RECOVERY AND REUSE OF ETHANOL-CONTAINING CONDENSATE IN BANANA PEEL-DERIVED BIOFLOCCULANT PRODUCTION FOR TURBIDITY REMOVAL

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ABSTRACT

Ethanol precipitation is widely used to isolate plant-derived bioflocculants, but repeated use of fresh solvent increases material demand. This preliminary study evaluated the reuse of ethanol-containing condensate from the production of banana peel-derived bioflocculant. Spent precipitation liquor was processed by rotary evaporation using a one-factor-at-a-time design at 100–150 mbar, 150–250 rpm, and 40–60°C. Condensate recovery, bioflocculant yield, and kaolin-turbidity removal were evaluated using single determinations. Recovered condensate was blended with fresh ethanol at ratios ranging from 0:10 to 10:0 (v/v), and the two liquids were qualitatively compared by gas chromatography-mass spectrometry (GC-MS). Maximum condensate recovery was 77.5% at 100 mbar, 250 rpm, and 60°C. However, the highest turbidity removal among the recovery conditions was 62.88% at 100 mbar, 250 rpm, and 40°C, with a condensate recovery of 62.5%. The 5:5 blend achieved the highest observed turbidity removal among the tested ratios (78.4%; yield 0.82 wt%), compared with 72.0% for fresh ethanol alone. GC-MS showed a greater relative contribution from minor detected peaks after recovery, but did not determine ethanol purity. These findings suggest preliminary feasibility of partial condensate reuse. Replicated experiments, quantitative ethanol and water analysis, and repeated recovery–reuse cycles are required to confirm performance and process suitability.

Keywords: *Antisolvent precipitation, condensate reuse, agricultural waste valorisation, solid-liquid, SDG 6, SDG 12*

INTRODUCTION

Turbidity is an important indicator of water quality because suspended and colloidal particles reduce water clarity and may interfere with downstream disinfection. Coagulation-flocculation is widely used to destabilise these particles and promote their aggregation into settleable flocs. Although aluminium- and iron-based coagulants are effective, their application increases chemical consumption and generates sludge requiring further handling and disposal [1]-[2]. These concerns have encouraged research into natural bioflocculants as alternative treatment materials.

Plant-derived bioflocculants contain polysaccharides, proteins, and other macromolecules that facilitate particle aggregation. According to Kurniawan et al. [3], hydroxyl, carboxyl, and amino groups contribute to adsorption, charge neutralisation, and polymer bridging. However, their performance depends not only on the selected feedstock but also on its preparation, extraction, and purification. This is consistent with Ahmad et al. [4], who reported that extraction conditions influence the release and recovery of active compounds from plant materials.

Banana peel is a promising bioflocculant feedstock because it is an abundant residue containing pectin, cellulose, hemicellulose, starch, and other polymeric constituents [5]-[7]. Among these components, pectin and other polysaccharides are particularly relevant because their hydroxyl and carboxyl groups can interact with suspended particles, thereby promoting polymer bridging. Ma et al. [8] isolated a polysaccharide-based bioflocculant, BP50-2, from banana-peel waste and demonstrated its flocculation activity. This agrees with broader evidence that polymer structure, molecular characteristics, and functional groups influence bioflocculant performance [3].

Ethanol precipitation is commonly employed to recover polysaccharides from aqueous plant extracts. Ethanol reduces the polarity of the liquid medium and weakens the hydration of dissolved polysaccharides, causing them to aggregate and precipitate [9]-[10]. Ethanol concentration, solvent-to-extract ratio, precipitation temperature, and polymer characteristics can influence the amount and type of material recovered. Tai et al. [10] reported that different ethanol concentrations may precipitate polysaccharides with different molecular characteristics. This is consistent with Wang et al. [11], Li et al. [12], and Yu et al. [13], who demonstrated that ethanol concentration affected the composition, molecular weight distribution, and functionality of precipitated plant polysaccharide fractions.

Ethanol precipitation commonly requires a relatively large volume of fresh solvent. In the present process, ethanol was added in a

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volume twice that of the banana-peel extract. Repeated production would therefore increase fresh-solvent consumption and generate substantial quantities of spent precipitation liquor. Recovering and reusing the ethanol-containing liquid may reduce the demand for fresh ethanol. However, its suitability cannot be assessed solely from the volume collected because the condensate may contain water and extract-derived volatile compounds. These constituents could alter the effective ethanol concentration, precipitation selectivity, bioflocculant yield, and functional performance.

According to Chea et al. [14], the feasibility of solvent recovery depends on the waste-stream characteristics, the recovery technology, and the solvent quality required by the downstream process. Aboagye et al. [15] similarly emphasised that recovered solvents should be assessed according to their composition and intended reuse requirements. Therefore, a large condensate volume does not necessarily indicate high ethanol recovery or guarantee effective polysaccharide precipitation.

Rotary evaporation provides a practical laboratory-scale method for recovering volatile components from spent precipitation liquor. Reduced pressure lowers the required evaporation temperature, while flask rotation produces a thin liquid film that improves heat and mass transfer. Vacuum pressure, rotation speed, and water-bath temperature may therefore affect condensate collection. Nevertheless, conditions that produce the largest condensate volume may also increase the transfer of water or other volatile components. Consequently, recovery performance should be evaluated alongside the yield and functionality of the bioflocculant subsequently produced from the recovered condensate.

Previous studies have investigated banana peel-derived bioflocculants [8], ethanol fractionation of plant polysaccharides [11]-[13],[16], and systems-level solvent recovery and reuse [14]-[15]. However, limited evidence is available on the recovery of spent ethanol-containing liquor from banana-peel bioflocculant production and its subsequent reuse for precipitation. In particular, it remains unclear whether rotary-evaporation conditions that produce greater condensate recovery also preserve the turbidity-removal performance of the resulting bioflocculant.

Table 1 compares the scope of the present study with selected literature. In general, previous studies addressed banana-peel bioflocculant production, polysaccharide precipitation and fractionation, or solvent-recovery frameworks. The present study, however, differs in that it experimentally links rotary-evaporation conditions, condensate reuse, bioflocculant yield, chromatographic characteristics, and downstream turbidity-removal performance within a single banana-peel processing system.

This study presents a preliminary descriptive assessment of condensate recovery and reuse in the production of banana peel-derived bioflocculants. The specific objectives were as follows: (i) to compare condensate volume recovery, bioflocculant yield, and turbidity removal across the investigated rotary-evaporation conditions; (ii) to determine which tested recovered-to-fresh ethanol ratio produced the highest observed turbidity removal while reducing fresh ethanol input; and (iii) to compare the qualitative GC-MS profiles of fresh ethanol and recovered condensate. Turbidity removal was defined as the primary selection criterion because preservation of bioflocculant function was the intended purpose of solvent reuse. Condensate volume recovery and bioflocculant yield were treated as secondary indicators.

This study seeks to address the limited evidence on whether ethanol-containing condensate recovered from banana-peel bioflocculant production can be reused while preserving the resulting product's turbidity-removal performance. It examines recovery conditions and the progressive substitution of fresh ethanol with recovered condensate, as well as bioflocculant yield and qualitative chromatographic profiles. This approach provides a preliminary assessment of the suitability of recovered condensate for reuse within the same production process.

METHODOLOGY

Materials and Chemicals

Fresh banana peels were collected from a banana fritter outlet in Shah Alam, Selangor, Malaysia. Distilled water was used throughout the extraction and preparation of synthetic turbid water. Hydrochloric acid (HCl, 0.5 M) was used to adjust pH, while

Table 1 Comparison of the present study with selected literature

Study	Feedstock/Product	Ethanol Usage	Recovery Method	Solvent Reuse	Functional Focus
Ma et al. [8]	Banana-peel bioflocculant	Precipitation and purification	Not reported	Not evaluated	Structure and flocculation performance
Tai et al. [10]	Natural polysaccharides	Ethanol precipitation	Review scope	Not the primary focus	Precipitation mechanisms and process factors
Carr et al. [16]	Hemicellulose hydrolysate	Antisolvent precipitation	Not the primary focus	Not evaluated	Polymer recovery and fractionation
Aboagye et al. [15]	Industrial solvent streams	Process-wide solvent use	Multiple technologies	Systems-level assessment	Solvent-recovery and reuse framework
Present study	Banana peel-derived bioflocculant	2:1 ethanol-to-extract ratio (v/v)	Rotary evaporation	0 to 100% substitution tested	Condensate recovery, yield, GC-MS profile, and turbidity removal

Note: "Not reported" indicates that the corresponding outcome was not evaluated in the cited study

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95% ethanol was used to precipitate the extracted bioflocculant. Ethanol at 70% concentration and acetone were used to wash the precipitated material. Kaolin was used to prepare synthetic turbid water for the jar-test experiments.

Preparation of Banana-Peel Powder

The preparation procedure was adapted from Mada et al. [17]. Fresh banana peels were washed thoroughly under running water to remove adhering dirt and surface contaminants. The cleaned peels were oven-dried at 60°C for 24 h and subsequently ground into powder. The powder was passed through a laboratory sieve with a nominal aperture size of 250–500 µm to obtain a more uniform particle-size distribution and was subsequently stored in a dry container until extraction.

Extraction and Precipitation of Banana Peel-Derived Bioflocculant

The bioflocculant was extracted using a hot-acid extraction procedure. Briefly, the sieved banana-peel powder (40 g) was mixed with 500 mL of distilled water. The pH of the suspension was adjusted to 2.0 using 0.5 M HCl under continuous stirring. The suspension was then heated at 95°C for 4 h using a stirring hot plate. After extraction, the mixture was cooled to room temperature and filtered through muslin cloth to separate the solid residues from the liquid extract. The extracted bioflocculant was precipitated by adding 95% ethanol to the liquid extract at an ethanol-to-extract ratio of 2:1 (v/v). The mixture was stirred for 10 min and left overnight at room temperature to allow precipitation. The resulting precipitate was separated by filtration and washed with 70% ethanol, followed by a small quantity of acetone, to remove residual impurities. The washed precipitate was dried in an oven at 50°C for 3 h. The mass of the dried banana peel-derived bioflocculant was calculated using Equation 1 and recorded.

$$\text{Bioflocculant yield (wt\%)} = \frac{m_b}{m_p} \times 100\% \quad (1)$$

where m_b is the mass of dried bioflocculant obtained (g), and m_p is the initial mass of dried banana-peel powder used for extraction (g).

Recovery of Ethanol by Rotary Evaporation

The spent ethanol collected after bioflocculant precipitation was recovered using a rotary evaporator equipped with a water bath, condenser, chiller, vacuum system, and receiving flask. For each experimental run, 200 mL of the spent ethanol mixture was transferred into the evaporation flask. The chiller temperature was maintained between −10 and −20°C to facilitate the condensation of ethanol vapour. A one-factor-at-a-time experimental approach was used to examine the effects of three rotary-evaporation variables: vacuum pressure, flask rotation speed, and water-bath temperature. The investigated levels were tabulated in Table 2.

The volume of condensate collected in the receiving flask was measured at the end of each run. Because the condensate could contain ethanol, water, and other volatile compounds, the volume-based response was termed condensate volume recovery. It was calculated using:

Table 2 The value and range of parameters to be manipulated during the ethanol recovery process using a rotary evaporator

Variables	Unit	Manipulated Values
Vacuum pressure	mbar	100, 125, 150
Rotational speed	rpm	150, 200, 250
Temperature	°C	40, 50, 60

$$\text{Condensate Volume Recovery (\%)} = \frac{V_r}{V_i} \times 100\% \quad (2)$$

where V_r is the condensate volume collected (mL), and V_i is the initial volume of spent ethanol introduced into the evaporation flask (200 mL). This measurement quantifies recovered liquid volume but does not establish ethanol concentration or purity.

The study used a one-factor-at-a-time exploratory design and did not estimate factor interactions. Conditions were compared using a predefined hierarchy in which turbidity removal by the resulting bioflocculant was the primary response, because preserving downstream function was the purpose of solvent reuse; condensate volume recovery was secondary, and bioflocculant yield was supporting information.

Evaluation of Bioflocculant Produced Using Recovered Condensate

Condensate recovered under each rotary-evaporation condition was reused as the precipitating solvent in a new bioflocculant-production cycle, as illustrated in Figure 1. The hot-acid extraction and precipitation procedures were carefully followed, with recovered condensate replacing fresh ethanol during precipitation. The resulting bioflocculant was collected, washed, dried, and weighed. Yield was calculated using Equation 1, and functional performance was evaluated using the jar-test procedure. Turbidity removal was the primary selection criterion, condensate volume recovery was secondary, and bioflocculant yield provided supporting information.

Preparation of Synthetic Turbid Water

Synthetic turbid water was prepared by dispersing 0.2 g of kaolin in 300 mL of distilled water in a 500 mL beaker. The suspension was mixed at 400 rpm for 10 min using a jar-test apparatus to obtain a uniform dispersion of kaolin particles. The initial turbidity of each suspension was measured before the addition of bioflocculant.

Jar-Test Analysis

The turbidity-removal performance of each bioflocculant sample was evaluated using a jar-test analysis. A bioflocculant dosage of 0.03 g was added to 300 mL of synthetic turbid water as a screening condition, allowing products obtained under different solvent conditions to be compared at the same mass dosage. The suspension was subjected to rapid mixing at 200 rpm for 5 min, followed by slow mixing at 40 rpm for 10 min. The treated suspension was then left undisturbed for 2 h to allow the formed flocs to settle. After sedimentation, a 10 mL sample was carefully collected from the supernatant without disturbing the settled flocs. Final turbidity was measured using a turbidimeter. Turbidity-

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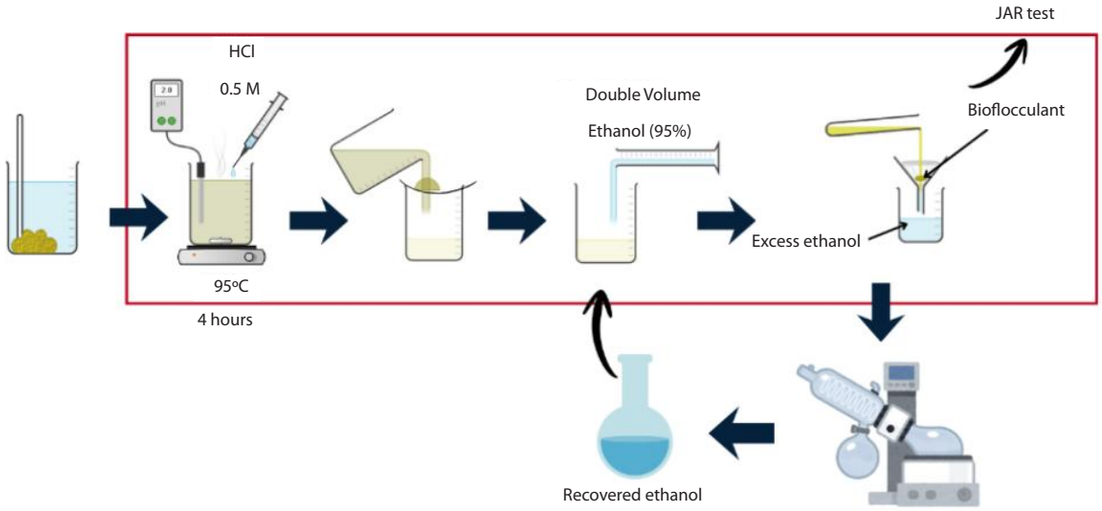


Figure 1 Schematic representation of banana peel-derived bioflocculant extraction, ethanol precipitation, ethanol recovery by rotary evaporation, solvent reuse, and subsequent jar-test evaluation

removal efficiency was calculated using:

$$\text{Turbidity removal efficiency (\%)} = \frac{T_i - T_f}{T_i} \times 100\% \qquad (3)$$

where T_i and T_f are the initial and final turbidity values, respectively.

The same preparation and jar-test conditions were applied throughout. The source dataset contained single determinations and did not include replicate measurements; therefore, standard deviations, error bars, and inferential statistical comparisons were not calculated. Results are reported descriptively as preliminary observations.

Effect of Recovered-to-Fresh Ethanol Ratio

The feasibility of partial or complete substitution of fresh ethanol with recovered condensate was evaluated by preparing different recovered-to-fresh ethanol ratios. Condensate obtained at 100 mbar, 250 rpm, and 40°C was used because this condition produced the highest observed turbidity removal among the rotary-evaporation conditions tested. The recovered-to-fresh ethanol ratios investigated ranged from 0:10, 1:9, 2:8, 3:7, 4:6, 5:5, 6:4, 7:3, 8:2, 9:1 to 10:0. The 0:10 treatment represented precipitation using fresh ethanol alone, whereas the 10:0 treatment represented precipitation using recovered condensate alone. For every treatment, the total precipitation-solvent volume was maintained at the ethanol-to-extract ratio of 2:1 (v/v).

Following precipitation, the bioflocculant was collected, washed, dried at 50°C for 3 h, and weighed. Its turbidity-removal performance was evaluated using the jar-test procedure. The ratio with the highest observed turbidity removal was identified as the most favourable within the tested set; fresh ethanol substitution and bioflocculant yield were considered secondary descriptors.

Gas Chromatography-Mass Spectrometry Analysis of Fresh and Recovered Condensate

Fresh and recovered condensate were analysed using gas chromatography-mass spectrometry (GC-MS) to compare their chromatographic profiles. A 1 µL sample volume was introduced using an automated liquid sampler. The injector was operated in split mode at 250°C with a split ratio of 30:1. Helium was used as the carrier gas at a column flow rate of 1 mL/min. Chromatographic separation was performed using an Agilent HP-5MS capillary column (30 m × 250 µm × 0.25 µm) with 5% phenyl methyl siloxane. The initial oven temperature was maintained at 60°C for 2 min. It was subsequently increased to 180°C at 10°C/min, then to 280°C at 20°C/min. The final temperature was maintained for 5 min, giving a total run time of 24 min. The mass-spectrometer transfer-line temperature was maintained at 280°C. Mass spectra were acquired in scan mode over a mass-to-charge ratio of m/z 30–550, with a solvent delay of 2 min.

Fresh ethanol and recovered condensate were compared qualitatively using retention times and relative peak areas of detected chromatographic features. Tentative compound identities were assigned by mass-spectral-library matching. Because no certified calibration standards, internal standard, or independent water analysis were used, relative peak areas were not interpreted as ethanol concentration or purity.

RESULTS AND DISCUSSION

Effects of Rotary-Evaporation Conditions on Ethanol Recovery and Bioflocculant Performance

The rotary-evaporation conditions influenced condensate volume recovery, bioflocculant yield, and turbidity-removal performance differently, as presented in Table 3. Across all conditions, condensate volume recovery ranged from 62.5% to 77.5%, bioflocculant

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Table 3 Effects of rotary-evaporation conditions on condensate volume recovery and the resulting bioflocculant performance. Values are single determinations (n = 1); variability and statistical significance were not estimated

Vacuum Pressure (mbar)	Rotation Speed (rpm)	Bath Temperature (°C)	Condensate Volume Recovery (%)	Bioflocculant Yield (wt%)	Turbidity Removal (%)
100	150	50	62.5	**0.71**	57.56
125	150	50	75	0.5	55.49
150	150	50	75	0.4	56.66
100	200	50	65	0.38	59.47
100	250	50	62.5	0.62	60.14
100	250	40	62.5	0.64	**62.88**
100	250	60	**77.5**	0.54	54.05

yield ranged from 0.38% to 0.71%, and turbidity removal ranged from 54.05% to 62.88%. The condition that produced the largest condensate volume recovery did not produce the bioflocculant with the highest yield or turbidity-removal performance. In Table 3, the bold values identify the highest observed condensate volume recovery (77.5%), bioflocculant yield (0.71 wt%), and turbidity removal (62.88%) across the tested conditions.

This divergence highlights an important difference between solvent recovery and solvent fitness for reuse. According to Aboagye et al. [15], recovery volume alone is insufficient for assessing a recovered solvent because its composition and ability to meet downstream process requirements must also be considered. Chea et al. [14] similarly emphasised that solvent-recovery strategies should be evaluated according to both recovery efficiency and the quality requirements of the intended reuse application. In the present study, recovered condensate was not the final product but served as an antisolvent to precipitate active polymer fractions. Therefore, its capacity to produce an effective bioflocculant was more important than the recovered volume alone.

Effect of Vacuum Pressure

At 150 rpm and 50°C, increasing the pressure from 100 to 125 mbar increased ethanol recovery from 62.5% to 75.0%. A further increase to 150 mbar did not improve recovery. This plateau suggests factors other than pressure, such as evaporation duration, initial solvent composition, vapour production rate, condenser performance, or the volume of non-volatile residue—limited further solvent collection. The relationship between pressure and recovery was nonlinear because rotary evaporation depends on interactions among pressure, bath temperature, vapour–liquid equilibrium, heat transfer, and condensation capacity. Under a stronger vacuum, represented by the lower absolute pressure of 100 mbar, ethanol boils at a lower temperature. However, rapid boiling may cause foaming, entrainment, or vapour production beyond the instantaneous condensation capacity. Conversely, increasing the absolute pressure to 125 or 150 mbar may have moderated vapour generation and improved condensation.

Bioflocculant yield decreased from 0.71% at 100 mbar to 0.50% at 125 mbar and 0.40% at 150 mbar. Turbidity removal remained within a relatively narrow range of 55.49% to 57.56%. Hence, the greater solvent recovery at 125 and 150 mbar did not translate into improved precipitation or flocculation performance. Recovered solvents can contain water and soluble or volatile compounds originating from the process stream. Aboagye et al. [15] identified waste-stream composition and the quality required for reuse as central challenges in solvent recovery. Ruan et al. [18] also demonstrated that ethanol-containing streams generated during pectin processing may retain phenolic acids, flavonoids, and other extract-derived compounds. Although their study used citrus peel and an ethanol-salt separation system, it showed that ethanol streams associated with plant-polysaccharide processing may contain compounds other than ethanol and water. Such constituents could influence subsequent polysaccharide precipitation.

Effect of Rotation Speed

At 100 mbar and 50°C, ethanol recovery increased slightly from 62.5% at 150 rpm to 65.0% at 200 rpm before returning to 62.5% at 250 rpm. Rotation created a thin liquid film on the wall of the evaporation flask, increasing the surface area for heat and mass transfer. Nevertheless, the narrow recovery range indicated that increasing rotation beyond 150 rpm had little effect on the recovered volume under the tested conditions. The influence of hydrodynamic conditions on antisolvent processes is system-dependent. Carr et al. [16], for example, investigated hemicellulose precipitation using a spinning-disc reactor and found that disc speed had less influence on product recovery than the antisolvent-to-solvent ratio. Although their system differed from rotary evaporation, their results similarly suggested that increased rotational mixing does not necessarily increase polymer or solvent recovery when other process variables are controlling.

Bioflocculant yield decreased from 0.71% at 150 rpm to 0.38% at 200 rpm and then increased to 0.62% at 250 rpm. In contrast, turbidity removal increased progressively from 57.56% to 59.47% and 60.14%. This inverse response indicates that precipitate mass was not a reliable indicator of flocculation effectiveness. Ma et al. [8] reported that banana peel-derived BP50-2 is a high-molecular-weight heteropolysaccharide and identified adsorption bridging as its primary mechanism for flocculating kaolin particles. In polymer bridging, performance depends on characteristics such as molecular weight, chain length, charge, conformation, and the availability of adsorption sites. A greater precipitate mass does not necessarily contain a greater proportion of polymer chains with these favourable characteristics.

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Evidence from other polysaccharide systems supports this interpretation. Wang et al. [11] obtained different hawthorn-pectin fractions via ethanol precipitation and observed differences in their surface structure, molecular weight distribution, monosaccharide composition, and functional properties. Li et al. [12] similarly reported that gradient ethanol precipitation produced pectin fractions with different galacturonic-acid content, esterification, molecular weight, and adsorption performance. Yu et al. [13] further demonstrated that different ethanol levels altered the molecular weight, acetylation, and monosaccharide composition of *Dendrobium officinale* polysaccharides.

Although these studies investigated different plant materials and functions, they consistently demonstrated that ethanol precipitation can modify the composition and functionality of the recovered polymer fraction. The increase in turbidity removal at 250 rpm may therefore reflect differences in the effective ethanol concentration or selectivity of the recovered solvent rather than an effect of rotation speed on precipitate mass alone.

Effect of Water-Bath Temperature

Water-bath temperature produced the clearest trade-off between ethanol recovery and downstream bioflocculant performance. At 100 mbar and 250 rpm, recovery remained at 62.5% at 40 and 50°C but increased to 77.5% at 60°C. The greater thermal driving force at 60°C likely accelerated ethanol evaporation and increased the volume of condensate collected. However, bioflocculant yield decreased from 0.64% at 40°C to 0.54% at 60°C, while turbidity removal decreased from 62.88% to 54.05%. Therefore, the additional condensate collected at 60°C did not function as a more effective precipitating solvent. This finding should not be interpreted as direct thermal degradation of the final bioflocculant, because the spent ethanol-containing filtrate (not the subsequently produced bioflocculant) was heated during recovery. A more plausible explanation is that the higher temperature changed the condensate composition. Faster evaporation may have increased the co-recovery or mechanical entrainment of water and volatile plant-derived compounds. If the effective ethanol concentration decreased, the solvent may have precipitated a different quantity or fraction of polysaccharides.

The importance of ethanol concentration is well established in the literature. Tai et al. [10] explained that ethanol concentration is a critical parameter governing the precipitation of polysaccharides with different molecular sizes and structures. Huang et al. [9] similarly reported that different ethanol concentration ranges are used to isolate distinct polysaccharide fractions. More recent experimental evidence supports this principle. Yu et al. [13] found that increasing ethanol concentration changed the molecular weight and composition of precipitated polysaccharides, while Li et al. [12] showed that pectin fractions obtained at different ethanol levels possessed different adsorption properties.

Baghdadi et al. [19] also demonstrated that the purification method affected lime-peel pectin recovery, purity, appearance, and sugar content. They found that ethanol purification yielded higher recovery but also recovered more non-pectin components than an alternative protein-based purification method. This supports the present observation that a greater recovered or precipitated quantity does not necessarily indicate higher material quality. Mollea and Chiampo [20] further showed that ethanol use in cocoa-husk pectin production could be reduced without changing pectin characteristics, but only within a suitable solvent-to-extract range. At ratios below that range, relevant pectin losses occurred. Similarly, Carr et al. [16] found that increasing the ethanol antisolvent-to-solvent ratio from 1:1 to 10:1 increased hemicellulose recovery from approximately 4% to 32%. These findings demonstrate that ethanol quantity and concentration directly affect polymer recovery and quality.

Selection of the Recovery Condition

Among the conditions investigated, 100 mbar, 250 rpm, and 40°C produced the highest observed turbidity removal of 62.88%, with a condensate volume recovery of 62.5% and a bioflocculant yield of 0.64%. In comparison, the highest condensate volume recovery, 77.5%, was obtained at 60°C, but the resulting bioflocculant achieved only 54.05% turbidity removal. Therefore, the condition of 100 mbar, 250 rpm, and 40°C was selected for the recovered-to-fresh ethanol substitution experiment. This selection prioritised the intended downstream function of the recovered solvent while retaining moderate solvent recovery. The finding highlights an important process-design consideration: Maximising solvent recovery volume alone may be inappropriate when the recovered solvent is intended for a precipitation process whose product must retain a specific functionality.

In the present study, the selected condition is described as the most favourable condition among those tested, rather than an optimum condition. A one-factor-at-a-time design examines a restricted number of combinations and does not quantify interactions among pressure, rotation speed, and bath temperature. Replicated factorial or response-surface experiments would be required for formal process optimisation.

Effects of Recovered-to-Fresh Ethanol Ratio

The effect of progressively replacing fresh ethanol with recovered condensate was evaluated using the solvent recovered at 100 mbar, 250 rpm, and 40°C. Bioflocculant yield and turbidity-removal performance at the different recovered-to-fresh ethanol ratios are presented in Figure 2.

Bioflocculant produced using fresh ethanol alone (0:10) achieved a yield of 0.60 wt% and turbidity removal of 72%. Complete substitution with recovered condensate (10:0) produced a slightly higher yield of 0.64 wt% but reduced turbidity removal to 62.6%. This contrast indicates that recovered condensate remained capable of precipitating the bioflocculant; however, the amount recovered did not reflect its functional effectiveness. The lower turbidity removal may be associated with differences in solvent composition, including water accumulation or trace impurities that affected the type or quality of the precipitated polymer fractions.

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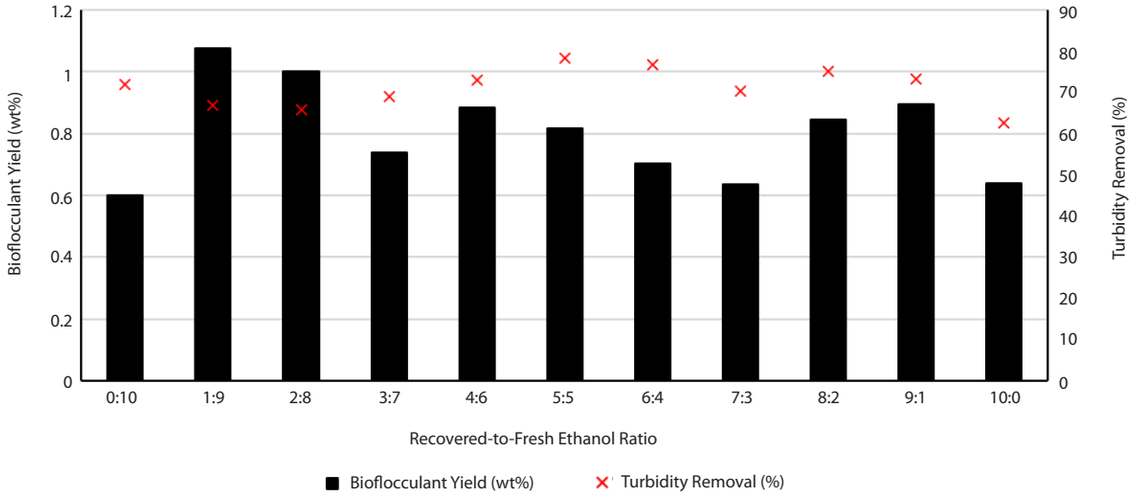


Figure 2 Effect of recovered-to-fresh ethanol ratio on bioflocculant yield and turbidity removal

Partial substitution produced non-monotonic responses in both bioflocculant yield and turbidity removal. Turbidity removal initially decreased to 65.7% at a recovered-to-fresh ethanol ratio of 2:8, increased to a maximum of 78.4% at 5:5, and remained comparatively high at 6:4 and 8:2, with removals of 76.8% and 75.0%, respectively. Thus, the highest observed turbidity removal was achieved when half of the fresh ethanol was replaced with recovered condensate.

The non-monotonic trend indicates that bioflocculant performance was not governed solely by the proportion of recovered condensate. If recovered condensate behaved only as a diluted or less-pure form of fresh ethanol, a progressive decline in performance would have been expected as its proportion increased. Instead, the observed fluctuations may reflect differences in final ethanol concentration, selective precipitation of polymer fractions, co-precipitation of non-active compounds, and experimental variability.

This interpretation is supported by Yu et al. [13], who demonstrated that ethanol concentration influenced the molecular weight and composition of precipitated polysaccharides. Li et al. [12] similarly found that gradient ethanol precipitation produced pectin fractions with different molecular characteristics and adsorption performance. Carr et al. [16] reported that the antisolvent-to-solvent ratio affected the recovery of hemicellulose from lignocellulosic hydrolysates. These studies demonstrate that ethanol concentration and solvent composition influence not only the quantity of polymer precipitated but also the characteristics of the recovered polymer fraction.

The highest bioflocculant yield of 1.08 wt% was obtained at the 1:9 recovered-to-fresh ethanol ratio, but the resulting bioflocculant achieved only 66.8% turbidity removal. In comparison, the 5:5 ratio produced a lower yield of 0.82 wt% but achieved the highest turbidity removal of 78.4%. Likewise, recovered condensate alone produced a slightly higher yield than fresh ethanol alone, but substantially lower turbidity removal. These results confirm that bioflocculant yield was not directly representative of functional performance. The higher yield at 1:9 may have resulted from the co-precipitation of compounds that contributed to the dried mass but had limited flocculating activity. Conversely, the 5:5 solvent composition may have favoured the precipitation of polymer fractions with more effective adsorption and bridging characteristics. However, this explanation remains tentative because the precipitates were not characterised by Fourier-transform infrared spectroscopy, molecular weight analysis, carbohydrate composition analysis, or zeta potential measurement.

Overall, partial substitution of fresh ethanol with recovered condensate was more favourable than complete replacement. Among the ratios evaluated, the 5:5 mixture provided the most promising balance between reducing fresh ethanol consumption and maintaining effective turbidity removal. These preliminary findings demonstrate the feasibility of incorporating recovered condensate into the production of banana peel-derived bioflocculants and provide a basis for further process refinement and repeated-cycle evaluation.

Gas Chromatography-Mass Spectrometry Comparison of Fresh and Recovered Condensate

The total ion chromatograms of fresh ethanol and the recovered condensate were qualitatively compared using GC-MS. Table 4 summarises retention times and relative peak-area distributions. Both samples had the same dominant detected peak at 2.520 min. Its relative area was 98.92% in fresh ethanol and 95.53% in recovered condensate, while the combined area of minor detected peaks increased from 1.08% to 4.47%. These normalised areas describe only detected chromatographic features under the stated method and are not measurements of solvent purity.

The identical retention time and tentative library match suggest that the same dominant detected volatile compound was present

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Table 4 GC-MS profile comparison of fresh and recovered condensate

Sample	Retention Time of Dominant Peak (min)	Dominant Peak Area (%)	Combined Minor Peak Area (%)	Tentative Library Match
Fresh ethanol	2.52	98.92	1.08	1,1-diethoxyethane
Recovered condensate	2.52	95.53	4.47	1,1-diethoxyethane

in both samples. Nevertheless, the increase in combined minor peak area indicates that the recovered condensate had a more complex volatile profile than fresh ethanol. These minor components may have originated from the banana-peel extract, the precipitation process, solvent handling, or compounds carried over during rotary evaporation. Plant-extraction streams can contain a range of extract-derived constituents; Ruan et al. [18], for example, detected phenolic acids, flavonoids, and other compounds in ethanol-containing streams generated during pectin processing.

The chromatographic differences may partly explain the variation in bioflocculant performance. Bioflocculant precipitated using fresh ethanol alone achieved 72.0% turbidity removal, whereas complete substitution with recovered condensate resulted in a lower removal of 62.6%. Although recovered condensate remained capable of precipitating a functional bioflocculant, its higher contribution from minor detected compounds and possible differences in its ethanol-water composition may have affected the precipitation selectivity and characteristics of the recovered polymer fraction.

This interpretation is consistent with previous studies, which showed that solvent composition influences polysaccharide precipitation. Tai et al. [10] identified ethanol concentration as a critical parameter affecting the precipitation of polysaccharides with different molecular sizes and structures. Yu et al. [13] similarly demonstrated that changes in ethanol concentration altered the molecular weight, acetylation, and monosaccharide composition of precipitated polysaccharides. Therefore, the lower performance observed with recovered condensate alone does not necessarily indicate that less material was precipitated. Indeed, recovered condensate alone produced a bioflocculant yield of 0.64 wt%, slightly higher than the 0.60 wt% obtained using fresh ethanol, but its turbidity-removal performance was lower. This further demonstrates that bioflocculant yield did not directly represent functional quality.

Blending recovered condensate with fresh ethanol improved the observed performance. The 5:5 recovered-to-fresh ethanol mixture produced the highest turbidity removal of 78.4%, compared with 72.0% for fresh ethanol alone and 62.6% for recovered condensate alone. The addition of fresh ethanol may have increased the effective ethanol concentration and diluted the minor constituents present in the recovered solvent, thereby creating more favourable conditions for precipitating active polymer fractions. However, this proposed mechanism could not be confirmed from GC-MS alone because the ethanol and water concentrations of the samples were not quantitatively determined.

The dominant peak detected in both chromatograms was tentatively assigned to 1,1-diethoxyethane rather than ethanol. This compound, also known as acetaldehyde diethyl acetal, has previously been identified as a volatile constituent of bioethanol samples [21]. However, because the GC-MS method employed a 2-min solvent delay, the early-eluting ethanol signal may have been excluded or suppressed to protect the detector from solvent overload. Thus, the dominant recorded peak should not be interpreted as the principal component of the original sample.

In addition, the relative peak-area values do not represent absolute ethanol purity. They describe only the proportional areas of compounds detected under the selected analytical conditions. Quantitative determination of ethanol concentration would require calibration using certified ethanol standards and an appropriate internal standard. Measurement of water content would also be necessary to determine whether dilution contributed to the lower performance of recovered condensate. Overall, the GC-MS results show that fresh and recovered condensate shared the same dominant detected chromatographic feature, while recovered condensate contained a greater relative contribution from minor volatile components. When analysed together with the jar-test results, the findings suggest that recovered condensate was suitable for partial reuse but less effective as a complete replacement for fresh ethanol. Partial blending, particularly at the 5:5 ratio, appeared to moderate the compositional differences and provided the most promising balance between reducing fresh ethanol consumption and maintaining bioflocculant performance.

CONCLUSIONS

The results suggest that recovered ethanol-containing condensate should be evaluated by its suitability for downstream precipitation, alongside condensate volume recovery. The condition yielding the greatest condensate recovery (77.5% at 100 mbar, 250 rpm, and 60°C) did not produce the highest turbidity removal. Instead, 100 mbar, 250 rpm, and 40°C gave the highest observed removal among the recovery conditions (62.88%), and this condition was selected for the substitution experiment. Bioflocculant yield did not consistently track turbidity removal. Among the tested solvent ratios, the 5:5 recovered-to-fresh ethanol blend achieved the highest observed removal (78.4%) while replacing half of the fresh ethanol used for precipitation. This ratio represents a promising tested composition, rather than a statistically validated optimum. Qualitative GC-MS indicated differences in the relative contribution of minor detected peaks but did not establish ethanol purity, water content, or the causes of performance differences. Overall, the results provide preliminary support for partial condensate reuse.

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The one-factor-at-a-time design and single determinations require follow-up through replicated factorial experiments, quantitative solvent analysis, bioflocculant characterisation, dose-response evaluation, and repeated recovery–reuse cycles. Techno-economic and life-cycle assessments are needed to evaluate scalability, economic viability, and environmental benefits.

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CONFLICT OF INTEREST

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

AUTHORS' CONTRIBUTION

Alifah Ilyana Abdul Razak collected and analysed the data, and prepared the first draft of the manuscript. Kiew Peck Loo and Tan Lian See critically reviewed and revised the manuscript for intellectual content. All authors read and approved the final manuscript.

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