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Research Article

Modelling the effect of microwave-assisted extraction parameters on polyphenol yield from *Persea americana* leaf, seed and stem bark

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Abstract

The antioxidant and anti-inflammatory properties of polyphenols from plant extracts have driven interest in plant-based alternatives for the management of diabetes mellitus. *Persea americana* (avocado) leaf, seed and stem bark are traditionally used in Cameroon for diabetes management. The effects of microwave assistance extraction conditions on polyphenol compounds have not been scientifically established. This study applied Response Surface Methodology (RSM) using a Central Composite Design to study the effect of Microwave Assisted Extraction condition parameters - power (30 –70 %W), time (5 –10 min), volume of solvent (100 –200 mL) and particle size of ≤ 0.25 mm and 0.25 < size ≤ 0.45 mm of oven dried powder of *P. americana* for maximizing polyphenol yields. A total of 17 experimental runs were conducted, and the polyphenol content was quantified by Folin–Ciocalteu method. Leaf extracts showed the highest polyphenol concentrations (up to 23.78 ± 0.01 μg GAE/mL) compared to those of seeds and stem bark. Solvent volume was identified as the most significant factor ($p < 0.05$), with a significant negative linear effect across samples and also a quadratic positive effect, except for stem bark 0.25 ≤ size ≤ 0.45. Finer particle sizes (≤ 0.25 mm) significantly enhanced the extraction efficiency. The developed regression models demonstrated high predictive accuracy, with values ranging from 0.89 to 0.96 and a low average absolute deviation (AAD < 0.15). These findings provide a robust, validated extraction protocol for producing polyphenol-rich *P. americana* extracts with potential antidiabetic activity, supporting their development into standardised phytotherapeutic formulations.

1. Introduction

Polyphenols are naturally occurring compounds found in plant foods, such as fruits, vegetables, herbs, spices, tea, dark chocolate, and wine [1]. More than 8,000 polyphenols have been identified. They can be further categorized into 4 main groups: Flavonoids (quercetin, kaempferol, catechins, and anthocyanins), phenolic acids (ferulic and chlorogenic acids in coffee and cereal grains), which account for around 60% and 30% of all polyphenol, respectively; polyphenolic amides (capsaicinoids in chili peppers and avenanthramides in oats) and other polyphenols, which include stilbenes in grapes and berries, resveratrol in red wine, ellagic acid in berries, curcumin in turmeric, and lignans in flax seeds, and sesame seeds [1-3]. Several studies have reported the antioxidant and anti-inflammatory properties of polyphenols, especially flavonoids and phenolic acids, which can be used in the management of type 2 diabetes mellitus (T2DM) [4, 5]. They can protect against oxidative stress, improve insulin sensitivity, regulate glucose metabolism, and inhibit glucose absorption from the gut [6-8]. They enhance glucose uptake by increasing the expression of glucose transporter type 4 (GLUT4) [6, 7, 9, 10], a protein that facilitates glucose transport into cells [10, 11]. They promote glycogen synthesis, a process of storing glucose in the liver [11, 12], by downregulating glycogen synthase kinase-3β (GSK-3β) [9], an enzyme that inhibits glycogen synthesis [11]. They have anti-inflammatory effects [6, 7], inhibit glucose absorption by targeting the α-glucosidase enzyme [6, 7, 11], and reduce hepatic glucose production [6, 7, 11]. Due to the above mention properties of polyphenols, they have attracted the attention of the food, pharmaceuticals, cosmetics and traditional medicine [13-17].

Therefore, many researchers are using plants to extract polyphenols to use as natural therapy for the management of many diseases including diabetes. *P. americana* (avocado) is among the many plants that researchers have been using for the management of diabetes and other ailments like malaria, toothache, high blood pressure, painful menstruation, diarrhoea, and diabetes [12, 18-19]. *P. americana* (avocado) belongs to the family of *Lauraceae* native to tropical America but is presently cultivated worldwide. In Cameroon, it is extensively grown by smallholder farmers in the West, Littoral, Centre, and North West Regions. Phytochemical screenings of aqueous extracts from *P. americana* leaves, seeds and stem bark, have revealed the presence of several bioactive compounds such as polyphenols, saponins, tannins, flavonoids, alkaloids, and polysaccharides [12, 20]. Several *in vivo* studies using animal models have shown that these compounds have anti-diabetic effects, mostly linked to polyphenols [6-8, 21-23].

For *P. americana* extract to be more effective in the treatment of T2DM, it must be rich in polyphenols. The effectiveness of polyphenol-rich extracts largely depends on the extraction method employed. This is a critical step in isolating bioactive molecules from plant matrices and is influenced by parameters such as the solvent type, temperature, extraction time, and energy inputs [24-26]. Different conventional techniques (Soxhlet extraction, decoction, infusion, and maceration) and nonconventional techniques (enzyme-assisted extraction, ultrasound-assisted extraction and microwave-assisted extraction) have been reported for the extraction of bioactive compounds [24, 27]. However, conventional techniques which are commonly used are associated with some disadvantages, such as long processing times, tedious extraction processes, massive organic solvent usage, high-energy input, low yield, low quality, high apparatus requirements, and environmental issues [24, 27, 28]. Many studies have found that extraction temperature significantly impacts the type of polyphenols extracted, as various polyphenols degrade at different temperatures [29-31].

To overcome these limitations, microwave-assisted extraction (MAE) has emerged as a green, effective, and cost-effective alternative. This technique uses microwave energy to heat polar solvents in contact with samples by ionic conduction and dipole rotation, which improves cell wall destruction and increases the solubility of bioactive compounds [28, 32]. Moreover, its lower energy requirement, low temperature, good product quality, shorter extraction time, lower operating costs and improved efficiency have made it more popular [24, 27, 33, 34]. However, the efficiency of the MAE process depends on several variables such as extraction power, time, solvent composition, and solvent-to-sample ratio [35, 36, 37]. Hence, this study aimed to investigate the effect of MAE conditions, specifically extraction time, power, and volume of water for maximizing the yield of polyphenols from the leaves, seeds, and stem bark of *P. americana* using response surface methodology.

2. Materials and methods

2.1. Sample collection and preparation

Mature leaves and stem bark of *P. americana* as well as ripe avocado fruits were harvested from five trees of–approximately ten years old and 8 m high in *Bamunka Ndop*, *Ngoketunjia* Division (North-West Region, Cameroon). The seeds were removed from the avocado fruits using a sharp stainless knife. The seeds, leaves and stem barks were cleaned, washed under running tap water, cut into small sizes and allowed to drain. The drained samples were dried on separate trays in a ventilated oven (*Heraeus*, Germany) at 45 °C for 24 h.

The dried samples were placed in a house blender (*Magic*, China) and ground at high speed for 1.5 min, then sieved for 20 min on a vibrator (*Glen Creston Ltd*, England). Two sieves with *particle* sizes of 0.25 and 0.45 mm were used in this study. The 2 particle sizes (≤ 0.25 mm, $0.25 < \text{size} \leq 0.45$ mm) for each sieved plant part were kept in separate polyethylene bags for analyses.

2.2. Microwave assisted extraction experimental design

The microwave optimisation extraction of polyphenols from each sample was carried out employing a response surface methodology consisting of a Central Composite Rotatable Design (CCRD) of 17 experimental runs that included 3 central points, 6 axial points and 8 factorial points [38]. The extraction variables studied were microwave power (17.9-82% W), volume of water (69.8-230.2 mL), and extraction time (3.5-11.5 min), as shown in Table 1. Two grams of powdered material from each plant part and particle size were placed in microwave-safe containers and extracted using a Hisense domestic microwave oven according to the RSM experimental design. This was followed by assessing the total phenolic content of the extract from each run.

The relationship between the response variable (Y) and extraction factors was modelled using the following second-order polynomial equation:

$$Y = \beta_0 + \beta_1 P + \beta_2 V + \beta_3 T + \beta_{12} PV + \beta_{13} PT + \beta_{23} VT + \beta_{123} PVT + \beta_{11} P^2 + \beta_{22} V^2 + \beta_{33} T^2$$

Where, Y represents the total phenolic content (TPC); P, V, T are the independent variables (Power, Volume, Time, respectively), and β terms refer to regression coefficients for constant, linear, interaction, and quadratic effects.

Table 1. Independent variables and their levels used in the response surface design.

N^0 run	Power level (W %)	Volume (mL)	Time (min)
1	30	200	10
2	30	100	5
3	50	150	7.5
4	70	200	5
5	70	100	10
6	50	150	7.5
7	50	150	7.5
8	70	100	5
9	30	100	10
10	70	200	10
11	30	200	5
12	50	150	11.5
13	50	230.2	7.5
14	17.9	150	7.5
15	50	150	3.5
16	82.1	150	7.5
17	50	69.8	7.5

2.3. Evaluation of total phenolic content

A total polyphenol content was determined using the Folin-Ciocalteu method described by [39]. An aliquot (0.1 mL) of the extract was mixed with 0.75 mL of Folin-Ciocalteu reagent. After 5 min, 0.75 mL of a solution of sodium carbonate (6%) was added. The mixture was homogenized and incubated in the dark at room temperature for 90 min and the absorbance read at 725 nm (UVmini-1240, UV-Vis Spectrophotometer, and Shimadzu-Japan) against the blank reagent. Gallic acid (0-1000 μg/mL) was used as the standard.

2.4. Statistical analysis

All experiments were performed in triplicate for each dried sample, and the results were expressed as the mean ± standard deviation. Data from the central composite design were analyzed using Statistica 10 (StatSoft, USA). ANOVA was used to evaluate the significance of the model terms ($p < 0.05$). Regressio Cn coefficients, model adequacy statistics (R^2, AAD, Bf), and response surface plots were generated to assess the fit and predictive accuracy of the developed model.

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Table 2. Polyphenol contents in oven dried powder of *P. americana* after varying extraction conditions.

Run	Power (%)	Vol (mL)	Time (min)	TPC (µg GAE/ mL)					
				Leaf ≤ 0.25mm	Seed ≤ 0.25mm	Stem bark ≤ 0.25mm	Leaf 0.25<size≤ 0.45 mm	Seed 0.25<size≤ 0.45mm	Stem bark 0.25<size≤ 0.45 mm
1	30	200	10	7.91 ± 0.75	4.64 ± 1.25	7.00 ± 0.56	4.52 ± 3.80	1.80 ± 0.75	3.22 ± 0.25
2	30	100	5	16.61 ± 1.45	13.86 ± 0.75	15.90 ± 0.61	12.80 ± 8.45	8.26 ± 2.05	8.31 ± 0.45
3	50	150	7.5	10.77 ± 0.82	6.18 ± 6.1	7.61 ± 1.45	3.46 ± 0.15	4.97 ± 3.01	4.58 ±1.05
4	70	200	5	7.88 ± 4.80	4.35 ± 3.35	6.69 ± 0.45	6.05 ± 0.75	3.15 ± 2.43	3.95 ± 3.41
5	70	100	10	16.68 ± 5.09	16.02 ± 0.42	16.38 ± 0.30	10.28 ± 7.01	15.22 ± 1.5	15.53 ± 4.0
6	50	150	7.5	11.15 ± 1.05	5.32 ± 1.15	7.51 ± 2.52	3.45 ± 4.01	4.26 ± 1.05	4.48 ± 0.5
7	50	150	7.5	10.40 ± 3.00	7.05 ± 6.1	7.70 ± 3.15	3.48 ± 0.53	5.68 ± 8.00	4.67 ± 0.62
8	70	100	5	13.53 ± 0.13	15.18 ± 4.2	15.53 ± 2.45	13.80 ± 2.2	12.59 ± 0.5	14.05 ± 2.05
9	30	100	10	12.95 ± 0.23	14.12 ± 2.1	12.95 ± 1.05	15.98 ± 0.5	7.82 ± 0.51	6.07 ± 1.5
10	70	200	10	8.15 ± 6.01	8.03 ± 0.5	8.03 ± 8.01	4.82 ± 4.25	6.25 ± 0.95	4.57 ± 0.22
11	30	200	5	7.76 ± 0.01	4.03 ± 0.21	6.82 ± 0.5	5.97 ± 1.01	2.60 ± 2.3	2.28 ± 0.5
12	50	150	11.5	10.56 ± 4.01	7.66 ± 3.01	10.34 ± 2.5	8.59 ± 0.55	10.41 ± 2.8	7.52 ± 2.05
13	50	230.2	7.5	6.86 ± 0.61	2.26 ± 0.40	2.26 ± 3.22	5.38 ± 0.30	4.06 ± 3.01	0.80 ±3 .01
14	17.9	150	7.5	4.96 ± 0.50	6.39 ± 0.23	6.79 ± 4.01	6.43 ± 0.41	3.63 ± 0.6	2.02 ± 2.5
15	50	150	3.5	6.16 ± 0.29	10.59 ± 0.5	9.39 ± 0.4	10.47 ± 0.8	2.96 ± 4.01	5.21 ± 2.90
16	82.1	150	7.5	10.59 ± 1.11	6.17 ± 2.01	10.01 ± 0.75	9.96 ± 4.7	4.96 ± 0.9	7.75 ± 0.55
17	50	69.8	7.5	23.78 ± 0.01	18.08 ± 0.75	23.40 ± 2.01	12.74 ± 0.65	23.18 ± 2.0	6.75 ± 0.25

Microgram gallic acid equivalents/millilitre (µg GAE/ mL)

3. Results and discussion

The total polyphenol content (TPC) of *Persea americana* (leaf, seed, and stem bark) obtained under different microwave-assisted extraction (MAE) conditions and presented in Table 2. The values ranged from 1.80 ± 0.75 to 23.78 ± 0.01 µg gallic acid equivalents/millilitre (GAE/mL), depending on the plant part, particle size, and extraction parameters. At comparable microwave powers and extraction times, leaf samples globally appeared to have higher polyphenol yields than seed and stem bark extracts. This is evident at 50% power and 7.5 min extraction (Run 3), where the leaf powders yielded 10.77 ± 0.82 µg GAE/mL compared to 6.18 ± 6.10 µg GAE/mL for seeds and 7.61 ± 1.45 µg GAE/mL for stem bark. The particle size strongly influenced the extraction efficiency. Finer powders (≤ 0.25 mm) led to a more important TPC in the extracts than coarser fractions (0.25 < size ≤ 0.45 mm), regardless of plant part. Under identical extraction conditions (Run 5), the TPC of leaf powders decreased from 16.68 ± 5.09 µg GAE/mL with particle size below 0.25 mm to 10.28 ± 7.01 µg GAE/mL with bigger particle size (0.25–0.45 mm).

The estimated effects presented in Table 3, obtained from ANOVA analysis, reveal that the extraction efficiency of total polyphenols (TPC) from *Persea americana* is mainly determined by the solvent volume, followed by microwave power and extraction time [40, 41]. These statistical findings are supported by the trends observed in Table 2. The second-order polynomial models fitted the experimental data well, explaining over 88% of the variation in TPC (R^2 = 0.887–0.949).

Regardless of plant part and particle size, the linear effect of solvent volume was significantly negative ($p < 0.05$). This indicates that increasing the extraction solvent volume from 70 to 200 mL generally reduced the TPC. For instance, as shown in Table 2, when *P. americana* leaves (≤ 0.25 mm) were extracted at the same power level (30%) and duration (5 min), increasing the solvent volume from 100 mL (Run 2) to 200 mL (Run 11) caused the TPC to decrease by more than 50% (from 16.61 ± 1.45 µg GAE/mL to 7.76 ± 0.01 µg GAE/mL). This observation was also made for the seed and stem bark fractions. An optimal range of solvent volume was also observed, that indicated by the significant quadratic positive effect of this variable (V^2) in almost all samples. The highest TPCs were

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Table 3. Estimated effects of MAE conditions on polyphenols content in oven dried powder of *P. Americana.*

Factor	Leaf ≤0.25mm	Seed ≤0.25mm	Stem bark ≤0.25mm	Leaf 0.25<size≤ 0.45mm	Seed 0.25<size ≤0.45mm	Stem bark 0.25<size ≤0.45mm
Linear						
Power	1.52729	0.99981	1.3894	0.20181	2.87327*	4.16793*
Volume	-8.39976*	-9.66032*	-10.0611*	-6.59096*	-9.24474*	-6.00850*
Time	1.05785	0.10378	0.1437	-0.91923	2.49999*	0.68586
Quadratic						
Power ^{2}	-1.86621	0.59598	0.7742	3.41473*	-1.23763	1.24895
Volume ^{2}	4.00056*	3.62126*	4.2220*	4.09157*	6.01515*	0.38423
Time^2	-1.41251	2.80711*	1.9112*	4.45733*	0.61978	2.39896*
Interaction						
Power x vol	-0.07232	0.12321	-0.5384	1.27054	-1.68036	-3.04375*
Power x time	1.73661	0.91429	1.2420	-1.62411	1.74286	0.85089
Vol x time	0.22946	0.79643	0.9063	-0.58304	0.02857	0.58304
R2	0.90300	0.94900	0.9430	0.93200	0.90800	0.88700

*Factors with a significant effect on the response ($p < 0.05$), Vol: volume

observed at the lowest solvent volumes (69.8-100 mL), and the gap in the TPC difference reduced when comparing the results obtained at the highest solvent volumes (example run 17 vs. 6 and Run 6 vs. 13).

The linear power effect was positive and significant, particularly for the seed and stem bark fractions of larger particle sizes (0.25 < size ≤ 0.45 mm). When the stem bark powder (0.25 < size ≤ 0.45 mm) was extracted for 5 min using 30% power (run 11) and 70% power (run 4) while keeping the solvent volume constant (200 mL), TPC increased from 2.6 to 3.15 with seeds, and from 2.28 to 3.95 μg GAE/mL with stem bark. A positive quadratic effect of power was observed particularly with leaf samples of larger size where TPC values of 6.43, 3.48, and 9.96 were obtained applying powers of 17.9, 50, and 82.1%, respectively, with the same solvent volume and same extraction duration (Run 14 vs 7 vs 16).

The effect of extraction time the effect was generally weak but significantly positive, with a mostly quadratic effect. For several samples. This curvilinear response showed the highest TPC values at approximately 7.5 min.

A significant interaction between the variables was only observed between power and volume (P×V) for the stem bark with a larger particle size (0.25 < size ≤ 0.45 mm). This interaction was negative. Indeed, as illustrated in Fig. 1, an increase in the solvent volume tended to reduce the positive effect of the Microwave Power.

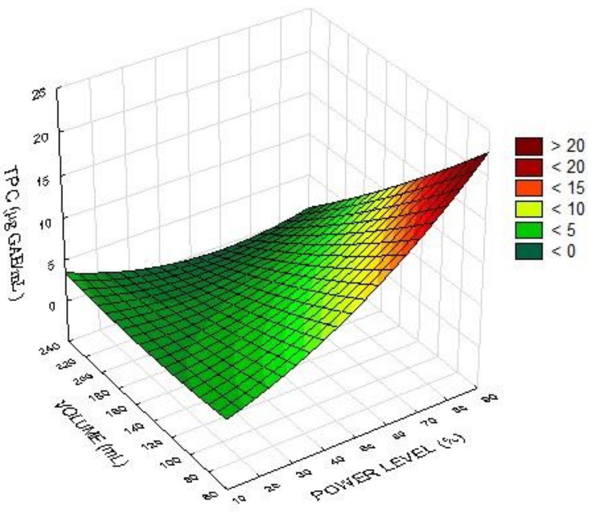

Figure 1. Variation of TPC with Microwave power level and solvent volume (Time=7.5 min).

Table 4 presents the regression models obtained for predicting the TPC of *Persea americana* leaf, seed, and stem bark powders under different particle size conditions (≤ 0.25 and 0.25–0.45 mm). This approach helped improve the coefficients of determination (R^2), which ranged between 0.89 and 0.96. The reliability and predictive accuracy of the obtained models were appreciated through the low average absolute deviation (AAD < 0.15) and bias factors (Bf ≈ 1). Volume was identified as the key variable that

Table 4. The influence of MAE parameters on total polyphenol content in oven dried powder of *P. americana* using the regression equation.

Sample (mm)	R^2	Regression equation	AAD	B_f
Leaf size ≤0.25	0.92	$52.51-0.24*P\mathbf{-0.46*V}-1.7*T+0.0025*PV+0.068*PT+0.018*VT-0.00033*PVT-0.0022*P^2\mathbf{+0.00081*V^2}-0.11*T^2$	0.08	1.07
Seed size ≤ 0.25	0.96	$51.34+0.0025*P\mathbf{-0.30*V}-3.45*T-0.0009*PV-0.0095*PT-0.0031*VT+0.00012*PVT+0.00084*P^2\mathbf{+0.00074*V^2}+0.23\mathbf{*T^2}$	0.11	0.88
Stem bark size ≤ 0.25	0.95	$65.21-0.27*P\mathbf{-0.42*V}-4.46*T-0.00073*PV+0.032*PT+0.01*VT-0.00013*PVT+0.001*P^2\mathbf{+0.0009*V^2}+0.15*T^2$	0.13	1.09
Leaf 0.25 ≤ size ≤ 0.45	0.93	$39.81-0.0011*P\mathbf{-0.19*V}-1.73*T-0.002*PV-0.068*PT-0.02*VT+0.00035*PVT+0.0042*P^2\mathbf{+0.00081*V^2}+0.35*T^2$	0.01	0.97
Seed 0.25 ≤ size ≤ 0.45	0.92	$34.42+0.28*P-0.39*V-0.69*T-0.0012*PV+0.011*PT-0.002*VT+0.00004*PVT-0.0017*P^2\mathbf{+0.0012*V^2}+0.041*T^2$	0.01	0.93
Stem bark 0.25 ≤ size ≤ 0.45	0.89	$31.09-0.13*P-0.11*V-5.22*T-0.00001*PV+0.039*PT+0.012*VT-0.0002*PVT+0.0018*P^2+0.00011*V^2+0.2*T^2$	0.12	0.86

AAD: average absolute deviation; B_f: Bias factor; Parameters in bold are significant ($p < 0.05$).

significantly determined the TPC content.

4. Discussion

The results of this study demonstrate that the extraction efficiency of total polyphenols (TPC) from *Persea americana* is significantly influenced by microwave-assisted extraction (MAE) conditions, including solvent volume, microwave power, extraction time, and particle size. The observed TPC values (1.80–23.78 µg GAE/mL) indicated that *P. americana* leaves contain higher extractable phenolic compounds compared to the seed and stem bark, which, also confirmed that the species is rich in flavonoids, tannins, and phenolic acids [42, 43]. This difference can be attributed to the metabolic role of phenolics in protecting leaf tissues from oxidative stress and ultraviolet radiation, resulting in higher accumulation of these compounds in leaves relative to storage and structural organs, such as seeds and bark [44].

The solvent volume was identified as the most significant factor ($p < 0.05$) affecting the TPC yield across all plant parts and particle sizes. The negative linear effect of solvent volume observed in the ANOVA (Table 3) suggests that excessive dilution of the extraction medium reduces the solvent–matrix contact and consequently the mass transfer rate. Similar trends were reported [40, 41], which demonstrated that a moderate solvent-to-solid ratio favours polyphenol recovery by maintaining concentration gradients that drive diffusion. The positive quadratic effect (V^2) found in all matrices indicates the existence of an optimal volume range (approximately 70–100 mL), beyond which the efficiency declines due to solute saturation and reduced microwave absorption by the medium.

Microwave power also showed a significant influence on TPC, particularly in coarser fractions ($0.25 < \text{size} \leq 0.45$ mm). The positive power effect suggests that an increased energy input enhances cell wall rupture and solvent penetration, facilitating the release of bound polyphenols [45, 46]. However, the negative quadratic term observed in some equations (Table 4) indicates that very high power may promote the degradation of heat-sensitive phenolics through oxidation and polymerization [41, 46, 47]. Therefore, moderate power levels (approximately 50%) appear optimal for balancing the extraction efficiency and compound stability of *P. americana.*

Extraction time exhibited a mild but mostly positive and quadratic influence on TPC, with optimal yields occurring at approximately 7.5 min. This curvilinear response implies that polyphenol release initially increases with exposure time but plateaus or declines afterward due to thermal degradation or re-adsorption phenomena. This improved sample wetting and matrix penetration, thereby enhancing the extraction efficiency, which is in agreement with earlier reports [48, 49]. Comparable kinetics have been described for the microwave-assisted extraction of

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polyphenols from other plant matrices, such as olive leaves and guava peels [50, 51]. Particle size is another determinant of extraction efficiency. Finer powders (≤ 0.25 mm) consistently produced higher TPC values than coarser ones. A reduced particle size increases the surface area and shortens the diffusion paths, thereby improving the solvent accessibility and microwave energy absorption [52]. This trend was consistent across all plant parts and confirmed the importance of proper sample pre-treatment in optimizing MAE.

The regression models developed (Table 4) showed excellent predictive performance ($R^2 = 0.89–0.96$, AAD < 0.15, Bf ≈ 1), confirming that the second-order polynomial equations adequately describe the relationships between the MAE parameters and TPC. Among the models, the seed powder (≤ 0.25 mm) exhibited the highest predictive accuracy ($R^2 = 0.96$), followed by stem bark (0.95), and leaf (0.92). These high coefficients of determination and low deviation values underscore the reliability of the established models in predicting polyphenol yields under different operational conditions. The negative interaction between power and solvent volume (P×V) observed in the stem bark fraction indicates that increasing the solvent volume mitigates the positive effect of microwave power, possibly due to the reduced energy density within the extraction medium.

Overall, these results highlight that optimal extraction of polyphenolic compounds from *P. americana* is achieved under controlled MAE conditions characterized by moderate microwave power (≈ 50%), limited solvent volume (≈ 70–100 mL), intermediate extraction time (≈ 7.5 min), and fine particle size (≤ 0.25 mm). The findings demonstrate the potential of MAE as an efficient and rapid green technology for recovering bioactive compounds from *P. americana* matrices, with minimized solvent use and energy consumption compared with conventional techniques. Future optimization studies could integrate response surface methodology (RSM) or artificial intelligence-based modelling to refine these parameters for industrial-scale applications.

5. Conclusions

In conclusion, we investigated the effect of microwave assisted extraction conditions in the extraction of polyphenols from oven-dried powder of *P. americana* leaf, seed, and stem bark using the RSM process. For maximum recovery of polyphenols using MAE, the linear and quadratic volumes of the solvent (water) in the regression equation had significant effects on all the responses, except for the stem bark of particle size 0.25 ≤ size ≤ 0.45, which had no effect. In addition, seeds with a particle size ≤ 0.25 mm showed a significant effect ($p \leq 0.05$) with quadratic time. The results from ANOVA analysis showed an interaction effect between linear power and linear volume for stem bark with particle size of 0.25 mm < size ≤ 0.45 mm.

Disclaimer (artificial intelligence)

Author(s) hereby state that no generative AI tools such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators were utilized in the preparation or editing of this manuscript.

Authors' contributions

Conceptualization, methodology, biochemical analyses, data curation, resources, writing – original draft preparation, writing – review and editing, M.N.K.; conceptualization, methodology, data curation, formal analysis, writing – review and editing; A.D.T.K.; methodology, biochemical analyses, data curation, writing – review and editing, F.L.E.E.; conceptualization, methodology, visualization, supervision, validation; R.F.D.; visualization, supervision, validation, N.C.P.

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Availability of data and materials

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare no conflicts of interest.

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