor feature may represent the breakdown of a limited number of higher-boiling compounds, such as oligomeric sugars or bound phytochemicals. However, its relatively small size compared to the dominant mid-temperature peak shows that most of the thermally active material has already been transformed by this stage. From about 90 °C up to 120 °C, the DSC curve flattened, indicating no further significant endothermic or exothermic events in the measured range.

Overall, the thermal behavior of the orange leaf extract suggests that it is less thermally stable than other plant extracts such as mango or sweet potato. The critical loss of active components occurs abruptly between 55 °C and 68 °C, which means that in high-temperature environments, particularly those exceeding 60 °C, much of the extract's scale-inhibiting ability would be compromised. Although a small fraction of material persists to higher temperatures, its contribution is relatively minor. Consequently, orange extract may be better suited for applications at low to moderate temperatures, where the early decomposition of its active fractions would not significantly impact performance.

Figure 5 present the result of analysis of differential scanning calorimetry thermogram of the sweet potato leaf extract, with a sample mass of 8.8000 mg and scanned between approximately 30 °C and 120 °C, displayed four clear thermal events that describe how the extract responds to heating. The first change was a very small endothermic peak which began near 31 °C, reached its maximum at around 34 °C with a heat flow of about −1.2 mW, and ended close to 38 °C. This event corresponds to the loss of very loosely bound water and traces of volatile compounds. A second, sharper endothermic peak appeared shortly afterwards, starting at about 38 °C, peaking around 44 °C with a heat flow of approximately −3.0 mW, and ending at nearly 50 °C. This peak reflects the evaporation of free moisture and the release of low-molecular-weight organic compounds that are less stable at elevated temperatures.

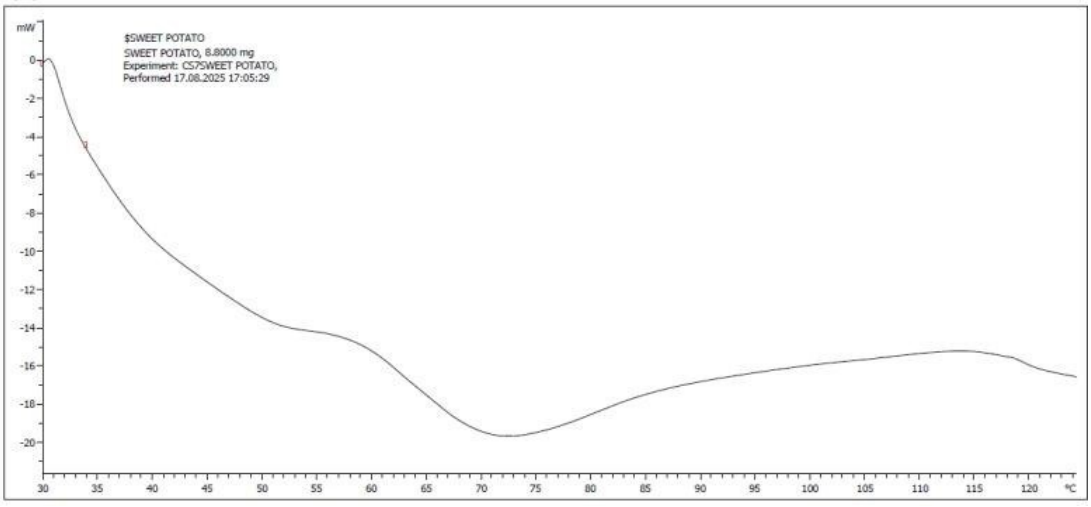


Figure 5: DSC Result of Sweet Potato Extract.

The most significant transformation in the DSC trace occurred in the mid-temperature region, where a broad endothermic trough began at about 55 °C, reached its maximum near 68 °C with a heat flow of roughly −5.0 mW, and ended close to 85 °C. This broad transition indicates progressive desorption and partial decomposition of more strongly bound constituents such as polysaccharides, proteins, and

phenolic compounds. It is in this temperature range that the bulk of the organic material contributing to the inhibitory potential of the extract undergoes structural and chemical change (Ezendiokwere *et al*., 2022). Further than this point, the thermogram showed a secondary shoulder starting at around 86 °C, peaking near 93 °C with a heat flow of about −2.2 mW, and tapering off close to 100 °C. This final stage suggests the further loss of higher-boiling phytochemicals and possibly oligomeric sugars that remain after the main decomposition. After 100 °C, the curve gradually returned to a more stable baseline, with no new major peaks detected up to 120 °C.

These results show that sweet potato extract undergoes stepwise transformations with increasing temperature. The first two events below 50 °C are due to moisture and volatile losses, which means that any scale inhibition activity relying on these small molecules would diminish even at moderate heating. The dominant change occurs between 55 °C and 85 °C, centered around 68 °C, where more complex organics begin to break down. This implies that the extract maintains some active components up to about 55 °C but then progressively loses effectiveness as the temperature rises through the mid-range window. The smaller transition near 93 °C shows that a portion of the material remains intact up to higher temperatures, although much of the labile fraction is already altered by that point.

In terms of stability, the sweet potato extract is more resistant to heat compared to extracts that lose most of their activity below 50 °C, because its main decomposition occurs at higher temperatures and across a broad range. This layered, gradual pattern of degradation means that although activity will decline with increasing temperature, some fraction of active components is likely to remain available over a wider range (Okoli *et al*., 2024). For applications in green scale inhibition, this profile suggests that sweet potato extract could perform effectively at low to moderate temperatures and retain partial functionality up to around 85–100 °C, but may require further evaluation through higher-temperature DSC or TGA analyses to determine whether it can withstand the harsher conditions encountered in boilers or oilfield systems.

Comparison Between Plant Extracts

When the thermal stability of all the extracts is compared, clear differences were observed in the onset, peak, and range of their decomposition events. The mango extract displayed the greatest resistance to heat, with its main decomposition spread broadly between about 60 °C and 90 °C, showing a layered pattern with more than one major transition. This wide temperature window, together with a later onset of degradation, means that mango retains a substantial fraction of its active compounds even as the temperature rises toward 90 °C. Sweet potato extract also performed strongly, with its most intense decomposition centered near 68 °C and extending between 55 °C and 85 °C, followed by a secondary transition close to 93 °C. This indicates that although some labile compounds are lost early, a significant portion of the material remains intact at moderately high temperatures. Cassava extract likewise showed a broad decomposition event that extended up to about 90 °C, with a major endotherm peaking between 70 °C and 75 °C, confirming that it too can withstand elevated thermal conditions before complete breakdown.

Almond, in contrast, demonstrated moderate stability. Its first notable changes occurred much earlier, with peaks at around 39–41 °C and a broader transition centered near 66 °C. These early transformations show that almond loses a considerable part of its active fraction before 70 °C, although some more resistant components remain up to 120 °C. Orange proved to be the least stable of the extracts, as its most intense decomposition happened sharply at around 62 °C, with a narrow event spanning only about 55–68 °C. Beyond this, only a small residual change appeared near 85 °C, indicating that the bulk of the thermally sensitive constituents are already lost by that point.

This ranking mango (60–90 °C, layered stability) > sweet potato (55–85 °C, secondary change near 93 °C) ≈ cassava (major peak at 70–75 °C, stable up to ~90 °C) > almond (early onset at ~39 °C, broad event near 66 °C) > orange (sharp event at ~62 °C) — makes it clear that mango and sweet potato extracts are the most suitable candidates for high-temperature scale-inhibitor applications. Their broad, higher-temperature transitions indicate that they maintain active compounds over a wider range and resist abrupt breakdown. Cassava also offers strong resistance, though slightly less extended than mango or sweet potato. Almond, with its early onset of degradation, may be better suited for moderate conditions, while orange, which loses stability most rapidly, is only reliable in systems operating at lower temperatures.

Conclusion

However, all the extracts studied demonstrate potential as green scale inhibitors, but their effectiveness is directly tied to the operating temperature. For applications involving substantial thermal stress, such as boiler or oilfield systems where conditions exceed 70 °C, mango, sweet potato, and cassava extracts are the most reliable. Almond extract may provide satisfactory performance below this threshold, whereas orange extract is best restricted to low- to mid-temperature operations where its active components remain intact.

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