Heliyon 6 (2020) e03664

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Effect of temperature on equilibria for physical and reactive extraction of protocatechuic acid

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ARTICLE INFO

Keywords:
Chemical engineering
Physical chemistry
Temperature
Reactive extraction
Mechanism
Protocatechuic acid
Separation

ABSTRACT

Owing to its biological and chemical applications, the separation of protocatechuic acid, a polyphenol compound, is of interest to researchers. Extraction studies with initial acid concentration (0.001–0.01 kmol m^{-3}) using aminic extractant tri-n-octyl amine (TOA) (0.2287 kmol m^{-3} -1.1436 kmol m^{-3}) in diluent octanol at diverse temperature ranges from 288 K - 313 K was done. Parameters like loading ratio, distribution coefficient, equilibrium complexation constant, diffusion coefficient, number of stages necessary for protocatechuic acid counter-current extraction were obtained; this information is useful in designing a process for the *in situ* separation of the acid from the fermentation broth as well as from the waste streams. The increase in temperature distribution coefficient was found to increase up to the temperature of 303 K and was found to decrease with a further rise in temperature. The entropy and enthalpy values for the reaction at different temperatures were obtained. The highest extraction of 91.1 % and distribution coefficient of 1.14 were obtained at 313 K for an acid concentration of 0.01 kmol $m^{-3,}$ and TOA concentration of 1.1436 kmol m^{-3} and 4 stages are required for counter-current extraction process for acquiring the required separation efficiency. Development of 1:1 complex of protocatechuic acid and TOA take place as concluded from the values of the loading ratio.

1. Introduction

The susbtane 3,4-dihydroxybenzoic acid is commonly known as protocatechuic acid (PCA). It is a phenolic acid that belongs to the category of polyphenols, which are chemicals naturally occurring in many plants and fruits and considered as a chief metabolite of polyphenol compounds like procyanidins and anthocyanins [1]. Phenolic compounds are obtained from phenylalanine through the shikimic acid pathway [2]. Protocatechuic acid is found mainly in berries and food spices (3–189 mg kg^{-1}), lettuce (200–4000 mg kg^{-1}), black tea, and green tea (up to 20 mg l^{-1}), etc. [3, 4, 5]. But the cost of natural extraction of PCA is comparatively higher, making the process less feasible. Industrially it is produced mainly from chemical synthesis of Vanillin. The focus has been shifted towards the green route of production of carboxylic acids considering from environmental and sustainability point of view. Production of PCA from the fermentation broth using *Bacillus thuringiensis, Bacillus anthracis,* and *Bacillus cereus* is reported in the literature [6, 7, 8, 9, 10, 11, 12, 13, 14, 15].

PCA possesses numerous pharmacological actions such as antioxidant, hepatoprotective, antibacterial, antiulcer, antidiabetic, antiageing, anticancer, antiviral, antifibrotic, anti-inflammatory, antiatherosclerotic, analgesic, cardiac, and nephroprotective activities [9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. Medicinal application is the primary use of PCA, with a market share of 72.91% in 2017. Apart from its pharmacological significance, PCA is used for synthesizing plastics, polymers, and bio-based active films.

The methods in practice to date for the separation of PCA from waste streams of food processing industries like olive oil wastewater includes Fenton oxidation, adsorption, microbial degradation, etc. Even though the production of carboxylic acid through fermentation route is considered as green technique, the overall reclamation of carboxylic acid from aqueous effluent and fermentation broth, which are usually present in small quantities faces some limitations. The conventional methods used for the retrieval of these acids from aqueous waste streams and fermentation broth includes precipitation, ultrafiltration, chromatographic techniques, solvent extraction, electrodialysis, adsorption, etc. [19, 20]. The purification and retrieval of the anticipated product account for about 50% of the total production cost, which requires the development of an integrated unit combing fermentation and separation that will be cost and energy effective. Amongst the separation methods employed for

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https://doi.org/10.1016/j.heliyon.2020.e03664
Received 27 February 2019; Received in revised form 24 May 2019; Accepted 20 March 2020

carboxylic acid recovery, reactive extraction is an effective method possessing several advantages when compared to conventional techniques like better control of pH in the fermentation broth, re-extraction of acid, and reusability of solvents, better product recovery, and selectivity, energy efficiency, etc. Reactive extraction using extractants and diluents has been used successfully for the recovery of several carboxylic acids [21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31].

The overall yield of the product can be improved by reactive extraction; wherein liquid-liquid extraction is combined with chemical reaction. Studies on the reactive separation of carboxylic acids, especially from dilute acid solutions, shows that the use of conventional solvents like alcohols, ketones, esters, etc. gives lower distribution ratios and extraction efficiencies. Thus specific extractants that give higher extraction efficiencies through reversible chemical complexation are used [20]. Extractants belonging to this category are mainly phosphorus-based oxygen-containing extractants and amine extractants. Physical properties like surface tension, density, viscosity, etc. of the solvent phase are improved, and also solvation to the complex formed is provided when the extractants are dissolved in diluents [32, 33]. Ethers, ketones, and alcohols belonging to the category of polar diluents, provides higher solvation for the extractant – acid complex formed [20]. The extractant – acid complex solubility is centered on dipole-dipole interaction, hence polar diluents like alcohol having higher dielectric constant values are preferable [32].

Some literature is availabile on the equilibrium studies on the reactive separation of PCA [34, 35, 36, 37, 38]. Apart from reactive extraction, for the retrieval of PCA from the aqueous waste stream of food processing industries, the methods in practice till date includes microbial degradation [39], ultrafiltration [40], adsorption [41], H_2O_2/UV or O_3/UV [42], etc., each of the methods facing its own merits as well as certain limitations. The current study emphasizes the study of thermodynamic aspects of reactive extraction of PCA in the temperature ranges from 288 K and 313 K using TOA as an extractant in diluent octanol. The extractant – diluent system was chosen based on previous studies. Temperature studies are important, considering the operating temperature ranges for reactive extraction and also for back-extraction/regeneration steps. Temperature studies on carboxylic acid reactive extraction of which include citric acid [43, 44], lactic acid [45], succinic acid [46], acrylic, propionic, and butyric acid [32] have been reported in the literature. The results of the study are presented as distribution coefficient, equilibrium complexation constant, extraction efficiency, loading factor, and the enthalpy and entropy of reaction and the effect of temperature on these values.

2. Materials and method

The aqueous phase was prepared by varying protocatechuic acid (98% purity, Avra Synthesis Pvt Ltd, India) concentrations in the ranges of 0.01 kmol m^{-3} to 0.001 kmol m^{-3}. The extractant tri-n-octylamine (TOA), was obtained from Spectrochem India, with purity >98%. Diluent 1-octanol was purchased from Avra Synthesis Pvt Ltd. Aqueous solutions of PCA were prepared using distilled water. The acid concentrations for the study were decided based on PCA concentration obtained from fermentation broth [47]. Particulars of chemicals used for the current research are mentioned in Table S1.

The extraction experiments were performed by taking equivalent volumes (5 mL) of the aqueous phase and organic phases in a conical flask and shaking in orbital shaking incubator, which is temperature-controlled (REMI S-24BL, Mumbai India) for 5 h for attaining equilibrium. The organic phase was prepared by varying the concentration of TOA from 10 % to 50 % by volume in octanol. After the batch extraction experiment, the phases were separated by centrifuging (REMI R–4C, Mumbai India) for 5 min at 4000 RPM. Further, the aqueous phase concentration was determined by using a UV/VIS spectrophotometer at 260 nm (Shimadzu 1800, Japan). Organic phase acid concentration was determined by mass balance considering no loss of phases in water coextraction. Temperature effects on PCA extraction were explored by choosing six temperatures in the ranges of 288–313 K. Few sets of experiments were duplicated for checking the result consistency and were found to be within ±2%.

The equilibrium results are discussed in terms of distribution coefficient (K_D), degree of extraction (%E), and loading ratio (Z), and is calculated by using Eqs. (1), (2), and (3), respectively.

K_D, the distribution coefficient could be defined as the ratio of acid concentration in the organic phase ($[HP]_{org}$) to the aqueous phase ($[HP]_{aq}$) at equilibrium because of a minor change in phase volume.

$$K_D = \frac{[HP]_{org}}{[HP]_{aq}} \tag{1}$$

Extraction efficiency (E %) is characterized as the ratio of the concentration of PCA in the extracted phase to the initial PCA concentration in aqueous solution and is given by Eq. (2)

$$E = \frac{K_D}{1 + K_D} * 100 \tag{2}$$

Loading ratio (Z) denoted by the magnitude to which organic phase can be loaded with PCA is useful in determining the equilibrium complexation constant:

$$Z_{PCA} = \frac{[HA]_{org}}{[TOA]^0_{org}} \tag{3}$$

where $[TOA]^0_{org}$is the initial concentration of extractant in the organic phase.

3. Result and discussion

3.1. Physical extraction

Physical extraction, i.e., extraction of acid by using diluent alone, was carried out in octanol. The results for physical extraction at different temperatures and various acid concentrations are presented in Table S2.

Extraction of PCA by diluent octanol could be defined in terms of three phenomena [20]:

(1) Aqueous phase ionization of PCA

$$(HP)_{aq} \leftrightarrow H^+ + P^- \tag{4}$$

$$K_{HP} = [H^+][P^-] / [HP] \tag{5}$$

(2) undissociated acid partition into organic phase (P)

$$(HP)_{aq} \leftrightarrow (HP)_{org} \tag{6}$$

$$P = [HP]_{org} / [HP]_{aq} \tag{7}$$

(3) organic phase acid dimerization (D).

$$2(HP)_{org} \leftrightarrow (HP)^2_{org} \tag{8}$$

$$D = [HP]_{2,org} \Big/ [HP]^2_{org} \tag{9}$$

For physical extraction, the overall distribution coefficient which is the proportion of total PCA concentration in the organic phase to the

Table 1. Equilibrium of Protocatechuic acid with TOA in octanol at 288 K.

$[TOA]^0_{org}$ kmol m^{-3}	$[HP]_0$ kmol m^{-3}	$[HP]_{aq}$ kmol m^{-3}	$[HP]_{org}$ kmol m^{-3}	K_D	Avg K_D	E%	Avg E%	Z	K_E
0.2287	0.001	0.0003	0.0007	2.08	2.83	67.50	73.21	0.0030	14.56
	0.003	0.0008	0.0022	2.58		72.03		0.0094	
	0.005	0.0014	0.0036	2.58		72.10		0.0158	
	0.007	0.0018	0.0052	2.93		74.57		0.0228	
	0.01	0.0020	0.0080	3.96		79.85		0.0349	
0.4575	0.001	0.0003	0.0007	2.35	3.56	70.13	77.30	0.0015	9.23
	0.003	0.0007	0.0023	3.21		76.25		0.0050	
	0.005	0.0011	0.0039	3.44		77.48		0.0085	
	0.007	0.0014	0.0056	3.91		79.64		0.0122	
	0.01	0.0017	0.0083	4.88		82.99		0.0181	
0.6862	0.001	0.0003	0.0007	2.48	3.89	71.30	78.71	0.0010	6.74
	0.003	0.0007	0.0023	3.30		76.73		0.0034	
	0.005	0.0010	0.0040	4.12		80.47		0.0059	
	0.007	0.0014	0.0056	4.18		80.69		0.0082	
	0.01	0.0016	0.0084	5.39		84.36		0.0123	
0.9150	0.001	0.0002	0.0008	3.08	4.58	75.50	81.51	0.0008	5.83
	0.003	0.0006	0.0024	3.99		79.97		0.0026	
	0.005	0.0009	0.0041	4.85		82.92		0.0045	
	0.007	0.0011	0.0059	5.25		84.00		0.0064	
	0.01	0.0015	0.0085	5.73		85.15		0.0093	
1.1437	0.001	0.0002	0.0008	3.69	6.02	78.70	84.85	0.0007	6.30
	0.003	0.0005	0.0025	4.88		82.99		0.0022	
	0.005	0.0007	0.0043	5.99		85.70		0.0037	
	0.007	0.0009	0.0061	6.67		86.96		0.0053	
	0.01	0.0010	0.0090	8.88		89.88		0.0079	

Table 2. Equilibrium of Protocatechuic acid with TOA in octanol at 293 K.

$[TOA]^0_{org}$ kmol m^{-3}	$[HP]_0$ kmol m^{-3}	$[HP]_{aq}$ kmol m^{-3}	$[HP]_{org}$ kmol m^{-3}	K_D	Avg K_D	E%	Avg E%	Z	K_E
0.2287	0.001	0.0003	0.0007	2.08	2.93	67.50	73.99	0.0030	15.04
	0.003	0.0008	0.0022	2.69		72.93		0.0096	
	0.005	0.0012	0.0038	3.03		75.18		0.0164	
	0.007	0.0018	0.0052	2.99		74.94		0.0229	
	0.01	0.0021	0.0079	3.85		79.39		0.0347	
0.4575	0.001	0.0003	0.0007	2.45	3.76	71.00	78.12	0.0016	9.85
	0.003	0.0007	0.0023	3.29		76.67		0.0050	
	0.005	0.0011	0.0039	3.44		77.50		0.0085	
	0.007	0.0013	0.0057	4.39		81.46		0.0125	
	0.01	0.0016	0.0084	5.25		84.00		0.0184	
0.6862	0.001	0.0003	0.0007	2.83	4.19	73.86	79.98	0.0011	7.22
	0.003	0.0007	0.0023	3.59		78.20		0.0034	
	0.005	0.0010	0.0040	4.08		80.30		0.0059	
	0.007	0.0013	0.0057	4.58		82.09		0.0084	
	0.01	0.0015	0.0085	5.87		85.44		0.0125	
0.9150	0.001	0.0002	0.0008	3.07	5.14	75.44	82.67	0.0008	6.78
	0.003	0.0006	0.0024	4.09		80.37		0.0026	
	0.005	0.0008	0.0042	5.18		83.82		0.0046	
	0.007	0.0010	0.0060	6.00		85.71		0.0066	
	0.01	0.0012	0.0088	7.33		88.00		0.0096	
1.1437	0.001	0.0002	0.0008	3.96	6.10	79.84	85.29	0.0007	6.30
	0.003	0.0005	0.0025	5.28		84.07		0.0022	
	0.005	0.0007	0.0043	6.12		85.95		0.0038	
	0.007	0.0009	0.0061	7.00		87.50		0.0054	
	0.01	0.0011	0.0089	8.16		89.08		0.0078	

Table 3. Equilibrium of Protocatechuic acid with TOA in octanol at 303 K.

$[TOA]^0_{org}$ kmol m^{-3}	$[HP]_0$ kmol m^{-3}	$[HP]_{aq}$ kmol m^{-3}	$[HP]_{org}$ kmol m^{-3}	K_D	Avg K_D	E%	Avg E%	Z	K_E
0.2287	0.001	0.0003	0.0007	2.46	3.49	71.10	77.05	0.0031	18.30
	0.003	0.0008	0.0022	2.87		74.17		0.0097	
	0.005	0.0011	0.0039	3.57		78.10		0.0171	
	0.007	0.0014	0.0056	3.93		79.71		0.0244	
	0.01	0.0018	0.0082	4.61		82.18		0.0359	
0.4575	0.001	0.0002	0.0008	3.01	4.27	75.05	80.38	0.0016	11.04
	0.003	0.0007	0.0023	3.60		78.27		0.0051	
	0.005	0.0010	0.0040	4.07		80.29		0.0088	
	0.007	0.0012	0.0058	4.98		83.29		0.0127	
	0.01	0.0015	0.0085	5.68		85.02		0.0186	
0.6862	0.001	0.0002	0.0008	3.26	5.16	76.50	82.67	0.0011	9.03
	0.003	0.0006	0.0024	4.05		80.20		0.0035	
	0.005	0.0009	0.0041	4.59		82.10		0.0060	
	0.007	0.0010	0.0060	6.10		85.92		0.0088	
	0.01	0.0011	0.0089	7.81		88.65		0.0129	
0.9150	0.001	0.0002	0.0008	4.04	5.96	80.14	84.80	0.0009	7.72
	0.003	0.0005	0.0025	4.63		82.25		0.0027	
	0.005	0.0008	0.0042	5.56		84.75		0.0046	
	0.007	0.0009	0.0061	6.67		86.96		0.0067	
	0.01	0.0010	0.0090	8.90		89.90		0.0098	
1.1437	0.001	0.0002	0.0008	4.81	7.22	82.80	87.23	0.0007	7.42
	0.003	0.0004	0.0026	5.94		85.60		0.0022	
	0.005	0.0006	0.0044	7.49		88.22		0.0039	
	0.007	0.0008	0.0062	7.64		88.42		0.0054	
	0.01	0.0009	0.0091	10.23		91.10		0.0080	

Table 4. Equilibrium of Protocatechuic acid with TOA in octanol at 308 K.

$[TOA]^0_{org}$ kmol m^{-3}	$[HP]_0$ kmol m^{-3}	$[HP]_{aq}$ kmol m^{-3}	$[HP]_{org}$ kmol m^{-3}	K_D	Avg K_D	E%	Avg E%	Z	K_E
0.2287	0.001	0.0004	0.0006	1.85	2.62	64.88	71.86	0.0028	12.63
	0.003	0.0009	0.0021	2.37		70.30		0.0092	
	0.005	0.0013	0.0037	2.71		73.08		0.0160	
	0.007	0.0018	0.0052	2.92		74.47		0.0228	
	0.01	0.0023	0.0077	3.26		76.55		0.0335	
0.4575	0.001	0.0003	0.0007	2.20	3.38	68.79	76.33	0.0015	8.14
	0.003	0.0008	0.0022	2.85		74.05		0.0049	
	0.005	0.0011	0.0039	3.44		77.49		0.0085	
	0.007	0.0015	0.0055	3.81		79.20		0.0121	
	0.01	0.0018	0.0082	4.59		82.11		0.0179	
0.6862	0.001	0.0003	0.0007	2.43	3.83	70.88	78.34	0.0010	6.18
	0.003	0.0007	0.0023	3.15		75.88		0.0033	
	0.005	0.0010	0.0040	3.95		79.81		0.0058	
	0.007	0.0013	0.0057	4.20		80.78		0.0082	
	0.01	0.0016	0.0084	5.39		84.35		0.0123	
0.9150	0.001	0.0003	0.0007	2.75	4.32	73.30	80.43	0.0008	5.18
	0.003	0.0006	0.0024	3.65		78.49		0.0026	
	0.005	0.0009	0.0041	4.59		82.10		0.0045	
	0.007	0.0011	0.0059	5.22		83.92		0.0064	
	0.01	0.0016	0.0084	5.39		84.35		0.0092	
1.1437	0.001	0.0002	0.0008	3.48	5.59	77.66	83.94	0.0007	5.73
	0.003	0.0005	0.0025	4.50		81.83		0.0021	
	0.005	0.0007	0.0043	5.71		85.09		0.0037	
	0.007	0.0010	0.0060	6.32		86.34		0.0053	
	0.01	0.0011	0.0089	7.93		88.80		0.0078	

Table 5. Equilibrium of Protocatechuic acid with TOA in octanol at 313 K.

$[TOA]^0_{org}$ kmol m^{-3}	$[HP]_0$ kmol m^{-3}	$[HP]_{aq}$ kmol m^{-3}	$[HP]_{org}$ kmol m^{-3}	K_D	Avg K_D	E%	Avg E%	Z	K_E
0.2287	0.001	0.0004	0.0006	1.63	2.27	62.02	68.89	0.0027	11.66
	0.003	0.0010	0.0020	2.03		66.97		0.0088	
	0.005	0.0015	0.0035	2.23		69.08		0.0151	
	0.007	0.0019	0.0051	2.69		72.90		0.0223	
	0.01	0.0027	0.0074	2.77		73.50		0.0321	
0.4575	0.001	0.0004	0.0006	1.81	3.00	64.40	74.05	0.0014	7.87
	0.003	0.0008	0.0022	2.70		72.94		0.0048	
	0.005	0.0012	0.0038	3.05		75.29		0.0082	
	0.007	0.0016	0.0054	3.49		77.71		0.0119	
	0.01	0.0020	0.0080	3.98		79.90		0.0175	
0.6862	0.001	0.0003	0.0007	2.21	3.12	68.80	75.10	0.0010	5.33
	0.003	0.0008	0.0022	2.69		72.92		0.0032	
	0.005	0.0012	0.0038	3.03		75.20		0.0055	
	0.007	0.0015	0.0055	3.63		78.40		0.0080	
	0.01	0.0020	0.0080	4.04		80.16		0.0117	
0.9150	0.001	0.0003	0.0007	2.32	3.54	69.88	77.34	0.0008	4.47
	0.003	0.0007	0.0023	3.29		76.70		0.0025	
	0.005	0.0011	0.0039	3.63		78.38		0.0043	
	0.007	0.0014	0.0056	4.13		80.51		0.0062	
	0.01	0.0019	0.0081	4.32		81.21		0.0089	
1.1437	0.001	0.0003	0.0007	2.77	4.61	73.46	81.07	0.0006	4.86
	0.003	0.0007	0.0023	3.60		78.27		0.0021	
	0.005	0.0009	0.0041	4.78		82.70		0.0036	
	0.007	0.0011	0.0059	5.25		84.00		0.0051	
	0.01	0.0013	0.0087	6.63		86.90		0.0076	

overall (analytical) PCA concentration in all its prevailing forms in aqueous raffinate, can be represented as

$$K_D^{diluent} = \frac{P + 2P^2 D[HP]_{aq}}{1 + K_{HP}/[H^+]_{aq}} \tag{10}$$

For the present study dilute aqueous solutions of PCA (0.001–0.01 kmol m^{-3}) were considered; hence the denominator term of the above equation can be neglected and be simplified to

$$K_D^{diluent} = P + 2P^2 D[HP]_{aq} \tag{11}$$

The K_D values for the temperature ranges 288–313 K along with the dimerization (D) and partition (P) coefficients values are given in Table S2. Antony et al. [36] did studies at 298 K in octanol. PCA-octanol solvation occurs through hydrogen bonding (O···H) amongst O atom from –OH group of octanol and H atom from –COOH group of PCA. As can be observed from Table S2, the values of partition coefficient (P) increase with the rise in temperature up to 303 K. The distribution coefficient K_D was found to increase with the rise of initial PCA concentration in the aqueous phase, and with rise in temperature of the system (up to 303 K). Further, the increase in temperature leads to a decrease in K_D values.

It can be observed that with the increase in operating temperature results in an increase in distribution coefficient and extraction efficiency, which could imply that higher temperatures could yield better extraction (up to 303 K).

3.2. Reactive extraction

To improve the extraction efficiency, reactive extraction of PCA was done using TOA in diluent octanol. TOA concentration varied between 0.2287 to 1.1436 kmol m^{-3}. Usage of extractant had led to an enhancement in extraction in expressions of extraction efficiency and distribution coefficient for all acid concentrations and temperature ranges under study, as can be observed from Tables 1, 2, 3, 4, and 5.

The first among the references related to the use of aliphatic amines as extractant and their acid-binding properties were mentioned by Smith and Page [48]. Accordingly, from the aqueous phase, carboxylic acid transfers to the organic phase, i.e., the solvent phase and forms complex with an amine, the mechanism of extraction being acid-base neutralization. Since the solubility of TOA in water is significantly less (0.050 mg L^{-1} at 298 K), the complex formed stays practically in the organic phase [44].

For carboxylic acid extraction from dilute aqueous solution, the interactive forces between the solute and solvent phases should be strong enough, as water solubility of acids is enhanced by the presence of carboxylic and hydroxyl groups. Polar diluents like alcohols are preferred over non-polar diluents as they are found to enhance the extraction efficiency of aminic extractants used [49].

The complexation reaction between PCA and TOA can lead to 1:1, 2:1 or n:1 complexes, which could be represented by the following equations

$$[HP]_{aq} + [TOA]_{org} \leftrightarrow [TOA : HP]_{org} \tag{12}$$

$$[HP]_{aq} + [TOA : HP]_{org} \leftrightarrow [TOA : (HP)_2]_{org} \tag{13}$$

$$[HP]_{aq} + [TOA : (HP)_{n-1}]_{org} \leftrightarrow [TOA : (HP)_n]_{org} \tag{14}$$

Where K_E represents equilibrium complexation constant and can be obtained as

$$K_{E(n:1)} = \frac{[TOA : (HP)_n]_{org}}{[TOA]_{org}[HP]^n_{org}} \tag{15}$$

For reactive extraction containing aqueous and organic phases, i.e., biphasic systems, the complexation reaction could take place at the interface or either in the organic or aqueous phases [50]. It is presumed

Table 6. Calculation of entropy and enthalpy values for Protocatechuic acid extraction at different TOA concentrations.

$[TOA]^0_{org}$ kmol m^{-3}	K_E	$Ln\ K_E$	T (K)	$1/T$ (×10–3, 1/K)	ΔH (J/mol)	ΔS (J/mol. K)
0.2287	14.56	2.68	288	35	2758.06	14.86
	15.04	2.71	293	34		
	16.82	2.82	298	34		
	18.30	2.91	303	33		
	12.63	2.54	308	32	-3083.93	-4.97
	11.66	2.46	313	32		
0.4575	9.23	2.22	288	35	2042.07	11.51
	9.85	2.29	293	34		
	10.38	2.34	298	34		
	11.04	2.40	303	33		
	8.14	2.10	308	32	-1287.01	-0.01
	7.87	2.06	313	32		
0.6862	6.74	1.91	288	35	2652.74	13.04
	8.05	2.09	293	34		
	7.22	1.98	298	34		
	9.03	2.20	303	33		
	6.17	1.82	308	32	-5593.57	-14.55
	5.33	1.67	313	32		
0.9150	5.83	1.76	288	35	3097.28	14.30
	6.78	1.91	293	34		
	7.09	1.96	298	34		
	7.72	2.04	303	33		
	5.18	1.64	308	32	-5622.38	-14.99
	4.47	1.50	313	32		
1.1437	6.30	1.84	288	35	1954.01	10.39
	6.30	1.84	293	34		
	6.80	1.92	298	34		
	7.42	2.00	303	33		
	5.73	1.75	308	32	-6323.07	-17.06
	4.86	1.58	313	32		

that PCA complexation occurs in the organic phase since PCA has non-zero solubility in the organic phase; also, the extractant TOA has good hydrophobicity.

For all concentrations of TOA and all acid concentrations at the various temperatures studied the value of Z was determined to be less than 0.5, which signifies no overloading and the development of 1:1 PCA:TOA complex and stoichiometry of the overall reaction can be found as

$$\frac{Z}{1-Z} = K_E[\mathrm{HP}]_{\mathrm{aq}} \tag{16}$$

A plot of $\frac{Z}{1-Z}$ vs. $[\mathrm{HP}]_{\mathrm{aq}}$ could yield equilibrium complexation constant Z.

With an increase in PCA concentration from 0.001 to 0.01 kmol m^{-3} E % (extraction efficiency) was found to improve, with the highest E% obtained at 0.01 kmol m^{-3} of PCA. This behavior can be attributed to the increase in driving force to house PCA in the organic phase and also the emaciation of the bond amongst water molecules and acid molecules due to the more accessibility of molecules of PCA in aqueous phase [51].

The extractant concentration varied from 10 % to 50 % by volume, and higher TOA concentration was constrained due to factors such as the increase in cost due to higher price of TOA, the higher concentration of extractants may induce toxicity to microorganisms present in the fermentation broth, back-extraction, etc. [52]. Because of the toxicity effects that can be caused by the extractant, for food-grade applications of PCA, in *in-situ* retrieval from the fermentation broth, the acquired data can be used for the development of a process in which membranes can be employed for separating the product and biomass.

Reactive extraction of PCA by TOA occurs by ion exchange or intermolecular hydrogen bonding of extractant with the carboxylic acid. Highest K_D was obtained at 1.1436 kmol m^{-3} of TOA at the temperature of 303 K.

The variation of the degree of extraction with temperature, E% was found to increase from 288 K to 303 K. A similar trends for K_D, was observed by Harington et al. [??] for lactic acid extraction using 20% tri-n-octylamine in sunflower oil at temperatures from 283 to 313 K. The optimal temperatures in fermentation broths are around 311.15 K. Hence compared to extraction experiments performed at room temperature at 311 K, it can result in better extraction, and the trend is considered positive [45].

Further, for 308–313 K, a decrease in extraction efficiency was observed. K_E (equilibrium complexation constant) could be related to temperature by the following equation if enthalpy (ΔH) and entropy (ΔS) of the reaction are presumed to be persistent over the considered temperature ranges [46].

$$\ln K_E = \frac{-\Delta H}{RT} + \frac{\Delta S}{R} \tag{17}$$

The K_E values were estimated for temperatures 288, 293, 298 (data for extraction of PCA using TOA in diluent octanol compared using data available in Antony et al., 2018 [36], 303, 308 and 313 K for the separation of PCA using TOA in octanol. It was observed that K_E values increased up to 303 K, but a sudden decrease at 308 K was seen. Therefore, the calculation of ΔH and ΔS K_E values for 288, 293, 298, and 303 K were considered. Ln K_E vs. 1/T was plotted, the slope is proportional to ΔH (enthalpy of reaction), and intercept to ΔS (entropy). The

Table 7. Diffusion coefficients (*DPA-S*) of protocatechuic acid into organic phase (TOA + octanol) using Wilke- Chang equation and Reddy-Doraiswamy equation at various temperatures.

Temperature (K)	Extractant concentration (in volume %)	$D_{PCA\text{-}S}$ (Wilke- Chang equation) ($cm^2\ s^{-1}$)	Average $D_{PCA\text{-}S}$ (Wilke- Chang equation) ($cm^2\ s^{-1}$)	$D_{PCA\text{-}S}$ (Reddy-Doraiswamy equation) ($cm^2\ s^{-1}$)	Average $D_{PCA\text{-}S}$ (Reddy-Doraiswamy equation) ($cm^2\ s^{-1}$)
288	10	1.147×10^{-6}	7.339×10^{-7}	7.888×10^{-7}	4.736×10^{-7}
	20	8.230×10^{-7}		5.406×10^{-7}	
	30	6.573×10^{-7}		4.145×10^{-7}	
	40	5.557×10^{-7}		3.379×10^{-7}	
	50	4.866×10^{-7}		2.863×10^{-7}	
293	10	1.167×10^{-6}	7.466×10-7	8.025×10^{-7}	4.819×10^{-7}
	20	8.373×10^{-7}		5.500×10^{-7}	
	30	6.687×10^{-7}		4.217×10^{-7}	
	40	5.654×10^{-7}		3.438×10^{-7}	
	50	4.951×10^{-7}		2.913×10^{-7}	
298	10	1.187×10^{-6}	7.594×10^{-7}	8.162×10^{-7}	4.901×10^{-7}
	20	8.516×10^{-7}		5.593×10^{-7}	
	30	6.801×10^{-7}		4.289×10^{-7}	
	40	5.750×10^{-7}		3.497×10^{-7}	
	50	5.035×10^{-7}		2.963×10^{-7}	
303	10	1.206×10^{-6}	7.721×10^{-7}	8.299×10^{-7}	4.983×10^{-7}
	20	8.659×10^{-7}		5.687×10^{-7}	
	30	6.915×10^{-7}		4.361×10^{-7}	
	40	5.847×10^{-7}		3.555×10^{-7}	
	50	5.120×10^{-7}		3.012×10^{-7}	
308	10	1.226×10^{-6}	7.848×10^{-7}	8.435×10^{-7}	5.065×10^{-7}
	20	8.802×10^{-7}		5.781×10^{-7}	
	30	7.029×10^{-7}		4.433×10^{-7}	
	40	5.943×10^{-7}		3.614×10^{-7}	
	50	5.204×10^{-7}		3.062×10^{-7}	
313	10	1.246×10^{-6}	7.976×10^{-7}	8.572×10^{-7}	5.147×10^{-7}
	20	8.944×10^{-7}		5.875×10^{-7}	
	30	7.143×10^{-7}		4.505×10^{-7}	
	40	6.039×10^{-7}		3.673×10^{-7}	
	50	5.289×10^{-7}		3.112×10^{-7}	

calculated values of ΔS and ΔH are reported in Table 6. Negative values of enthalpy point out the exothermic nature of the extraction process.

It can be observed that extraction efficiency decreases as temperature increases from 303 K to 313 K. The rise in temperature affects the interaction between PCA molecules and TOA molecules, which leads to a decrease in extraction efficiency. Using the thermodynamic approach, the decrease in entropy can be attributed to acid-extractant complex formation in the organic phase, which makes the system more ordered [46]. Thus it can be interpreted that beyond 303 K, the temperature has negatively affected the recovery of PCA for all initial acid as well as extractant concentrations. However, while comparing the extraction percentages, the effect was not drastic.

The five important potential interaction identified among the carboxylic acids and extractant includes van der Waals forces, hydrogen bonding, dipole interactions, hydrophobic interactions, and electrostatic forces, among this hydrogen bonding and hydrophobic interactions are the most important ones. Generally, $\Delta S < 0$ represents van der Waals forces and hydrogen bonding, $\Delta S > 0$ displays electrostatic and hydrophobic forces and further $\Delta S > 0$ and $\Delta H > 0$ classified as hydrophobic interaction, else van der Waals forces and hydrogen bonding [53].

3.3. Water coextraction

Water coextraction refers to the water that enters from the aqueous to the organic phase resulting from the solubility of water in the organic phase. Water coextraction studies were done for PCA –TOA-octanol system at various acid and extractant concentrations at various temperatures. Water coextraction studies are important for the extraction process of dilute polar organic solutions as both, the process economy and the solvent selectivity are affected by it [54]. During the regeneration step, it is necessary to recover the extracted acid back, and the coextraction of water can affect the process economics.

For the extraction process using amine extractants, in general, acid selectivity over water is high, when compared to extraction using conventional solvents [46]. Phase volume measurements indicated no particular tendency for water coextraction in general. The temperature did not have any significant effect on water coextraction. In all the cases studied, it was observed that water coextraction was less than 5%, thus concluding the selectivity of PCA over water is high in the extraction process by the extractant and further water coextraction has slight influence upon process feasibility. Further low water coextraction values were expected as PCA is a monocarboxylic acid, and water molecules is co-extracted by the carboxylate groups.

3.4. Diffusion coefficient

Through diffusion as well as solubilization mechanism transfer of PCA molecules to the interface of the aqueous phase and organic phase take place [55]. In the organic phase, diffusional resistances are accounted mainly for the higher molecular weight of the organic complexes produced and also the higher viscosity of the organic phase [56]. Stefan diffusion applies for the case of the solvent/extraction system, which is an ideal, where in the organic diluent will be practically water-immiscible, and merely the solute only will pass the interface [57].

Table 8. Minimum solvent – to – feed (S/F) ratio and number of theoretical stages (NTS) for the recovery of protocatechuic acid at various temperatures.

Temperature (K)	XPCA in	XPCA out	KD	(S/F)min	(S/F)act	EX	NS
288	0.001	0.0002	3.69	0.2130	0.3195	1.1805	2.6989
	0.003	0.0005	4.88	0.1701	0.2551	1.2449	3.0721
	0.005	0.0007	5.99	0.1430	0.2145	1.2855	3.3697
	0.007	0.0009	6.67	0.1304	0.1955	1.3045	3.5323
	0.01	0.0010	8.88	0.1012	0.1518	1.3482	3.9898
293	0.001	0.0002	3.96	0.2016	0.3024	1.1976	2.7887
	0.003	0.0005	5.28	0.1593	0.2390	1.2610	3.1830
	0.005	0.0007	6.12	0.1405	0.2108	1.2893	3.4005
	0.007	0.0009	7.00	0.1250	0.1875	1.3125	3.6069
	0.01	0.0011	8.16	0.1092	0.1638	1.3362	3.8504
298	0.001	0.0002	4.24	0.1910	0.2865	1.2135	2.8777
	0.003	0.0005	5.51	0.1535	0.2303	1.2697	3.2466
	0.005	0.0007	6.30	0.1371	0.2056	1.2944	3.4439
	0.007	0.0008	7.38	0.1193	0.1790	1.3211	3.6904
	0.01	0.0010	9.33	0.0968	0.1452	1.3548	4.0722
303	0.001	0.0002	4.81	0.1720	0.2580	1.2420	3.0530
	0.003	0.0004	5.94	0.1440	0.2160	1.2840	3.3576
	0.005	0.0006	7.49	0.1178	0.1767	1.3233	3.7131
	0.007	0.0008	7.64	0.1158	0.1737	1.3263	3.7440
	0.01	0.0009	10.23	0.0891	0.1336	1.3664	4.2279
308	0.001	0.0002	3.48	0.2234	0.3351	1.1649	2.6218
	0.003	0.0005	4.50	0.1817	0.2725	1.2275	2.9611
	0.005	0.0007	5.71	0.1491	0.2237	1.2763	3.2969
	0.007	0.0010	6.32	0.1366	0.2050	1.2950	3.4493
	0.01	0.0011	7.93	0.1120	0.1680	1.3320	3.8044
313	0.001	0.0003	2.77	0.2654	0.3981	1.1019	2.3487
	0.003	0.0007	3.60	0.2173	0.3260	1.1740	2.6662
	0.005	0.0009	4.78	0.1730	0.2595	1.2405	3.0432
	0.007	0.0011	5.25	0.1600	0.2400	1.2600	3.1758
	0.01	0.0013	6.63	0.1310	0.1965	1.3035	3.5236

There are many semi-empirical correlations developed to predict diffusivities in liquids, the popular ones being Wilke and Chang (1955) equation and Reddy-Doraiswamy equation. The Wilke and Chang equation for calculating the diffusion coefficient of PCA into the organic phase is as follows [58, 59].

$$D_{PCA-S} = \frac{7.4 \times 10^{-8} (\Delta M)^{0.5} T}{\mu (V_{PCA})^{0.6}} \tag{18}$$

Where D_{PCA-S} is the diffusivity of PCA diluted in solvent S ($cm^2\ s^{-1}$), the molecular weight of the solvent is M, the viscosity of solvent in cP is μ, T the temperature in K, V_{PCA} is the molar volume of solute, PCA in cc.(g mole)$^{-1}$ and ϕ is the association factor used for solvent (1.9 for methanol, 2.6 for water as the solvent, 1.5 for ethanol, 1.0 for non-associated solvents).

The following equation gives the Reddy-Doraiswamy equation for calculating the diffusion coefficient of PCA:

$$D_{PCA-S} = \frac{(C) M^{0.5} T}{\mu (V_{PCA} V_S)^{\frac{1}{3}}} \tag{19}$$

V_S is the molar volumes of the solvent in cc(g mole)$^{-1}$. And C is a constant whose value depends on the ratio of V_{PCA}/V_S. If $V_{PCA}/V_S \leq 1.5$, then $C = 10 \times 10^{-8}$ and for $V_{PCA}/V_S > 1.5$, $C = 8.5 \times 10^{-8}$. At different extractant concentrations over the different ranges of temperature considered, the value of the diffusion coefficient for PCA was calculated by using the above two equations, and the results are presented in Table 7.

3.5. Calculation of number of stages required

The lowest solvent to feed ratio and number of stages required for the countercurrent extraction of PCA using TOA in octanol at temperatures from 288 K to 313 K is calculated to access the viability of the extraction process. The lowest solvent to feed ratio required is computed using Eq. (20), further the actual solvent to feed ratio required is calculated by taking 1.5 times the minimum, for a finite number of stages extraction process [60].

$$\left(\frac{S}{F}\right)_{min} = \frac{x_{PCAin} - x_{PCAout}}{K_D x_{PCAin} - y_{PCAin}} \tag{20}$$

In Eq. (19) $x_{PCA\ in}$ and, $x_{PCA\ out}$ represents the PCA concentrations in the feed phase and the raffinate phases, and $y_{PCA\ in}$ is the original concentration of PCA in the extract phase.

Further, the modified Kremser equation represented by Eq. (21), is used to calculate the number of stages required for the extraction process [61].

$$NS = \frac{ln\left[\left(\frac{x_{PCAin} - y_{PCAin}/K_D}{x_{PCAout} - y_{PCAin}/K_D}\right)(1 - 1/E_x) + \frac{1}{E_x}\right]}{lnE_x} \tag{21}$$

In Eq. (22), E_x is the extraction factor which can be calculated as follows

$$E_x = K_D \frac{S}{F} \tag{22}$$

For calculating the minimum number of stages in counter-current extraction processes, the higher values of S/F obtained were used since lower values results in values much lesser than the practical minimum for extraction columns. The results obtained at different temperatures are summarised in Table 8. It can be observed that for attaining efficiency of 91.1 % at 303 K, nearly four stages will be required.

4. Conclusions

The effect of temperature on separation with reaction of PCA was done using aminic extractant TOA dissolved in alcohol, octanol in the temperature ranges from 288 K to 313 K the highest extraction efficiency was obtained as 91.09% and distribution coefficient as 10.22, at an acid concentration of 0.01 kmol m^{-3} and TOA concentration of 1.1436 kmol m^{-3} at 303 K. The values of loading ratios confirm the built of 1:1 complex of PCA and TOA in all the cases. From 288 K to 303 K extraction efficiency was found to be improved with temperature for all acid and extractant concentrations and was further found to decrease with a further rise in temperature. PCA – TOA complexation was found to be exothermic.

Declarations

Author contribution statement

Fiona Mary Antony: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Kailas L Wasewar; Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2020.e03664.

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