

Supplementary material

Life Cycle Assessment of Biocement: An Emerging Sustainable Solution?

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Methods

The purpose of the study was to evaluate the environmental and cost implications of calcium carbonate precipitated through MICP as compared to an equal mass of calcium carbonate precipitated using the commonly used carbonation technique. The purpose of this paper is not to conduct a full life cycle analysis, but rather to compare the environmental impacts of different biological routes to MICP. The aim of this paper is to inform future research and enable the most sustainable and economical biological pathways to MICP to be progressed from laboratory to field applications.

The functional unit (FU) for the assessment was defined as 1 kg of precipitated calcium carbonate. The scenarios included in the analysis are shown in Figure S1. The scope of the assessment for microbially precipitated calcium carbonate included the extraction and processing of raw materials as well as the environmental impact of any by – products produced during the MICP reaction, (Figure S2). Transport of raw materials to the plant, and the energy required to operate the fermenter were excluded from the analysis.

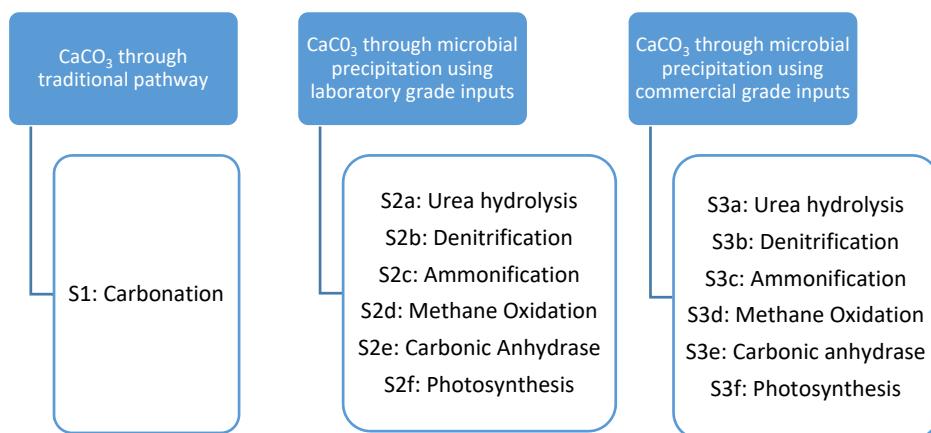


Figure S1. Scenarios included in analysis

The following assumptions have been made during the preparation of this environmental assessment:

- For the purpose of this lifecycle assessment the metabolic rate of different pathways to MICP has not been considered.
- It has been assumed that the MICP reactions are 100% efficient and all of the provided calcium source is converted into calcium carbonate.
- Waste products generated by the MICP process have been included in the analysis, however the treatment of these waste products, is outside the scope of this analysis.

- The assessment has been based on ecoinvent, V2.2 database,[1] with adaptations to an Australasian context where available. It is possible that the use of alternative databases may vary the results obtained in this paper. Investigation on alternative database sources is beyond the scope of this investigation.

Input for the production of laboratory grade calcium carbonate through the carbonation process were based on the cradle to gate assessment conducted by Mattila, et al. [2]. The scope of assessment included the extraction and transport of raw materials to the plant, energy requirements for the calcination process and waste produced during the reaction. Inputs assumed for the study of traditionally produced calcium carbonate are shown in Figure S2.

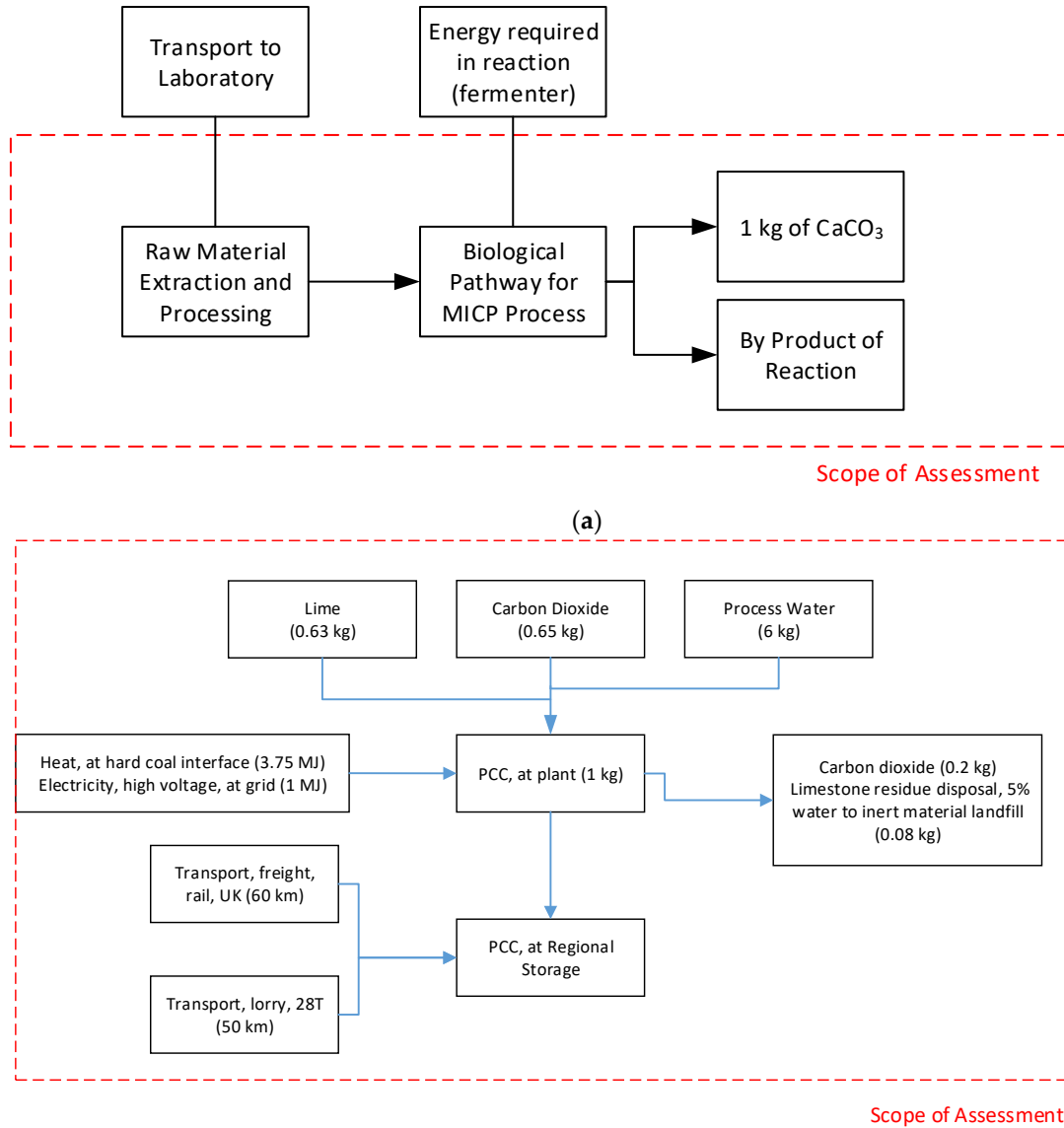


Figure S2. Boundaries of Environmental Assessment (a) Biologically precipitated calcium carbonate (b) Laboratory grade calcium carbonate, [2]

The assessment was conducted using SimaPro 8.0 software. The ecoinvent V2.2 database[1], was used for material inputs, with adaptations to an Australasian context where available. The carbon footprint and eutrophication potential were calculated using AUSLCI Version 3.0 while the embodied energy for each scenario was calculated using the Cumulative Energy Demand 2.01 methodology.

A summary of the required inputs and waste products for each microbial pathway is provided in Table S1. Chemical inputs required for the MICP reaction pathways were based on published experimental results as shown in Table S1.

Table S1. Summary of inputs / outputs for production of 1 kg of CaCO₃ through microbial route

Pathway	Inputs / Waste	Source
Urea hydrolysis	- 0.6 kg urea	van Paassen [3], Van Paassen [4]
	- 1.1 kg calcium chloride	
	- 0.1 kg yeast extract	
	- 15 kg water	
	- 0.72 kg ammonium waste	
Denitrification	- 0.68 kg sodium nitrate	Hamdan, et al. [5] Van Paassen, et al. [6]
	- 1.1 kg calcium chloride	
	- 0.1 kg yeast extract	
	- 0.00135 kg potassium phosphate	
	- 0.0012 kg magnesium sulphate	
	- 25 kg water	
	- 0.056 kg nitrogen waste	
Ammonification	- 1.6 kg calcium acetate	Rodriguez-Navarro, et al. [7] González-Muñoz, et al. [8] Chekroun, et al. [9]
	- 0.256 kg yeast extract	
	- 0.640 kg glucose	
	- 20 kg water	
	- 0.18 kg ammonia waste	
Methane Oxidation	- 1.1 kg calcium chloride	Ganendra, et al. [10] Whittenbury, et al. [11]
	- 0.005 kg magnesium sulphate	
	- 0.005 kg potassium nitrate	
	- 6.8E-5 kg potassium phosphate	
	- 1.79E-4 kg sodium phosphate	
	- 0.00016 kg methanol	
	- 0.160 kg methane gas	
	- 0.01 kg chelated iron solution	
	- .0025 kg trace element solution	
	- 20 kg water	
	- 0.34 kg hydrogen sulphide waste	
Carbonic anhydrase producing bacteria	- 1.1 kg calcium chloride	Kaur, et al. [12] Dhami, et al. [13]
	- 0.88 kg carbon dioxide	
	- 0.025 kg sodium chloride	
	- 0.0075 kg yeast extract	
	- 0.0075 kg beef extract	
	- 0.025 kg peptone	
	- 1.67E-6 kg zinc sulphate	
	- 25 kg water	
	- 0.44 kg carbon dioxide waste	
Photosynthesis	- 1.1 kg calcium chloride	Zhu and Dittrich [14] Dittrich, et al. [15]
	- 0.88 kg carbon dioxide	
	- 1.68 kg sodium bicarbonate	
	- 25 kg water	
	- 0.44 kg carbon dioxide waste	

In the case of laboratory grade scenarios calcium chloride was produced through the commonly used Solvay process, [16]. In the case of commercial grade sources, laboratory grade calcium chloride was

substituted with calcium chloride produced through the hypochlorination of allyl chloride, a co – product of the production of epichlorohydrin [17]. Laboratory grade sodium nitrate, (used for MICP via denitrification) was also replaced with a commercial nitrate fertilizer equivalent,[18].

A high-level cost assessment was conducted on all raw materials for each scenario. Unit rates for laboratory grade chemicals were sourced from laboratory chemical suppliers in Australia whilst rates for commercial grade chemicals were sourced from ICIS bulk chemical reports, [19]. Unit rates for laboratory and commercial grade chemicals are detailed in Table S2 and Table S3.

Table S2. Unit Rates for Laboratory Grade Chemicals

Product	Unit Rate (AUD) / kg	Source
Beef extract	204.4	Southern-Biological [20]
Calcium carbonate	60.8	Chemsupply[21]
Calcium chloride	50.6	Chemsupply[21]
Chelated iron solution	151	Sigma-Aldrich [22]
Glucose	37	Chemsupply[21]
Magnesium sulphate	43	Chemsupply[21]
Methane gas	49.5	Commonwealth-of-Australia [23]
Methanol	11.75	Chemsupply[21]
Peptone	115.5	Southern-Biological [24]
Potassium nitrate	55.6	Chemsupply[21]
Sodium bicarbonate	26	Chemsupply[21]
Sodium chloride	19.67	Chemsupply[21]
Sodium nitrate	48.6	Chemsupply[21]
Sodium phosphate	67	Chemsupply[21]
Trace element solution	1362.4	MPBio [25]
Urea	64	Chemsupply[21]
Water	0.0027	ABS [26]
Yeast Extract	129.8	Southern-Biological [27]
Zinc sulphate	23	Chemsupply[21]

Table S3. Unit Rates for Commercial Grade Chemical Replacements

Product	Unit Rate (AUD) / kg	Source
Beef extract	22.4	eBioChem [28]
Calcium acetate	1.4	PulisiChem [29]
Calcium chloride	0.34	ICIS [19]
Chelated iron solution	39	Bunnings [30]
Glucose	0.64	Melbourne-Food-Depot [31]
Magnesium sulfate	0.54	ICIS [19]
Methanol	2.98	ICIS [19]
Sodium bicarbonate	0.68	ICIS [19]
Sodium chloride	0.284	Bunnings [32]
Sodium nitrate	6.6	Amazon [33]
Sodium phosphate	2.38	ICIS [19]
Urea	0.81	ICIS [19]
Yeast extract	22.4	eBioChem [28]
Zinc sulphate	0.92	ICIS [19]

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