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Impact of Western Ghats Geography, Drying Methods and Solvent Polarity on Phytochemical Composition and Antioxidant Activity of *Baccaurea courtallensis* Fruit Rind Extract

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Abstract

Baccaurea courtallens is tree is an endemic species of fruit bearing plant growing in regions of Western Ghats. The present study investigates the influence of geographical variation, drying methods, and solvent polarity on the extraction yield, phytochemical composition, and antioxidant activity of fruit rind extracts. Samples collected from different regions of Western ghats of Kerala revealed that those from the Idukki district exhibited higher levels of total polyphenols, flavonoids, and anthocyanins, indicating the significant role of environmental factors in secondary metabolite accumulation. Among the drying techniques evaluated, continuous hot air drying demonstrated superior preservation of bioactive compounds compared to sun drying and dehumidified drying, although sun drying resulted in higher overall extraction yield. Solvent extraction studies showed that water produced the highest extract yield, while ethanol exhibited greater selectivity and efficiency in extracting key phytochemicals. Antioxidant activity assessed by the DPPH assay revealed that ethanol extracts possessed the lowest IC_{50} value (28 µg/mL), confirming their higher radical scavenging potential. A strong correlation was observed between phytochemical content and antioxidant activity, emphasizing that extraction efficiency depends more on compound specificity than total yield. Overall, the combination of from the Idukki region samples, continuous hot air drying, and ethanol extraction was identified as the optimal condition. The findings highlight the importance of optimizing pre-processing and extraction parameters to obtain phytochemical-rich extracts for potential applications in food, nutraceutical, and pharmaceutical industries.

Keywords

Western Ghats Geography, Baccaurea courtallensis, Fruit Rind Extract.

INTRODUCTION

The western Ghats which is recognised as a UNESCO world heritage site is home to many endemic species of plants. These plants are of greater nutraceutical and medicinal importance. *Baccaurea courtallensis* (*B. courtallensis*) is a fruit bearing tree which is endemic to Western ghats. This plant belongs to Euphorbiaceae (Phyllanthaceae) family. Its fruits are sour and red and they occur in clusters. In Karnataka and Kerala, it is referred to as Kolikukku and Mootipazham, respectively. Tribal communities have been used the fruits and other parts of this plant for nutritional and some medicinal purposes. They used this plant parts for treating ulcer, diarrhoea, piles and dysentery which shows light into the pharmacological importance of this plant [1].

Studies have revealed that a vast variety of phytochemicals, particularly secondary metabolites, are identified in and separated from plants. To a greater or lesser extent, these phytochemicals have many different activities, including analgesic, anti-inflammatory, anti-tumor, antiviral, anticancer, and anti-bacterial [2,3]. Flavonoids, phenols and phenolic glycosides, saponins and cyanogenic glycosides, stilbenes, tannins, nitrogen compounds (alkaloids, amines, betalains), terpenoids, and several other endogenous metabolites are notable examples of these phytochemical substances [4,5].

As it is growing in the forest region people are not common to *B. courtallensis* and very few scientific studies are available on this. Preliminary studies have reported the presence of diverse phytochemicals in *B. courtallensis*, including phenolics, flavonoids, tannins, and saponins. Preliminary phytochemical screening revealed that there are lot of phytochemicals in the leaves of this plant and the extract showed antioxidant activity [6]. Anti-bacterial activity was reported with the extracts made from fruit rinds of *B. courtallensis*. Phytochemical analysis showed the presence of flavonoids, tannins and steroids in the extracts made using methanol and benzene [7]. Cholesterol lowering activity was also described of the fruit extract of *B. courtallensis*. Water extracts of the fruits were screened for phytochemical constituents and showed the presence of alkaloids, flavonoids, terpenoids, saponins, phlobatannins, coumarin, anthocyanin, leuco-anthocyanin, phenols and carbohydrates [8]. Underutilised edible fruits of *B. courtallensis* from Agasthyamala forest reserve exhibited antioxidant activity [9]. However, the available studies are not systematic and not investigating the specificity of regions and different methods used for recovering phytochemicals.

The secondary metabolites are formed by the defence

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mechanism of plants. Geographical features such as climate, soil composition and altitude will affect the formation of secondary metabolites. The studies conducted in other fruits showed that variation of geography will affect the biological constituents in the plants [10][11][12]. Such type of studies is not available in the *B. courtallensis*. Method of drying will have an impact on the preservation and degradation of phytochemicals. The drying methods like shade drying sun drying and mechanical drying showed impact in the phytochemicals composition and antioxidant activity of other fruits [13][14]. In the case of *B. courtallensis*, no such studies are available for drying methods. Polarity of solvents play an important role in the extraction of phytochemicals from plant parts. In the preliminary studies on *B. courtallensis* specific solvents are used and no comparative study is available. Fruits rinds are considered as waste in most of the case. When going through recent studies on *Punica granatum* and *Garcinia cambogia*, it was observed that fruit rind contains higher amount of phytochemicals [15], [16].

Existing literature defines *B. courtallensis* as a promising source of phytochemicals. But only preliminary investigations are available on the antioxidant potential without considering the effect of geographical difference, method of drying and solvent polarity in extraction. The aim of the present study is to evaluate the effects geographical difference, different drying mechanism and polarity of the solvent for extraction on the phyto-chemical composition and antioxidant activity of the extract of fruit rinds of *B. courtallensis.*

MATERIALS AND METHODS

Collection of Fruits

The fruits were collected from three different regions of Western Ghats. It was collected from nearby areas of Agasthiamala in Thiruvanthapuram (TVM), Thekkadi in Idukki (IDK) and Parambikkulam in Palakkad (PKD). Around 20 kg of fruit was collected from each region with the help of tribal people. The fruits were washed with water after removing the damaged ones, and the fruit rinds were separated from seeds. Percentage of fruit rind and seed were noted for each variety and fruit rinds were taken for drying.

Drying of the Fruit Rinds

Three different drying methods were conducted. Sun drying, dehumidification and continuous hot air drying was the drying method used. About 3 kg fresh fruit rind was used for each experiment. Dehumidified drier (Bryair) was set at 50^0C and the material is evenly placed in the trays inside the drier and dried for 72 hours to reach the moisture level of less than 15% and the Dried material was coded as DHD. Continuous hot air drier (Ayush driers) was used for the next method. The temperature given was 75^0C and drying time was 3 hours to reach the moisture level of less than 15% and the Dried material was coded as CHAD. Sun drying was conducted by uniformly distributing the fruit rinds in stainless steel trays and kept for drying in sun. It took about 3 days to reduce the moisture level of about 15% and the Dried material was coded as SD.

Solvent Extraction

The variety and drying method were selected based on the phytochemical evaluation of the fruit rind. The IDK region was identified as the most suitable geographical source within the Western Ghats, while CHAD was found to be the most effective drying method. Consequently, fruit samples obtained from the IDK region and processed using the CHAD drying method were selected for subsequent extraction studies.

Before extraction the dried fruit rinds were processed using lab flaker to get uniform flakes.100g flakes were transferred into a separating funnel and 400 ml solvent was added. It is kept for one hour with occasional percolation. The miscella was collected to a clean round bottom flask. This was repeated for 4 times and all the miscella collected and filtered through filter paper to remove solid residues. The miscella was evaporated using a rotary evaporator to remove the solvent and get dry extract. The experiment was done with acetone, ethyl acetate, ethanol and water. Repeatability of the experiments were conducted with 4 number of experiments.

Estimation of Total Polyphenols

Estimation of total poly phenols was done using Folin–Ciocalteu method [17]. About 3- 4 g of fruit rind powder was accurately weighed and 25 mL of 80% methanol was added to it in a conical flask. The mixture was sonicated for 20 minutes to facilitate extraction and then centrifuged at 4000 rpm for 10 minutes. and all the clear supernatant was collected. This is repeated for two more times. All the supernatant was collected in a 100 ml standard flask and made up to the mark with 80% Methanol and this solution is used for the estimation of total polyphenols. In the case of extract About 0.2g of the extract is accurately weighed is dissolved in 100 ml 80% methanol and used for estimation. A stock solution of gallic acid (1 mg/mL) was prepared in methanol. Working standards ranging from 20 to 200 µg/mL were prepared by serial dilution and used to construct the calibration curve. 0.5 mL of the fruit rind extract (or standard solution) was mixed with 2.5 mL of 10% Folin–Ciocalteu reagent. The mixture was allowed to stand for 5 minutes at room temperature, after which 2 mL of 7.5% sodium carbonate solution was added. The reaction mixture was incubated in the dark at room temperature for 30 minutes to allow complete colour development. Absorbance was measured at 765 nm using a UV–Vis spectrophotometer against a reagent blank. The calibration curve was plotted using gallic acid standards, and the total polyphenol content of the fruit rind extract was calculated from the regression equation.

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$$\%\ Total\ poly\ phenols\ = \frac{C\ x\ V\ x\ D\ X100}{W}$$

Where, C = concentration of polyphenols obtained from the calibration curve (mg GAE/mL of extract), V = volume of extract used for the assay (mL), Dilution factor and W = weight of fruit powder taken for extraction (g) or weight of the extract (g)

Estimation of Flavonoids

Aluminium chloride method was used to estimate the percentage of flavonoids of fruit powder and extracts [18]. A stock solution of quercetin (1 mg/mL) was made in methanol and then diluted to make working standards that range from 20 to 100 µg/mL. To make the calibration curve, 1 mL of each standard solution was put in a different test tube. Then, 1 mL of 10% aluminium chloride, 1 mL of 1 M potassium acetate, and 2 mL of methanol were added to each tube. The mixture is left at room temperature for 30 minutes, and the absorbance is measured at 415 nm against a blank reagent. The standard calibration curve shows the relationship between concentration and absorbance.0.1 g of the extract is dissolved in 10ml Methanol. 1 mL of the extract is treated the same way by adding aluminium chloride, potassium acetate, and methanol, and then incubating for 30 minutes. The absorbance is measured at 415 nm. The calibration curve was used to figure out the amount of flavonoids present in the extract, which shown as mg quercetin equivalent (QE) per gram of extract.

$$\%\ Flavonoids\ = \frac{C\ x\ V\ x\ D\ \ x100}{W}$$

Where, C = Concentration from calibration curve (mg/mL, usually expressed as quercetin equivalent), V = Volume of extract (mL), D = Dilution factor, W = Mass of sample used (mg or g)

Total Anthocyanin Content

Total anthocyanin content was estimated using method using buffer solution at pH 3 by measuring absorbance value using UV-Visible spectrophotometer [19]. The pH 3 buffer was prepared using citric acid (Merck) and trisodium citrate (Merck). About 14.8g of citric acid and 38.2g of trisodium citrate is weighted using analytical balance (sartorius) and makeup to 500ml using distilled water.

The dried raw material of each sample was powdered. About 5g of each sample was taken and 30 ml of distilled water sonicated for 15 minutes and filter the top portion into a 250ml standard flask. Similarly, washes were given till all the colour is eluted from the raw material. Washes were collected and make up to 250ml using water. Give dilution using pH 3 buffer so that the absorbance is in the range of 0.2 and 0.8. Absorbance of the solution is taken using UV\visible spectrophotometer (Shimadzu) within the 515–535 nm wavelength range and the total anthocyanin is calculated. In the case of extract, a certain quantity of the extract accurately weighed into a standard flask and dissolved in Buffer pH 3 and same procedure repeated as above.

$$\%\ of\ anthocyanin\ =\ Absorbance\ x\ \frac{dilution}{Weight}\ x\ 300$$

Antioxidant Activity by DPPH Assay

2,2-diphenylpicrylhydrazyl (DPPH), a stable free radical, was used to measure the antioxidant activity of the extracts [20]. A standard solution of DPPH was by dissolving 0.02 g of DPPH in 100 mL of methanol, taking 10 mL of that solution, and then adding more methanol to make 100 mL. The sample solution was made by mixing 0.25 g of the sample with 25 mL of methanol. Different concentrations of the sample solution were prepared in 2 mL Eppendorf tubes by diluting with methanol. 100 µL of DPPH solution and 100 µL of sample solution of different concentration were pipetted into microplate wells. The plates kept at 25 °C for 20 minutes in the dark. Absorbance was measured at 517 nm using a SpectraMax i3X multi-mode microplate reader (Molecular Devices). The percentage inhibition at each concentration was calculated. A graph was plotted with concentration on the x-axis and percentage inhibition on the y-axis. The IC50, which indicates the concentration required to quench 50% of the initial DPPH, was determined from the graph.

RESULTS AND DISCUSSION

Characteristics of Fruits from Various Region

The assessment of the fruit's physical attributes indicated that the fruit from TVM exhibited a dark pink hue. The fruits from the other two locations, IDK and PKD, exhibited a faint pink hue. The percentage of fruit rind was highest in the IDK variety (65.2%), followed by PKD (62.9%) and TVM (60.1%). The moisture content was highest in the TVM variety at 84%, followed by PKD at 83% and IDK at 80%. Table 1. Summarises the attributes of fruits from several geographical regions of the Western Ghats.

Table 1. Characteristics of fruits from different geographical regions

Geographical region	Fruit Rind %	Seed %	Moisture content %
TVM	60.1	39.9	84
IDK	65.2	34.9	80
PKD	62.9	37.1	83

Effect of Geographical Variation and Drying Methods on the Bioactive Compounds

Influence of geographical variation from three regions namely TVM, EDK and PKD and three different drying methods - CHAD, SD and DHD on the phytochemicals of *B. courtallensis* fruit rind were evaluated. Table 2 represents the data of yield, flavonoid content, total poly phenol content and anthocyanin content from three geographical regions and dried using three different methods. Fig. 1 & Fig. 2 is the graphical representation of yield and phytochemical constituents respectively.

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Table 2. Yield and Phytochemical content from various regions using different drying methods

Geographical Region	Drying Method	MC %	Yield %	Flavonoid content (%)	Total poly phenol content (%)	Anthocyanin content (%)
TVM	CHAD	11.1	10.8	0.88	3.95	0.14
	SD	15.6	14.2	0.59	2.98	0.10
	DHD	13.1	11.8	0.85	3.95	0.14
EDK	CHAD	10.4	14.6	0.98	4.23	0.17
	SD	16.2	15.6	0.67	3.20	0.11
	DHD	12.1	14.8	0.89	3.95	0.15
PKD	CHAD	10.6	12.0	0.87	3.78	0.16
	SD	15.5	12.7	0.64	2.56	0.11
	DHD	12.8	12.3	0.88	3.50	0.15

The drying method and geographic origin of the samples significantly influenced the yield of fruit rinds, quantified as recovery post-drying. Although SD produced the greatest mass, this is ascribed to the elevated moisture content of the dry materials. The increased yield results from sun drying's prolonged moisture loss, potentially resulting in incomplete drying and a greater residual mass. Conversely, continuous hot air drying yielded the lowest moisture content values (10.8–14.6%), indicating superior moisture removal due to the consistent airflow and temperature. In comparison to alternative approaches, dehumidified drying exhibited moderate drying efficiency, evidenced by its intermediate yield values (11.8–14.8%).

Geography positively influenced the results, with samples from IDK consistently exhibiting superior yield values across all drying processes, followed by samples from TVM and PKD, respectively. This discrepancy may arise from variations in the initial moisture content, structural composition, and growth circumstances of the plant material. The results indicate that the increased yield is primarily attributable to the retention of residual moisture rather than the actual solid content. Conversely, reduced output from controlled drying techniques results in more efficient dehydration of the fruit rind.

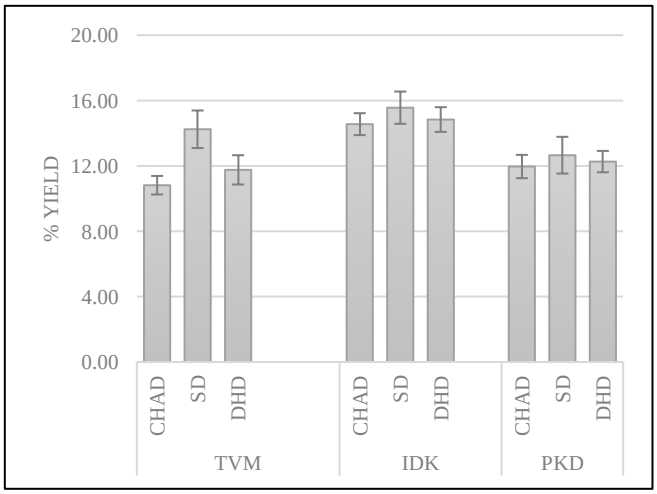

Figure 1. Effect of various Geographical region and drying methods on the yield of dried fruit rinds ((Data are presented as mean ± standard deviation of the mean (n = 4))

The phytochemicals namely the flavonoids, total polyphenols, and anthocyanins showed variation based on geography and drying method. Fig. 2 explains the impact of geographical variation and method of drying on the flavonoid content, total polyphenols, and anthocyanin content of the samples. A distinctive difference in retaining the phytochemicals was observed across the three drying methods, CHAD, SD, and DHD, in all geographical regions.

Among the drying procedures, CHAD demonstrated consistent retention of beneficial chemicals, evidenced by the considerably taller bars for flavonoids, total polyphenols, and anthocyanins across all locations. The samples from Idukki (IDK) had the highest values, with flavonoid concentration at 0.98%, total polyphenols at 4.23%, and anthocyanins at 0.17%. This suggests that regulated thermal processing reduces oxidative and enzymatic deterioration, thereby more effectively conserving phytochemicals. The retention of phytochemicals in the SD technique was minimal across all parameters, as evidenced by the shortest bars in the graph. The overall polyphenol content exhibited the lowest value specifically in the PKD, where it reduced to 2.56%. This reduction would arise from prolonged exposure to sunshine and oxygen, which promote the breakdown of phenolic chemicals. The anthocyanin content had the lowest value due to its rapid degradation in sunshine. DHD exhibited moderate values between CHAD and SD, suggesting that moisture-controlled drying conditions can preserve bio actives to a certain degree, albeit less successfully than CHAD. This trend indicates that drying processes significantly influence the retention of phytochemicals across the region.

Geographical variation significantly influenced the outcome. IDK samples consistently exhibited elevated amounts of all bioactive chemicals compared to TVM and PKD samples. This may result from variations in environmental conditions such as climate, altitude, and soil composition, which are recognised to influence the production of secondary metabolites. The graphs clearly indicate that CHAD is the optimal method for drying fruits to preserve flavonoids, total polyphenols, and anthocyanins. The IDK samples exhibited the highest phytochemical potential. This study demonstrates that the fruits from the Idukki region and the continuous drying method are

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advantageous for industrial application research. Additional research was conducted using his sample.

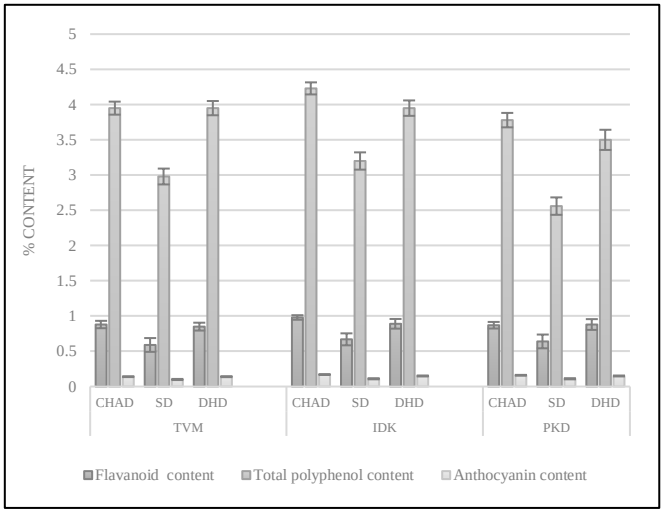

Figure 2. Effect of phytochemicals with geographical variation and drying methods ((Data are presented as mean ± standard deviation of the mean (n = 4))

Effect of Solvent Polarity on Extraction of Phytochemicals

The solvent polarity has a great significance on the extraction efficiency of phytochemicals. which is attributed to the solubility and selectivity of the compounds. The current extraction experiments evaluated the influence of different solvents on extraction yield, total polyphenols, flavonoids, and anthocyanins to identify the most suitable solvent system for optimal phytochemical recovery.

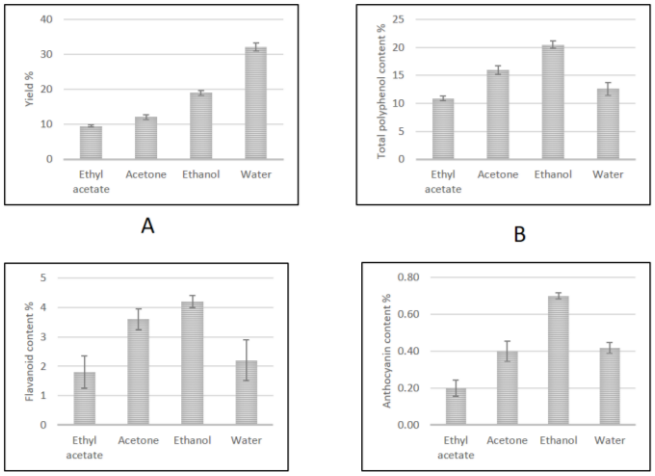

Figure 3. Effect of Solvent Polarity on yield (A), Total Polyphenols (B). Flavonoids (C) and Anthocyanin (D) ((Data are presented as mean ± standard deviation of the mean (n = 4))

Graph A shows that the highest extraction yield was obtained using water with a value of 32.2%, followed by ethanol at 19 %, acetone at 12.1%, and ethyl acetate at 9.5%. The higher yield in water can be attributed to its strong polarity, which enables the extraction of a broad range of hydrophilic constituents such as sugars, proteins, and other soluble compounds; however, this does not necessarily indicate selective extraction of bioactive compounds. In contrast, Graph B demonstrates that ethanol exhibited the highest total polyphenol content at 20.5%, followed by acetone at 16%, water at 12.6%, and ethyl acetate at 10.9%, indicating a clear difference from the yield pattern. This suggests that moderately polar solvents are more effective in extracting phenolic compounds, with ethanol showing superior efficiency due to its ability to solubilize both polar and moderately non-polar phenolic compounds, whereas water likely co-extracts non-phenolic impurities, thereby reducing the relative polyphenol concentration.

A similar trend is observed in Graph C for flavonoid content, where ethanol showed the highest value of 4.2%, followed by acetone at 3.6%, water at 2.2%, and ethyl acetate at 1.8%. This indicates that flavonoids are predominantly moderately polar compounds, making ethanol the most suitable solvent, while acetone also demonstrates reasonable efficiency, unlike water and ethyl acetate whose polarity differences limit their effectiveness. Likewise, Graph D shows that anthocyanin content was highest in ethanol at 0.7%, followed by water at 0.42%, acetone at 0.4%, and ethyl acetate at 0.2%. Anthocyanin, being polar flavonoid pigments, are better extracted using moderately polar solvents such as ethanol, which also provides improved stability and selectivity. Although water is highly polar, its lower efficiency may be due to the co-extraction of unwanted substances and the reduced stability of anthocyanin in highly aqueous environments.

The recovery data as explained in Fig. 4 further substantiates the significant impact of solvent polarity on the selective extraction of phytochemicals. The highest total polyphenol recovery was observed in water with a value of 95.9%, followed closely by ethanol with 92.1%, indicating that highly polar solvents are more efficient in extracting phenolic compounds. However, this may also suggest the co-extraction of non-phenolic impurities in water. In the case of flavonoids, ethanol exhibited the highest recovery at 81.4%, followed by water at 72.3%, while acetone and ethyl acetate showed comparatively lower recoveries of 44.3% and 43.6%, respectively. This pattern indicates that flavonoids are predominantly moderately polar compounds that are best extracted using ethanol. Similarly, anthocyanin recovery was highest in water at 79.6%, with ethanol showing a nearly comparable value of 78.2%, which can be attributed to their polar nature; however, ethanol offers better stability and selectivity during extraction.

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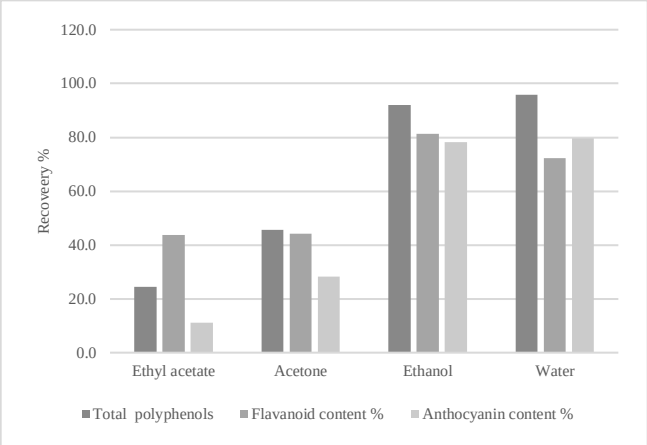

Figure 4. Effect of Solvent Polarity on the Recovery of Phytochemicals ((Data are presented as mean ± standard deviation of the mean (n = 4))

Overall, it was observed that ethanol is the best solvent because it has a good balance of efficiency, selectivity, and the ability to recover a wide range of bioactive compounds with little interference. Water does show slightly higher recovery percentages for some compounds. There will be room for more extraction studies to find the best mix of ethanol and water to get all the phytochemicals back.

Effect of Solvent Polarity on Antioxidant Activity

The IC_{50} values of extracts obtained with different solvents revealed marked variation in antioxidant activity. The ethanol extract exhibited the lowest IC_{50} value at 28 µg/mL, indicating the highest antioxidant potential among all the solvents tested. This was followed by the water extract with an IC_{50} value of 46 µg/mL and the acetone extract with 52 µg/mL, whereas the ethyl acetate extract showed the highest IC_{50} value at 137 µg/mL, reflecting the lowest antioxidant activity. The observed trend of ethanol showing the greatest activity, followed by water and acetone, with ethyl acetate being the least effective, clearly demonstrates that extracts obtained using moderately polar solvents possess superior radical scavenging capacity.

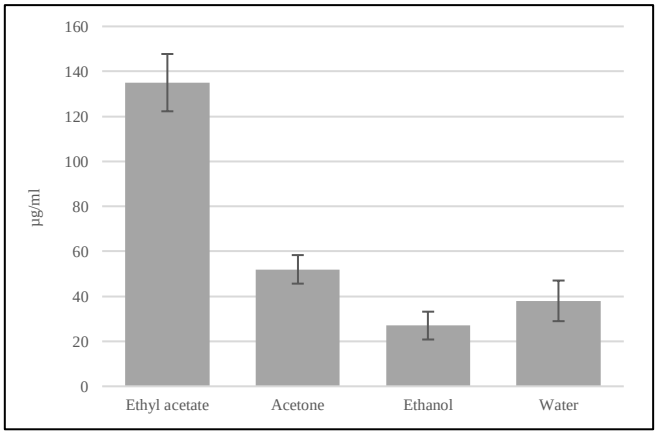

Figure 5. Effect of Solvent Polarity on Antioxidant Activity ((Data are presented as mean ± standard deviation of the mean (n = 4))

The DPPH assay evaluates antioxidant activity based on the ability of compounds to donate hydrogen atoms or electrons to the DPPH radical, thereby reducing its absorbance. The superior activity of the ethanol extract indicates a higher concentration of hydrogen-donating bioactive constituents, particularly polyphenols, flavonoids, and anthocyanins, which were also reported to be most abundant in ethanol in previous studies. This strong correlation suggests that these phytochemicals are primarily responsible for the observed antioxidant activity. The water extract also demonstrated considerable radical scavenging potential; however, its comparatively higher IC_{50} value indicates lower effectiveness than ethanol, possibly due to the co-extraction of non-antioxidant compounds that dilute the active constituents. The acetone extract exhibited moderate activity, suggesting partial extraction of antioxidant compounds. In contrast, ethyl acetate, due to its lower polarity, was less efficient in extracting key polar antioxidant molecules, resulting in reduced activity.

The results show that antioxidant activity goes up as the extraction efficiency of phenolic compounds goes up. The trend (ethanol > water > acetone > ethyl acetate) shows that ethanol is the best solvent for extracting strong natural antioxidants, which the DPPH assay confirms.

CONCLUSION

The current study illustrates that geographical variation, drying methods, and solvent polarity collectively affect the extraction yield and phytochemical composition of fruit rind extracts of *B. courtallensis*. Samples from the Idukki region (IDK) always had higher levels of total polyphenols, flavonoids, and anthocyanins than samples from other regions. This shows how much environmental conditions affect the accumulation of secondary metabolites. Drying methods were very important for keeping phytochemicals, and continuous hot air drying (CHAD) was better at keeping bioactive compounds than sun drying and dehumidified drying. Sun drying produced a higher extraction yield, but it also caused a lot of phytochemicals to break down, probably because they were exposed to heat, light, and oxygen for too long. Dehumidified drying worked okay, but it wasn't as good as CHAD at keeping phytochemicals safe.

The efficiency and selectivity of extraction were greatly impacted by solvent polarity. Water had the maximum extraction yield and recovery, but because non-bioactive components were also extracted, it had lesser selectivity. Ethanol, on the other hand, turned out to be the most efficient solvent, producing larger concentrations of anthocyanins and polyphenols and exhibiting superior antioxidant activity, as shown by lower IC_{50} values in the DPPH experiment. The restricted extraction of polar bioactive chemicals was shown by the low efficiency of semi-polar solvents such ethyl acetate. The results show a strong link between the amount of phytochemicals in a substance and its antioxidant activity. This shows that the amount of extract does not determine its quality. This study found that the best way to get the most

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phytochemicals and antioxidants out of IDK samples is to process them through CHAD and extract them with ethanol. These findings establish a scientific foundation for the standardisation of extraction protocols and endorse the use of fruit rind extracts as a natural source of antioxidants in food, nutraceutical, and pharmaceutical contexts.

Future research should concentrate on using advanced methods like ultrasound- or microwave-assisted extraction could make things even more efficient and cut down on processing time. Different solvent ratios can be systematically tested to get the most polyphenols, flavonoids, and anthocyanins back. Furthermore, comprehensive characterisation and isolation of bioactive compounds utilising LC–MS/MS and analogous techniques would facilitate the identification of essential functional constituents. It is also important to look into the extracts' stability and bioactivity (both in vitro and in vivo). These strategies will facilitate the advancement of refined, scalable methodologies for food, nutraceutical, and pharmaceutical uses.

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