CI&CEQ
Chemical Industry & Chemical Engineering Quarterly

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Chem. Ind. Chem. Eng. Q. 27 (3) 241–254 (2021) CI&CEQ

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SCIENTIFIC PAPER

UDC 58:66.061

TECHNO-ECONOMIC ANALYSIS OF CATECHIN MIX MANUFACTURE FROM *Camellia sinensis* LEAVES USING GREEN EXTRACTION TECHNOLOGY

Article Highlights

- Commercial manufacture of catechin mix from *Camellia sinensis* leaves was investigated
- Process modelling and economic analysis were performed by using SuperPro Designer software
- The conceptual process is economically attractive at large production scales
- Catechin mix selling price had highest perturbation on the selected economic parameters

Abstract

This work designed, modeled and performed economic analysis of the base case extraction and recovery of catechin mix (CM) from Camellia sinensis leaves (CSL) using deep eutectic solvent (DES) and microwave assisted extraction (MAE) with the assistance of SuperPro Designer software. Techno-economic analysis of three commercial scales of manufacture was also investigated and compared using profitability parameters. Sensitivity and uncertainty analyses were further carried out on the most viable commercial scale to determine input variable(s) of highest significance on the profitability of the process. The 3.30 kg CM/batch is the most economically desirable scale with return on investment of 324.65%, payback period of 0.31 years, internal rate of return of 163.83% and net present value of $1,059,595,224. Out of the input variables selected for the sensitivity and uncertainty analyses, CSL and DES costs have the least effect on the selected profitability parameters of the process.

Keywords: techno-economic analysis, Camellia sinensis, deep eutectic solvent, microwave assisted extraction.

Catechins belong to a class of natural phenolic compounds (flavan-3-ols) and they exhibit powerful antioxidant properties. Catechins occur naturally in varieties of food and herbs such as tea [1-3], berries [4,5], apples [6-8] and grapes [9,10]. However, catechins from green tea sources have remained the most extensively studied [11]. The major catechins in green tea are (-)-epigallocatechin-3-gallate (EGCG), (-)-epigallocatechin (EGC), (-)-epicatechin (EC) and (-)-epicatechin-3-gallate (ECG) [12] which are mainly responsible for the astringent and bitter taste of green tea brews [13]. Many scientific studies suggest that tea catechins have antibacterial, antiviral, and hepatoprotective effects. There are evidences that tea catechins are potent and play a significant protective and preventive role against cancer, diabetes, liver diseases, neurodegenerative diseases, and they have anti-obesity properties as well [14]. These numerous health benefits derived from tea catechins made them have wide applications in food and pharmaceutical industries [15] and increased interest in their efficient extraction and purification. Therefore, an efficient and safe extraction system is needed for the accurate quantification of the catechins in teas and tea products and as an efficient first step for the preparation

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Paper received: 28 May, 2020
Paper revised: 11 October, 2020
Paper accepted: 9 November, 2020

https://doi.org/10.2298/CICEQ200528044O

of catechins extracts and for the isolation of individual catechins [3].

Green extraction technique of extracting bioactive compounds is becoming popular [16-20] and has become one of the key issues in scientific and industrial research and development [18]. Green extraction permits the recovery and design of extraction processes which reduces energy consumption and uses alternative solvents and renewable natural products, minimizing the environmental impact, and ensures safe and high qualities of extract [16,18,21]. Over the years, a new kind of solvents, known as deep eutectic solvents (DES) was developed and has found wide applications due to their properties. In recent years, DES have received attention as extraction solvents for bioactive compounds over conventional solvents due to their environmental friendliness, non-hazardous nature, high solute extractability and low melting point. DES is a green solvent that is comprised of a mixture of simple, cheap, and naturally occurring compounds with a high safety profile [16] such as a hydrogen acceptor (usually choline chloride) and a hydrogen bond donor (generally natural plant-based organic ions, such as amino acids, carboxylic acids, sugars, etc.) in a solid state that associate with hydrogen bonding [19]. They have other fascinating properties like negligible volatility at room temperature, high water miscibility, non-flammability, and high viscosity. The high viscosity of DES can however be tuned by addition of water [17] and increasing temperature, which enhances high bioactive extractability and yield. At present, the recovery of phenol contents from DES after extraction are through liquid−liquid extraction using another solvent, solid−liquid extraction using resin or molecular sieves, and precipitation by addition of antisolvents [22].

Beside extraction solvents, the selection of extraction method is of important consideration for high yield of catechins. Conventional methods of extraction (such as heating, boiling, or refluxing) of polyphenols from plant matrix have been identified to take longer extraction times and large extraction solvents [18] making the extraction of bioactives inefficient and the process cost-ineffective. Recently, some environmentally friendly assisted extraction methods have been developed and have become popular because of their high extraction efficiency while maintaining the integrity of the solute compounds. Among the several assisted methods being presently investigated for the extraction of catechins is the microwave assisted extraction (MAE) method [23-26]. MAE is an extraction technique that uses microwave energy and solvent to extract the target compounds from various matrices. Microwaves are non-ionizing electromagnetic radiation within the frequency band of 300 MHz to 300 GHz with 915 MHz, considered most useful for industrial applications with its greater penetration depth [27]. MAE is viewed as green extraction technique and has been reported to save time and energy and is a highly efficient method of extraction [25,28]. Microwave heating has been shown to lead to wider process engineering benefits when carried out at large scale, such as a reduction in equipment size and simplification of processing steps when compared to conventional methods, which results in further economic benefits [29].

Although laboratory studies have indicated that catechins can be recovered from plant matrix such as *Camellia sinensis* leaves (CSL) using the newly developed green DES solvents and assisted extraction methods [15], a full economic evaluation for this type of extraction system is still needed to check the commercial viability of this process. Techno-economic analysis of the manufacture of catechins from CSL using choline-based DES combined with MAE has not been investigated at commercial scales to the best our knowledge. Computer aided process simulation (CAPS) is one of the tools that can be used to achieve the above objective. CAPS involves the use of computers packages to perform steady-state heat and mass balancing, as well as equipment sizing and costing calculations for a process [30]. CAPS offer other fascinating advantages such as pin-pointing the economic “hot-spot” of a process (the processing step of high capital and operating cost which gives low process yield and/or production throughput) and in process optimization [30]. Although the use of CAPS is relatively new in many process industries, it has been successfully used in simulating and debottlenecking industrial cocoa manufacturing processes [30], liquid biofertilizer plants [31], cellulosic butanol production [32], extraction of turmeric oil and ar-turmerone using supercritical carbon dioxide [33] and oleoresin production from malagueta peppers (*Capsicum frutescens*) by supercritical fluid extraction [34].

In this work, Superpro Designer v.9 software [35] was employed to model and analyze the economics of manufacture of purified catechin mix (CM) using choline-based DES and MAE. The objectives of this work are therefore to: *i*) develop and perform the economic analysis of the laboratory base case model using the experimental data of Li *et al.* [15]; *ii*) develop, assess and compare the economics of three commercial scales (0.063, 1.522 and 3.30 kg/batch of CM) using some economic parameters such as return on investment (ROI), payback period (PBP), internal rate of return (IRR), net present value (NPV), annual revenue and net profit; *iii*) carry out sensitivity and uncertainty analysis on the most viable commercial scale by incorporating Crystal Ball software into SuperPro Designer, in order to identify the input variables that will affect the profitability of the selected manufacturing scale profoundly.

METHODOLOGY

Process modeling and simulation of CM manufacture

The manufacture of CM from CSL using deep eutectic solvent of choline chloride and lactic acid (DES-4) and MAE technology was modeled and simulated using SuperPro Designer version 9 [35]. SuperPro Designer software which has several equip ment, unit operations and chemical compounds in its databank, was responsible for the calculation of mass and energy balances and for the sizing of all appropriate equipment available in the manufacturing process. It was also responsible for the calculation of heating agents and power requirements by each equipment. The major unit operations featured in the simulation were size reduction (raw material preparation), extraction, adsorption chromatography (separation and purification), evaporation and condensation units with main product being CM which comprised of (-)-epicatechin (EC), (-)-epigallocatechin (EGC), (-)-epicatechin gallate (ECG) and (-)-epigallocatechin gallate (EGCG).

Figure 1 is the flowsheet for the base case process designed by using SuperPro Designer software. The operating equipment conditions and solvent compositions used for the base case process were the means of the optimum process variable values of experimental investigations of Li *et al.* [15]. The values were used with the assumption that the industrial plant will have identical performance with laboratory scale if the same operating conditions are used for constructing an industrial plant [29], and these are presented in Table 1. The operation data considered for the extraction operation were extraction temperature, extraction time, solvent-to-feed ratio and extract yield while for the separation and purification unit were resin binding capacity, loading, eluant and wash flowrates.

In the course of building the base case, some of the components used for the process simulation were not present in the SuperPro Designer databank and therefore were registered as user-defined pure components and mixtures. Table 2 shows the components and solutions used with their respective types and referenced components. CSL, DES-4 and 90% aqueous ethanol were registered as stock mixtures and were initialized using biomass, $(NH_4)_2SO_4$ and ethanol (10 mass%), respectively, and were all user-defined. Except for choline chloride which was a user-defined component, other pure components' properties used in the simulation (such as lactic acid and water) were obtained from the databank of the software.

CSL was pulverized to 2 mm particle size using P-1/GR-101 that operates at 0.004 kg/h. The pulverized CSL, modeled to contain EC, EGC, ECG, EGCG, fiber and other components, was transferred along with DES-4 into a microwave extractor P-3/R-101. For microwave extraction, a magnetron microwave generator that generates electromagnetic energy is attached to achieve fast vessel heating with homogeneous microwave distribution throughout the vessel [29]. The electromagnetic energy delivered by a transmission line to microwave extractor was then

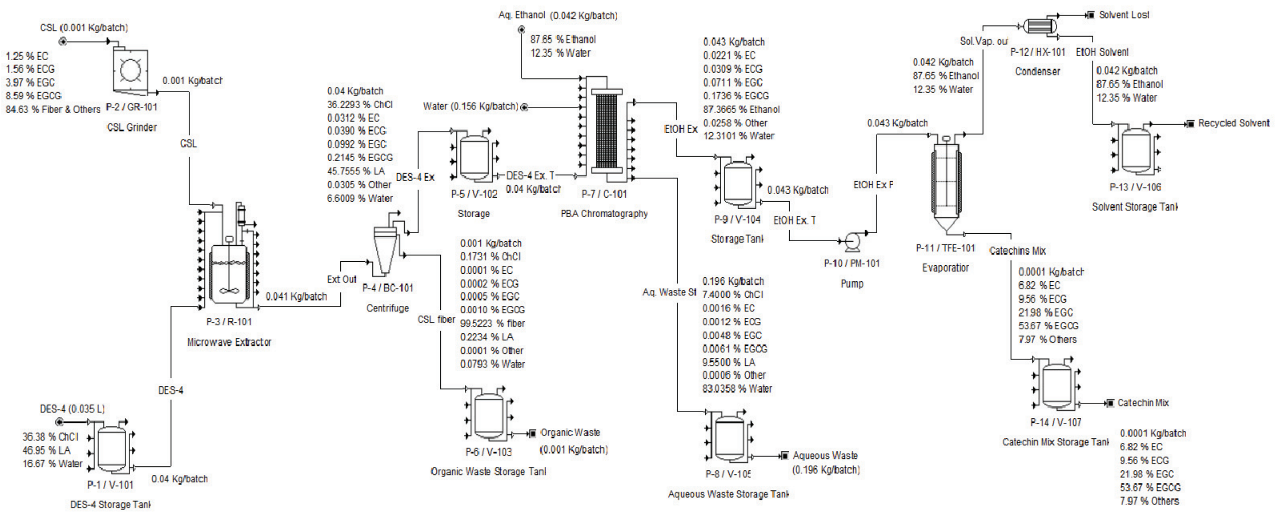

Figure 1. Simulation flowsheet and mass balance for base case production of CM.

used to heat the content of the extractor to 66 °C and extraction of bioactive from CSL continued for 8 min at this temperature.

Table 1. Operation conditions for the base case simulation of CM from CSL

Experimental conditions	Value
Extraction unit [15]	
Extraction temperature	66 °C
Extraction time	8 min
Solvent to feed ratio	1:35
Extraction yield	15.37 %[a]
(-)-epicatechin (EC)	12.5 mg/g
(-)-epigallocatechin (EGC)	39.7 mg/g
(-)-epicatechin gallate (ECG)	15.6 mg/g
(-)-epigallocatechin gallate (EGCG)	85.9 mg/g
Separation and purification units [15]	
Resin name - AB-8 macroporous resin	
Resin binding Capacity	6.342 mg/ml
Loading flowrate	3.000 BV/h
Washing flowrate	3.000 BV/h
Eluant flowrate	2.000 BV/h
Recovery yield in the packed column	
(-)-epicatechin (EC)	75.2 %
(-)-epigallocatechin (EGC)	76.3 %
(-)-epicatechin gallate (ECG)	84.5 %
(-)-epigallocatechin gallate (EGCG)	86.1 %
Evaporation and condensation Units (user defined)	
Process time for evaporation	30 min
Operating temperature for evaporation	85.59 °C
Operating pressure for evaporation	1.013 bar
Heat transfer coefficient of evaporator	2904.913 W/(m^2 K)
Heat transfer efficiency of evaporator	90 %
Operating temperature for condensation	20 °C
Operating pressure for condensation	1.013 bar
Heat transfer coefficient of condenser	860.440 W/(m^2 K)
Heat transfer efficiency of condenser	90 %
Solution compositions [15]	
DES-4	Choline chloride: lactic acid = 1:2 + 20% water
90 vol.% Ethanol	Ethanol:water = 90 :10

[a]Calculated from experimental data

The extract-solvent and solid mixture from microwave extractor P-3/R-101 was transferred to a bowl centrifuge P-4/B-101 for CSL fiber removal. The condition in P-4/B101 is complete CSL fiber removal while 10% removal of extract-solvent was assumed to account for product losses [36]. The separated fiber residue and extract-solvent mixture were transferred to P-6/V-103 and P-5/V102, respectively, for temporary storage. Separation of the extract-solvent mixture and purification of the extract were done in a packed bed adsorption (PBA) chromatography column P-7/C--101 with bed height and diameter of 0.250 and 1.80 m, respectively. The P-7/C-101 was packed with AB-8 macroporous resin with binding capacity of 6.342 mg/mL before the column operation began. The primary function of AB-8 macroporous resin in P-7/C--101 is to retain the main product (catechins) while allowing DES-4 solvent to pass through. Extract-solvent separation commenced by loading P-7/C-101 with extract-solvent mixture stored in P-5/V-102 at flowrate of 3 BV/h. The adsorbate laden AB-8 macroporous resin was washed with 3 BV of deionized water to remove DES-4 solvent and other associated impurities. The washed DES-4 solvent and bulk of water-soluble impurities of the extract were stored in P-8/V-105 as aqueous waste stream. 2 BV of 90% aqueous ethanol at flowrate of 6 BV/h was afterwards used to elute catechins and the ethanol-catechins mixture was stored in P-9/V-104 storage tank. One cycle per batch of chromatographic cleaning was done with recovery of 75.2, 84.50, 76.30 and 86.10% for EC, ECG, EGC and EGCG, respectively, with less than 10% impurities [15].

A centrifugal pump that operates at 1 bar and is 70% efficient was used to transport the ethanol-catechins mixture to a thin film evaporation unit P-11/ /TFE-101 with heat transfer coefficient and efficiency of 2104.913 W/(m^2 K) and 90%, respectively. The steam was used as the heating agent and the main product was obtained as “Catechin Mix”.

The evaporated aqueous ethanol was re-condensed in P-12/H-101 with heat transfer coefficient

Table 2. Components and solution used in flowsheet simulation

Stream	New registered?	Reference component (updated properties)	Database source
CSL	Yes (Stock mixture)	Biomass	User-defined
DES-4	Yes (Stock mixture)	$(NH_4)_2SO_4$	User-defined
Lactic acid	Yes (Pure component)	Lactic acid	Designer
Choline chloride	Yes (pure component)	Water	User-defined
Water	No	Water	Designer
90 % ethanol	Yes (Stock mixture)	Ethanol (10 % w/w)	User defined
Nitrogen	No	Nitrogen	Designer
Oxygen	No	Oxygen	Designer

and efficiency of 860.44 W/(m^2 K) and 90%, respectively, and stored in P-13/V-106. The process scheduling which allotted time to a specific process task was well documented and is as shown in Table 3. The setup time for all operations was assumed to be 5 min.

Scale-up studies and economic analysis

The batch extraction with microwave technology is restricted to smaller scales due to the limitation of maximum power (100 kW) that can be generated by currently available industrial microwave generator [29]. For this reason, three other batch sizes (0.063, 1.522 and 3.30 kg CM) that match the presently available industrial extractors in terms of size and microwave power requirements were selected. The selected batch sizes were simulated to determine the throughput, energy and equipment sizes needed to produce CM from CSL. The cost tools in SuperPro Designer software were used for obtaining information regarding the purchase cost of all conventional equipment (according to their respective sizes) while the cost of magnetron microwave generator was obtained from literature [37]. Therefore, in order to account for variability in equipment cost that resulted from process scale-up, the cost of a tunable 915 MHz magnetron microwave generator, capable of providing up to 100 kW was added to the cost of the extraction vessel needed to process a batch size. SuperPro Designer software was also used for the economic analysis of all scales of manufacturing of CM considered. Prior to conducting economic analysis of the process, all inlet and outlet streams were classified as raw material, waste and revenue, and their respective economic values were specified.

The amounts in kilograms for all production scales considered were also specified, as shown in Table 4. The cost of CSL was taken as $5/kg which represents the average cost of CSL found in the literature [38]. The costs of DES-4 and 90% ethanol were estimated from the price of pure lactic acid, choline chloride and water, which were obtained as 77.64, 79.0 and $0.1/kg [39], respectively. The selling price of purified CM consisting of EC, ECG, EGC and EGCG was obtained to be $0.53/mg [40]; however, a fraction (one-tenth) of this value was used for the simulation while CM selling price variability was considered in sensitivity analysis. This is to achieve close comparison with literature [41]. The costs of organic and aqueous waste treatment were assumed to be 2 and $0.5/kg [42], respectively.

Table 5 shows the various materials, assumptions, cost parameters and factors used for the simulation of the economics of the process. The process mode of operation was modeled as batch while the

Table 3. Scheduling summary for the base case model; PT = process time; ST = start time; MSR = master-slave relationship; setup time for all operation was taken as 5 min

Procedure/Equipment (operation)	Operation	PT	ST
P-1/V-101 (Storage)	Store DES-4 Solvent	10 min	Beginning of batch
P-2/GR-101 (Grinding)	Grind CSL	15 min	Beginning of batch
P-3/RV-101 (Extractor)	Transfer in CSL	MSR with Grind in P-2	At the end of grind CSL
	Transfer in DES-4	MSR with Transfer in CSL	At the end of transfer in CSL
	Heating	5 min	At the end of transfer in DES-4
	Extract	8 min	At the end of heating
	Transfer out mixture	MSR with Centrifuge in P-4	At the end of extract
P-4/BC-101 (Centrifuge)	Centrifuge mixture	20 min	Start with transfer out P-3
P-5/V-102 (Storage)	Transfer in extract	MSR with Centrifuge in P-4	Start with centrifuge in P-4
P-6/V-103 (Storage)	Transfer in fiber	MSR with Centrifuge in P-4	Start with centrifuge in P-4
	Store fiber	60 min	Start with transfer in fiber
P-7/C-101 (Chromatography)	Load	30 min	Start with transfer in extract in P-5
	Wash	2 h	At the end of load
	Elute	1.5 h	At the end of wash
P-8/V-104 (Storage)	Store	2 h	Start with wash in P-7
P-9/V-105 (Storage)	Transfer in	MSR with elute in P-7	Start with elute in P-7
P-10/PM101 (Pump)	Pump	MSR with transfer in in P-9	At the end of transfer in from P-9
P-11/TFE-101 (Evaporation)	Evaporate	30 min	At the end of pump in P-9
P-12/HX-101 (Condensing)	Condense	1 h	Start with evaporate in P-11
P-13/V-106 (Storage)	Store	1 h	At the end of condense in P-12
P-14/V-107 (Storage)	Store	2 h	At the end of evaporate in P-11

Table 4. Inlet and outlet stream classification

Streams	Type	Economic value ($/kg)	kg/batch of the scales			
			Base case	0.063 kg	1.522 kg	3.30 kg
Inlet						
CSL	Raw material	5	0.001	0.457	11.045	26.021
DES-4	Raw material	65.0962	0.04000	18.229	440.394	1037.525
Aq. Ethanol	Raw material	0.7	0.04200	19.413	468.985	1016.852
Water	Raw material	0.1	0.15610	71.370	1724.209	3758.332
Outlet						
Aqueous waste	Waste	0.5	0.196	89.610	2164.869	4693.868
Organic waste	Waste	2	0.001	0.383	9.257	20.071
Solvent lost	None	-	-	-	-	-
Recycled solvent	None	-	-	-	-	-
Catechins Mix	Revenue	53000	0.00013	0.0630	1.522	3.30

project lifetime of 15 years, startup time period of 4 months and annual production time of 7920 h were assumed for the simulation.

Economic analysis of different scales of manu-fac-ture of CM from CSL using DES-4 solvent which involved estimation of total capital investment and total operating costs was done according to the pro-cedure of Baral and Shah [32]. The total capital investment cost was comprised of the direct fixed capital (DFC) investment, working capital and start-up cost. The DFC is the fixed assets of an investment and it is calculated as the sum of plant direct cost (PDC), plant indirect cost (PIC) and miscellaneous cost (MC). The operating cost is the cost that is dir-ectly dependent on the production rate of the final product. Operating cost is comprised of raw materials

Table 5. Assumption used for economic analysis [32]; PC = equipment purchase cost; PDC = plant direct cost; PIC = plant indirect cost; DFC = direct fixed capital; working capital was estimated to cover expenses for 30 days of labor, raw materials, utility and waste disposal

Time parameters	Value	Financing parameters	Value	Construction plan	Value
Year of Analysis	2020	Equity (%)	40	1st year (% of DFC)	30
Year of construction	2020	Loan term (years)	10	2nd year (% of DFC)	40
Construction period (months)	30	Depreciation method	Straight line	3rd year (% of DFC)	30
Start-up period (months)	4	Depreciation period (year)	10	Plant direct cost (PDC) parameters	
Project life (year)	15	Income tax rate (%)	40	Process piping (% of PC)	35
Inflation rate (%)	4	Operating parameters:		Instrumentation (% of PC)	40
Plant indirect cost (PIC) parameter:		Annual operating time (h)	7920	Insulation (% of PC)	3
Engineering (% of PDC)	25	Salvage factor (% of DFC)	5	Electrical (% of PC)	10
Construction (% of PDC)	35	Start-up cost (% of DFC)	5	Buildings (% of PC)	45
Miscellaneous cost (MC) parameter:		Facility dependent cost:		Yard improvement (% of PC)	15
Contractor's fee, % of (PDC + PIC)	5	Maintenance and repair (% of DFC)	6	Auxiliary Facilities (% of PC)	40
Contingency (% of PDC +PIC)	10	Insurance (% of DFC)	1		
		Local taxes (% of DFC)	2		
		Factory expenses (% of DFC)	5		
		Lab/QC/QA cost (% of TLC)	15		
		Utility cost:			
		Microwave Energy	$0.13/kWh		
		Steam	$12/metric ton		
		Chilled water	$0.4/metric ton		
		Cooling water	$0.05/metric ton		
		Standard electricity	$0.1/kWh		

cost, labour cost, facility dependent cost, consumables cost, waste treatment and/or disposal cost, laboratory/QC/QA cost and utility cost. Profitability parameters such as return on investment (ROI), payback period (PBP) (the time required to recover the cost of an investment), net present value (NPV) (the difference between the current value of cash inflows and the present value of cash outflow), internal rate of return (IRR) (the rate of return at which the projects present NPV equal to zero [34]), annual revenue and net profit were also calculated and compared for all scales of manufacture of CM.

AB-8 macroporous resin was assumed to cost $\$8000/m^3$ [39]. The consumable life in the PBA chromatography was assumed to be 4 cycles and therefore AB-8 microporous resin was replaced after every 4 cycles of chromatography operation. The labor rate which includes basic rates, benefits, supervision, operating supplies and administration was assumed to be $69/h with four (4) operators working in the plant. Steam and chilled and cooling water were used as heating and cooling agents, respectively, with respective costs shown in Table 5. Microwave heating was used for the heating and extraction of CSL and the electricity required to generate microwave energy was assumed to cost $0.13/kWh and standard electricity was $0.1/kWh [29].

Sensitivity and uncertainty analyses

The 3.30 kg CM/batch scale has the most desirable economic indices with highest ROI and lowest PBP of 324.65% and 0.31 year, respectively. Input variables that have profound effects (with higher tendency of variability) on the economic parameters such as CSL cost, DES-4 cost, CM price and resin binding capacity, were subjected to sensitivity and uncertainty analyses using SuperPro Designer software and Monte Carlo simulations available in Crystal Ball software. Monte Carlo simulation (*via* Crystal Ball software) was incorporated into steady-state process simulation in SuperPro Designer using component object module (COM) function available in SuperPro Designer software, according to Lim and Foo [40]. The interaction between SuperPro Designer and Crystal Ball is facilitated by COM.

Table 6 shows the selected input variables, their assumed distributions and range of values used for the simulation of the process in Crystal Ball.

In the course of simulation in Crystal Ball, the assumption cells were the input variables while the forecast cells were the key selected economic parameters (revenue and net profit). 3000 iterations/simulations were run in order to ensure low mean standard error in the selected economic parameters.

Table 6. Input variables used for uncertainty analysis

Input variable	Base case values	Distributions	Range of variables
CSL cost	$5/kg	Uniform	0.42-7.00
DES-4 cost	$65.0962/kg	Normal	59-71
CM price	$53000/kg	Triangular	47700-58300
Resin binding capacity	6.342 mg/ml	Triangular	5.71-15.00

RESULTS AND DISCUSSION

Base case simulation and economic analysis

Figure 2 is the operational Gantt chart for the base case simulation for the manufacturing of CM from CSL. It should be noted that the entire process took 7.90 h to produce 0.00013 kg of CM, while the cycle time was 3.07 h.

The number of batches when based on the annual operating time of 7920 h was 2579 batches/ /annum. Table 7 is the summary of stream information for specific important streams in the process. As can be seen, the total content of 0.0001 kg of CM was produced per batch which is in close agreement with the laboratory scale results of Li *et al.* [15]. Therefore, the base case model (Figure 1) was able to represent the laboratory proof of concepts of manufacturing of CM reported by Li *et al.* [15]. Hence, the model can be used for the scale-up and economic studies of the manufacturing of CM from CSL using DES-MAE method. It should also be noted that the 0.00013 kg in Table 7 comprised of 0.00001 kg of EC, 0.00001 kg of ECG, 0.00003 kg of EGC, 0.00007 kg of EGCG, and 0.00001 kg other components.

Table 7 also shows how materials were transported in different process streams and further shows that the CM stream which is the only revenue stream in the process contained CM of high purity (>92%). Table 8 presents the results of major equipment sizing and economic evaluation of the base case model.

It is clear from Table 8 that base case model which represents laboratory proof of concept is not economically viable with gross margin of -34857.07%, ROI of -41.56%, NPV of $-48,958,721 with no realistic IRR and PBP. This is apparent because of the high investment and operating costs incurred which translate to very high production cost because of the relatively small capacity of the plant. It is therefore apparent that plant capacity scale-up is a must for this type of process to become profitable.

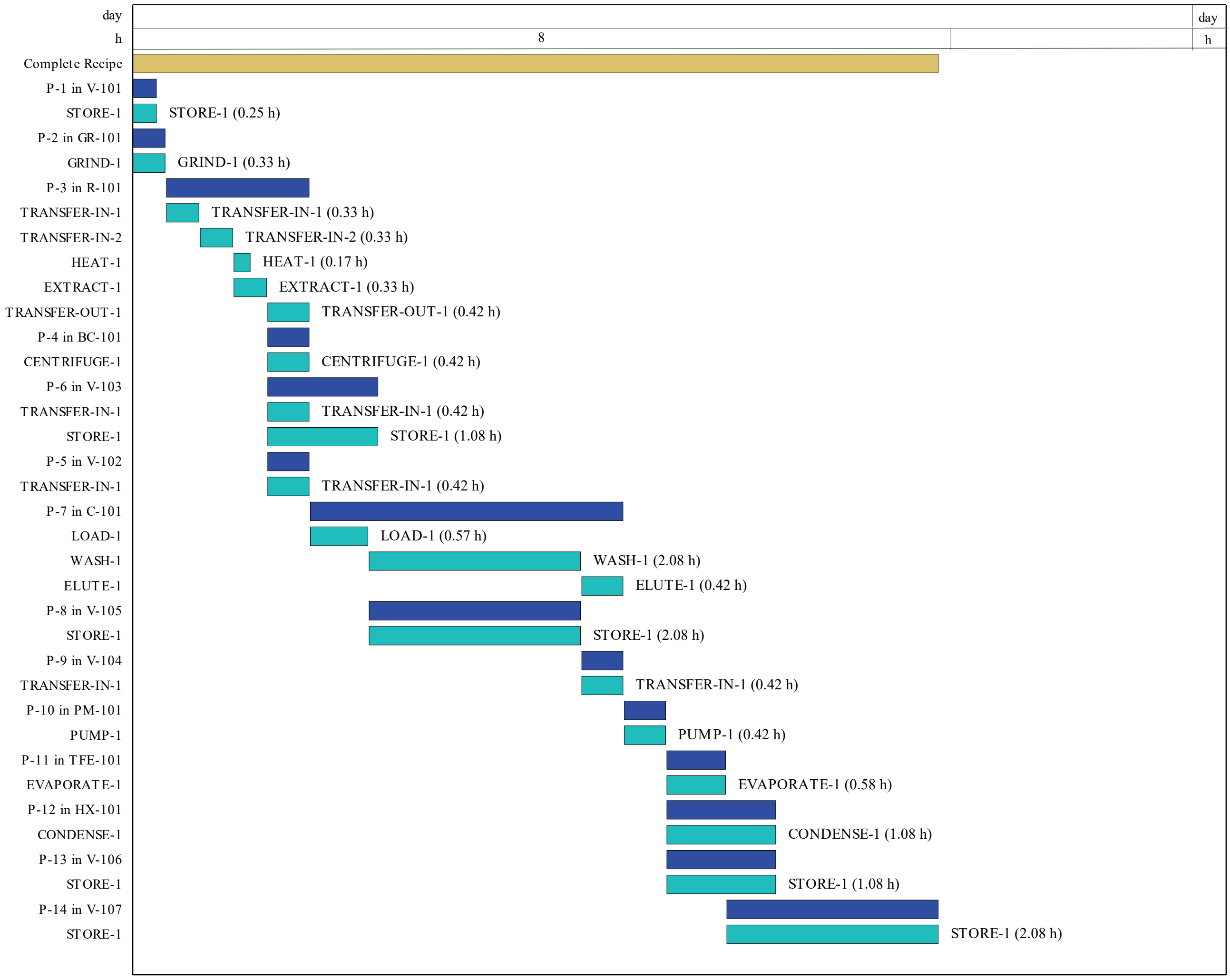

Figure 2. Operation Gantt chart of base case model.

Table 7. Stream Summary for the base case

Time Ref: Batch	CSL	DES-4	Aq. Ethanol	Water	EtOH Ex.P	DES-4 Ex	Catechin Mix
Type	Raw material	Raw material	Raw material	Raw material	-	-	Revenue
Total Flow (kg)	0.0010	0.0399	0.0425	0.1561	0.0426	0.0400	0.0001
Temperature (°C)	25.00	25.00	25.00	25.00	25.02	25.00	85.49
Pressure (bar)	1.013	1.013	1.013	1.013	11.116	1.013	12.167
Liq/Sol Vol flow (L)	0.0011	0.0350	0.0523	0.1569	0.0527	0.0353	0.0001
Total contents (kg)	0.0010	0.0399	0.0425	0.1561	0.0426	0.0400	0.00013
Choline chloride	0.0000	0.0145	0.0000	0.0000	0.0000	0.0145	0.00000
EC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00001
ECG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00001
EGC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00003
EGCG	0.0001	0.0000	0.0000	0.0000	0.0001	0.0001	0.00007
Ethyl alcohol	0.0000	0.0000	0.0372	0.0000	0.0372	0.0000	0.00000
Fiber	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.00000
Lactic acid	0.0000	0.0187	0.0000	0.0000	0.0000	0.0187	0.00000
Nitrogen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00000
Others	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00001
Oxygen	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00000
Water	0.0000	0.0066	0.0052	0.1561	0.0052	0.0066	0.00000

Table 8. Equipment, size and economic evaluation for base case

Equipment	Size
Centrifuge	
BC-101	0.113 L
Chromatography column	
C-101	0.024 L
Phase change unit	
HX-101	0.0001 m^2
TFE-101	0.0001 m^2
Microwave extractor	
R-101	0.042 L
Microwave generator	300W
Size reduction	
GR-101	0.004 kg/h
Storage (liquids)	
V-101	0.039 L
V-102	0.039 L
V-103	0.002 L
V-104	0.054 L
V-105	0.291 L
V-106	0.054 L
V-107	0.001 L

Table 8. Continued

Equipment	Size
Transport (liquids)	
PM-101	0.0001 kW
Economic Evaluation	
Gross Margin (%): 34857.07	
Return on investment (ROI,%): -41.56	
Payback period (PBP,year): N/A	
IRR (after tax) (%): N/A	
NPV at 7% ($): -48,958,721	

Scale-up study and economic analysis

Three other manufacturing scales of CM were evaluated with the aim of selecting the most economical scale. Hence, 0.063, 1.522 and 3.30 kg CM/batch which corresponded to annual production of 162.48, 3925.24 and 8510.70 kg CM/y, respectively, were selected for economic analysis. Table 9 shows the major equipment, sizes and respective costs for the selected manufacturing scales.

It is clear from Table 9 that equipment capacity is a function of throughput scales which is also dir-

Table 9. Major equipment, size and number for the manufacturing scales considered; Nu = number of units

Equipment	0.063 kg CM/batch	1.522 kg CM/batch	3.30 kg CM/batch
Centrifuge			
BC-101	Throughput = 56.124 L/h ($137000), Nu = 1	Throughput = 677.941 L/h ($334000), Nu = 2	Throughput = 587.965 L/h ($310000), Nu = 5
Chromatography column			
C-101	Column volume = 12.038 L ($167000), Nu = 1	Column volume = 290.324 L ($616000), Nu = 1	Column volume = 630.564 L ($904000),Nu = 1
Phase change unit			
HX-101	Heat transfer area = 0.221 m^2 ($42000), Nu = 1	Heat transfer area = 5.340 m^2 (42000), Nu = 1	Heat transfer area = 11.58 m^2 ($42000), Nu = 1
TFE-101	Heat transfer area = 0.073 m^2 ($116000), Nu = 1	Heat transfer area = 1.764 m^2 ($157000), Nu = 1	Heat transfer area = 3.826 m^2 ($239000), Nu = 1
Microwave extractor			
R-101	Size = 20.787 L, ($508000), Nu = 1	Size = 502.179 L, ($598000), Nu = 1	Size = 1088.824 L, ($665000), Nu = 1
Size reduction			
GR-101	Throughput = 1.989 Kg/h, ($91000), Nu = 1	Throughput = 48.006 Kg/h, ($91000), Nu = 1	Throughput = 104.084 Kg/h, ($91000), Nu = 1
Storage (liquids)			
V-101	Size = 19.430 L ($62000), Nu = 1	Size = 469.408 L ($62000), Nu =1	Size = 1017.771 L ($62000), Nu = 1
V-102	Size = 19.476 L ($62000), Nu = 1	Size = 470.516 L ($62000), Nu = 1	Size =1020.173 L ($62000), Nu = 1
V-103	Size =0.953 L ($62000), Nu =1	Size =23.016 L ($62000), Nu = 1	Size =49.903 L ($62000), Nu = 1
V-104	Size = 26.952 L ($62000), Nu =1	Size =651.130 L ($62000), Nu = 1	Size = 1411.779 L ($62000), Nu = 1
V-105	Size = 99.690 L ($62000), Nu =1	Size =2408.390 L ($62000), Nu = 1	Size = 5221.870 L ($64000), Nu = 1
V-106	Size = 26.771 L ($62000), Nu =1	Size =646.760 L ($62000), Nu = 1	Size = 1402.304 L ($62000), Nu = 1
V-107	Size = 0.040 L ($62000), Nu =1	Size =0.963 L ($62000), Nu = 1	Size = 2.089 L ($62000), Nu = 1
Transport (liquids)			
PM-101	Power = 0.003 kW ($11000), Nu =1	Power = 0.070 kW ($11000), Nu = 1	Power = 0.151 kW ($11000), Nu = 1

ectly proportional to the cost. Also, equipment like the bowl centrifuge is also required in multiples as production scale increases.

The result of economic analysis for the three scales is detailed in Table 10. Economic and profitability parameters such as total capital investment cost, total operating cost, annual revenue, net profit, ROI, IRR, NPV and gross margin were used to assess the three scales of manufacturing. Similar parameters were used by other authors [42,43] to assess the economic viability of industrial processes. Figure 3 is the stacked graph of total capital investment cost and corresponding operating cost for all scales of manufacture. As expected, these parameters were observed to increase as production scale increases. However, manufacturing scale of 0.063 kg CM/batch has the least total capital investment cost, total operating cost, annual revenue and ROI. It also had negative NPV and unrealistic IRR and therefore it not a desirable scale.

Table 10. Economic analysis of the three scales of production of CM

Parameter	0.063 kg CM/batch	1.522 kg CM/batch	3.30 kg CM/batch
Total capital investment ($)	12,307,253	28,310,281	47,766,238
Total operating cost ($/y)	9,628,483	94,200,255	197,254,476
Unit production cost ($/kg)	59260.5934	23998.6097	23177.2329
Annual revenue ($/y)	8,611,281	208,037,614	451,067,100
Return on investment (*ROI*, %)	0.35	247.76	324.65
Payback period (*PBP*, y)	287.07	0.40	0.31
IRR (after tax) %	N/A	131.48	163.83
NPV at 7% ($)	-13,520,220	472,327,434	1,059,595,224
Gross profit	-1,018,000	113,837,000	253,813,000
Net profit ($/y)	43,000	70,142,000	155,074,000

The unit production cost was also observed to reduce, as the scale of production increases. It is interesting to note that there is a reduction in unit production cost amounting to $821.3768/kg CM as production scale increased from 1.522 kg CM/batch to 3.30 kg CM/batch. The reduction in unit production cost of 3.42% and increase in total operating cost of 109.39% when the scale of manufacturing was increased 2.168-fold (1.522-3.30 kg CM/batch) indicated that some cost components in total operating cost have not been scaled proportionately. All component costs of total operating cost across all scales is presented in Figure 4 and major cost contributors were the raw material cost, facility dependent cost, labor cost, consumables cost and waste disposal cost. Figure 4 shows strong variations in distributions of some total operating cost components, particularly raw material cost, facility dependent cost, consumables cost and waste disposal cost, as the scale of production increased.

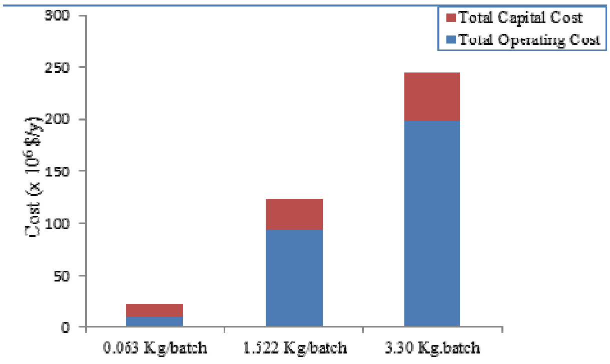

Figure 3. CM production cost of selected scales.

However, information regarding labor cost and laboratory/QA/QC cost on manufacturing scale basis (Figure 5) indicated that these costs, although took different percentages in the operating cost distributions of the three scales, are the same amount in dollars for all scales of production. This was responsible for the observed reduction in unit production cost in 3.30 kg CM/batch scale, since these costs were not increased proportionately. This is expected as the same number of laborers has been assigned to work in the CM production plant irrespective of scale of production, and the laboratory/QA/QC cost was estimated as a fraction of labor cost.

Therefore, except for 0.063 kg CM/batch, other manufacturing scales have positive *IRR* and *ROI* which made them realizable and economically viable [29,34]. However, the 3.30 kg CM/batch had the best economic parameters, with *ROI* of 324.65%, *PBP* of 0.31 year, *IRR* of 163.83%, *NPV* of $1,059,595,224 and total revenue of $451,067,100/y.

Sensitivity and uncertainty analyses

Both the annual revenue and net profit are identified as key economic predictors of an investment, therefore, the annual revenue and net profit of the production scale of 3.30 kg CM/batch were made the objective functions while the uncertain inputs were the CSL cost, DES-4 cost, CM price and resin binding capacity. The purpose of the analysis is to identify the variable (s) that predominantly perturbs the identified

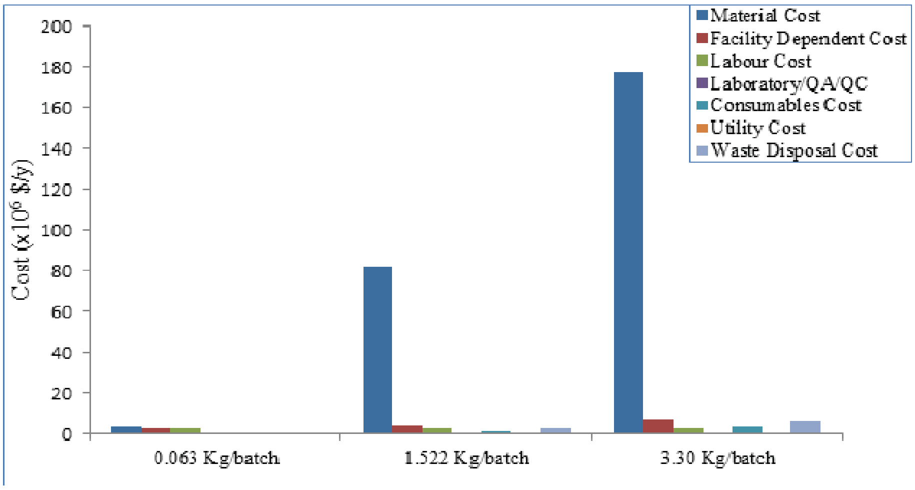

Figure 4. Components of annual operating cost for three scales of manufacture of CM.

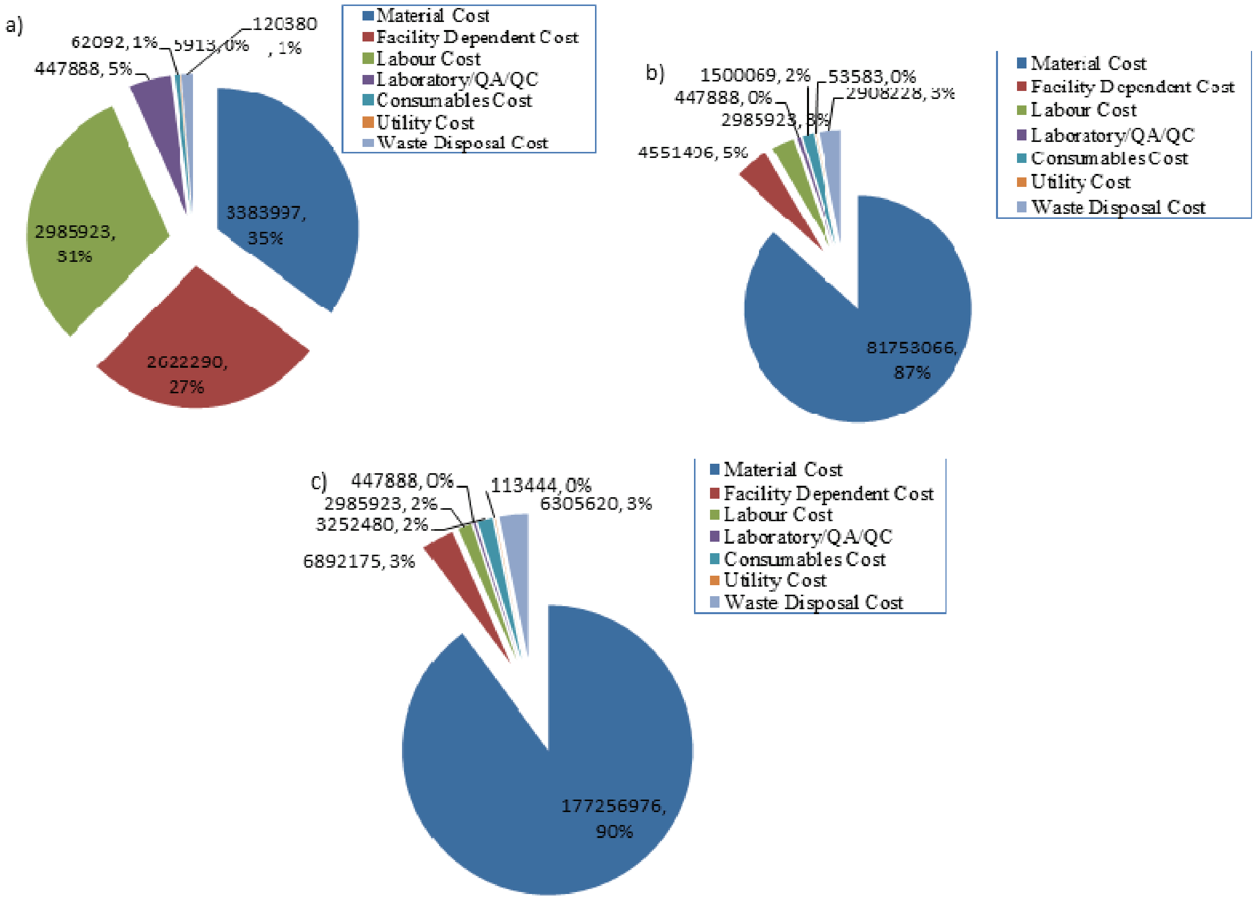

Figure 5. Cost contributions in $ and % of annual operating cost for all scales of CM production: a) 0.063, b) 1.522 and c) 3.30 kg CM/batch.

economic parameters. Uniform distribution was assumed for CSL cost, normal distribution for DES-4 solvent with a mean value of $65.0962/kg, while triangular distribution was assumed for both CM price and resin binding capacity. Figures 6 and 7 are the probability distributions for annual revenue and net profit, respectively.

The probability distributions were quantified in terms of their mean, median, mode and standard deviation. As observed in Figure 6, the probability distribution is normal with the mean and median values

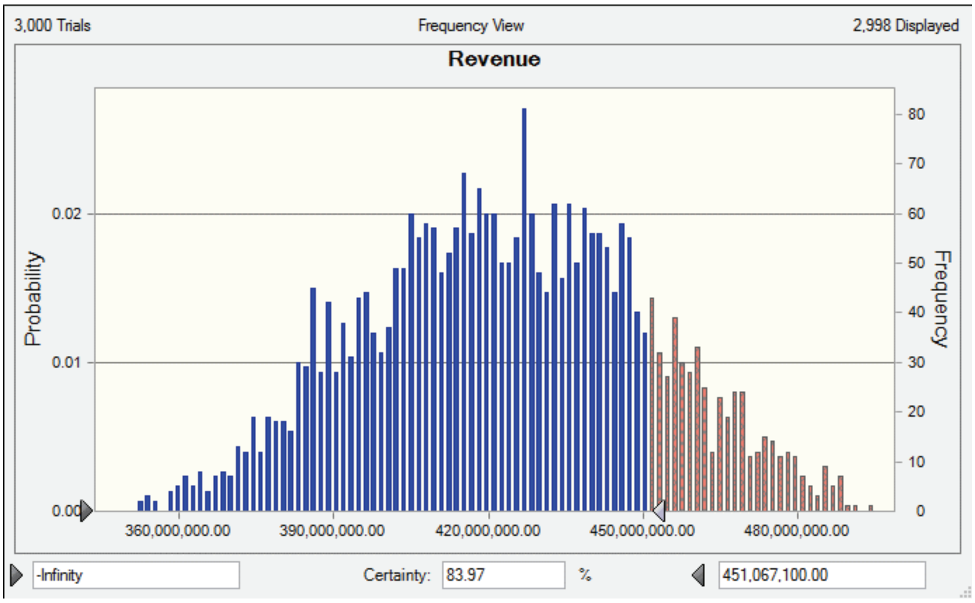

Figure 6. Probability distribution of annual revenue (3000 trials). Mean = 423,787,158.01, median = 425,066,866.72, S.D = 26,970,479.77, range: 343,990,025.65-497,781,503.52.

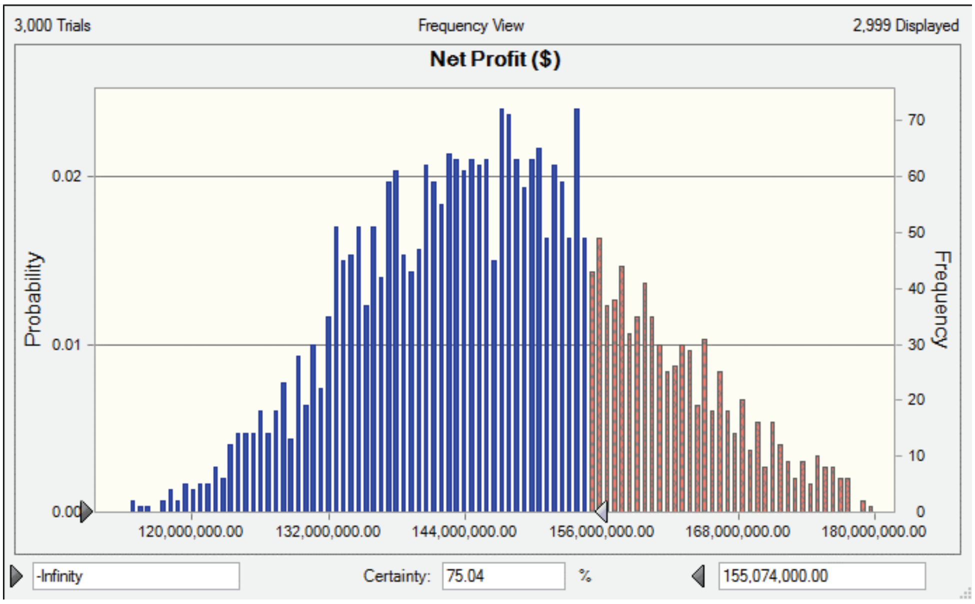

Figure 7. Probability distribution of net profit (3000 trials). Mean = 147,288,060.13, median = 147,412,892.74, S.D = 12,188,764.34, range: 113,891,883.09-180,946,329.93.

of 423,787,158.01 and $425,066,866.72/y, respectively. It should be noted as well that the difference between the mean value of simulated (through the sensitivity analysis) and base case value ($451,067,100/y) of the annual revenue is less than 7%, which indicated 83.97% possibility of achieving as high revenue/year. Similar observation was made in Figure 7, which indicated that a net profit of $155,074,000/y can be made with a certainty level of 75.04%.

The dynamic sensitivity chart for economic parameters (annual revenue and net profit) is presented in Figures 8 and 9, respectively. It is clear from Figures 8 and 9 that the final product selling price of CM and resin binding capacity had significant influence on both annual revenue and net profit, while raw material costs appeared not to perturb the selected parameters. For annual revenue (Figure 8), the contribution to variance is 38.1% CM selling price, -61.9% resin binding capacity, 0% DES-4 cost and 0% CSL cost; for net profit (Figure 9), 73.8% for CM selling price, -26.2% resin binding capacity, 0% DES-4 and 0% CSL cost.

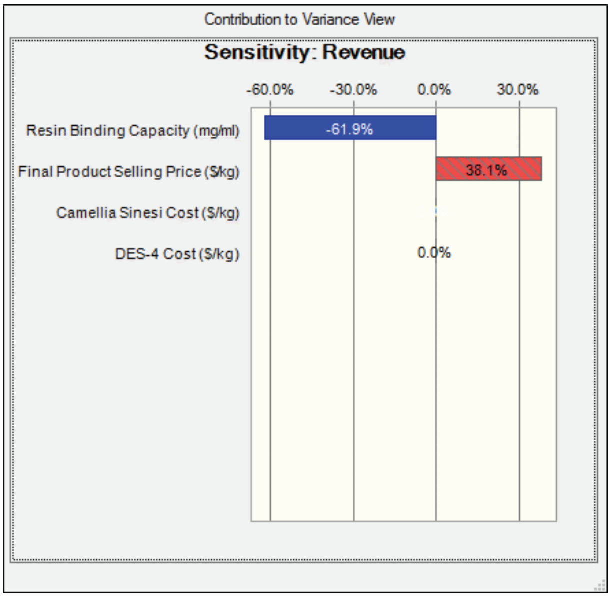

Figure 8. Contribution of uncertain parameters to the variance of annual revenue.

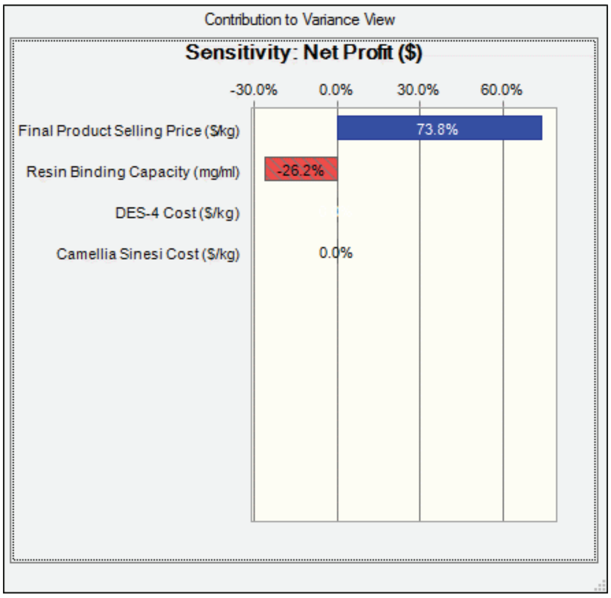

Figure 9. Contribution of uncertain parameters to the variance of net profit.

It should be noted that the negative contribution of resin binding capacity to the variance of both annual revenue and net profit signifies reverse proportionality [42].

CONCLUSION

Feasibility studies of different scales of manufacture of CM from CSL using DES solvent and MAE method was done using SuperPro Designer software. Except for the laboratory scale and 0.063 kg/batch, all other simulated scales have admirable economic indices. However, the manufacture of 3.30 kg CM/batch was found commercially most desirable with ROI of 324.65%, PBP of 0.31 year, IRR of 163.83%, and NPV of 1,059,595,224. The scale also had the highest revenue/year and net profit. Sensitivity analysis using Monte Carlo simulation (using Crystal Ball software) showed that CM selling price and resin binding capacity had most contributions to the uncertainty in the annual revenue and net profit. Although the effect of resin binding capacity is significant, it is in the reverse proportionality. It is therefore concluded that commercial manufacture of pure CM from CSL using DES-MAE method could be achievable and economically attractive. Future works may be necessary for the optimization of resin binding capacity for better adsorption and desorption of targeted catechins in order to improve the technicalities and economics of the process.

Nomenclature

CSL - *Camellia Sinensis* leaves
CM - Catechin mix
DES - Deep eutectic solvent
MAE - Microwave assisted extraction
IRR - Internal rate of return
ROI - Return on investment
NPV - Net profit value
PBP - Payback period
DFC - Direct fixed capital
PIC - Plant indirect cost
MC - Miscellaneous cost

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NAUČNI RAD

TEHNO-EKONOMSKA ANALIZA PROIZVODNJE SMEŠE KATEHINA IZ LIŠĆA *Camellia sinensis* KORIŠĆENJEM ZELENE TEHNIKE EKSTRAKCIJE

U ovom radu je dizajnirana, modelovana i izvedena ekonomska analiza klasične ekstrakcije smeše katehina (CM) iz lišća Camellia sinensis (CSL) upotrebom deutektičkog rastvarača (DES) i mikrotalasne ekstrakcije (MAE) uz pomoć softvera SuperPro Designer. Takođe, tehno-ekonomskom analizom upoređene su tri komercijalne proizvodnje koristeći parametre profitabilnosti. Analize osetljivosti i nesigurnosti dalje su sprovedene na najisplativijom komercijalnom nivou da bi se utvrdile ulazne promenljive od najvećeg značaja za profitabilnost procesa. Smeša katehina od 3,30 kg po šarži je ekonomski najpoželjniji kapacitet sa povraćajem ulaganja od 324,65%, periodom povrata od 0,31 godine, internom stopom povrata od 163,83% i neto sadašnjom vrednošću od 1.059.595.224. Od ulaznih promenljivih izabranih za analizu osetljivosti i nesigurnosti, troškovi lišća i eutektičkog rastvarača najmanje utiču na odabrane parametre profitabilnosti procesa.

Ključne reči: tehno-ekonomska analiza, Camellia sinensis, eutektički rastvarač, mikrotalasna ekstrakcija.