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## The use of microalgal sourced biodiesel to help underground mines transition to battery electric vehicles

Author(s) ORCID Identifier:

Corey Laamanen  0000-0002-1321-0491

Sabrina M. Desjardins  0000-0003-3691-7323

Shannon H. McLean  0000-0001-9900-640X

John A. Scott  0000-0002-2559-0188

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## Abstract

The use of fossil fuel sourced diesel underground has various associated health and environmental hazards, and additional energy demand and costs associated with necessary ventilation. One way to reduce these impacts is by utilizing a biodieselblend, which generates lower levels of harmful emissions from underground equipment and can be produced regionally, reducing the impact of transportation. Furthermore, this would help allow use of existing machinery during transition towards more widespread electrification underground. Therefore, the concept of an integrated supply and use chain within the mining industry is examined based on biodiesel from acidophilic photosynthetic microalgae cultivated using CO<sub>2</sub> in smelter off-gas. A life cycle assessment (LCA) was conducted to compare the environmental impacts of production, transportation, and end-use of fossil fuel sourced diesel to biodieselblended fuel across four underground metal ore mine sites (Canada, Poland, Zambia, and Australia). The outcomes from assessing four key environmental impact potentials (global warming, eutrophication, acidification and human toxicity) demonstrate the advantages of using biodiesel-blends. The integration of biodiesel resulted in changes of -22.5–+22.8% (global warming), -6.1–+27.3% (eutrophication), -18.9–+26.3% (acidification), and -21.0–-3.6% (human toxicity). The results showed reduction across all potentials for two mines and reduction in human toxicity potential for all sites.

## Keywords

Environmental benefits, microalgae, biofuel, life cycle assessment, metals, underground mining

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# The use of microalgal sourced biodiesel to help underground mines transition to battery electric vehicles

Corey A. Laamanen, Kyle Moreau, Sabrina M. Desjardins, Shannon H. McLean, John A. Scott\*

Laurentian University, Bharti School of Engineering, Canada

## Abstract

The widespread use of fossil fuel sourced diesel underground has various associated health and environmental hazards, and additional energy demand and costs associated with necessary ventilation. One way to reduce these impacts is by utilizing a biodiesel-blend, which generates lower levels of harmful emissions from underground equipment and can be produced regionally, reducing the impact of transportation. Furthermore, this would help allow use of existing machinery during transition towards more widespread electrification underground. Therefore, the concept of an integrated supply and use chain within the mining industry is examined based on biodiesel from acidophilic photosynthetic microalgae cultivated using CO<sub>2</sub> in smelter off-gas. A life cycle assessment (LCA) was conducted to compare the environmental impacts of production, transportation, and end-use of fossil fuel sourced diesel to biodiesel-blended fuel across four underground metal ore mine sites (Canada, Poland, Zambia, and Australia). The outcomes from assessing four key environmental impact potentials (global warming, eutrophication, acidification and human toxicity) demonstrate the advantages of using biodiesel-blends. The integration of biodiesel resulted in changes from  $-22.5$  to  $+22.8\%$  (global warming), from  $-18.9$  to  $+26.3\%$  (acidification), from  $-6.1$  to  $+27.3\%$  (eutrophication), and from  $-21.0$  to  $-3.6\%$  (human toxicity). The results showed reduction across all potentials for two mines and reduction in human toxicity potential for all sites.

**Keywords:** environmental benefits, microalgae, biofuel, life cycle assessment, metals, underground mining

## 1. Introduction

The environmental footprint of metal production is increasing as the demand for metals rise due to population and economic growth, whilst ore grades decline and become harder to access [1]. However, there is significant opportunity for improvement through improved energy efficiency and use of renewable resources, including biofuels [2]. One of the International Council on Mining and Metals' ten principles states "pursue continual improvement in environmental issues, such as water stewardship, energy use and climate change" [3]. To achieve continual improvement, the mining sector needs a balance between economic activity and environmental concerns, allowing for cost

efficient metal production without significantly reducing the quality of the environment for future generations [1,4]. To achieve these improvements, the first step is to quantify the environmental impacts of mining and identify ways to reduce them without compromising production [5].

A move to greater use of battery-electric vehicles (BEVs) helps address these concerns and is a trend in mining [6,7], but most existing underground mines still rely heavily on, and have a large investment in, fossil fuel powered diesel vehicles. The use of these diesel powered vehicles attributes directly to the necessary high levels of extractive ventilation, which account for up to 50% of a mine's total electrical energy costs [8]. This ventilation is key to limiting operator exposure to carbon monoxide,

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\* Corresponding author.  
E-mail address: [jascott@laurentian.ca](mailto:jascott@laurentian.ca) (J.A. Scott).

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hydrocarbons, nitrogen oxides and particulate matter emitted from diesel engines [9].

The use of BEVs results in higher productivities, improved preventative maintenance, lower underground emissions, and reduced scheduled and unplanned maintenance compared to their traditional diesel counterparts [10,11]. This leads to lower overall operational costs and the ability to offset any differences in initial capital costs [12]. While the move from lead acid to lithium ion batteries have made BEVs more economically and physically feasible, further development is required to provide lighter, safer, and longer lasting options [13]. There is a general need for new battery chemistries in order to deal with large scale implementation of BEVs [14]. Other related concerns with the utilization of current BEVs underground include developing proper disposal of depleted batteries [15], the capital costs of implementation [12], and fire hazards from damaged batteries reacting with moisture or thermal runaway as cell temperatures increase beyond 60 °C [15].

As such, while the potential of BEVs remains enticing, development and implementation will take time, not least due to very significant investment in diesel-powered vehicles. As such, there is potential to implement the use of BEVs as replacements when equipment reaches the end of its useful life, the length of which is dependent on the type of vehicle. For example, load-haul-dump machines (LHDs) should have a useful life of 12,000 h after a rebuild at 7500 h. With an average utilization of around 4000 h per year, LHDs need to be replaced every three years [16] (which is in line with the typical lifetime of the battery [12]). The useful lives of LHDs and other equipment should be improved with improving onboard diagnostics and improved maintenance practices [16]. There is, therefore, an opportunity for an interim solution for the mining industry to allow it to obtain maximum return on its existing investment in machines whilst transitioning to BEVs.

One approach is to improve overall environmental performance of existing diesel-powered infrastructure and reduce emissions underground, while still meeting performance and power requirements, is through increased use of biodiesel. A 75% biodiesel blend (B75) in underground mining operations resulted in a 22% reduction in respirable diesel particulate matter and a 28% reduction in nitrogen dioxide, when compared to low sulfur fossil fuel sourced diesel [17]. However, use of a B20 (20% biodiesel) blend underground was still found to reduce elemental and total carbon emissions by 20%, decrease in carbon monoxide emissions slightly, and reduce aerosol concentrations by 13% [18]. It is also worth considering that biofuels can

substantially contribute to regional energy security and socio-economic development [19].

While some results suggest that vehicles not optimized for biodiesel have shown a slight decrease (9%) in energy per litre compared to petrochemical diesel. Volumetric consumption of biodiesel is increased directly with the lower energy content per litre, as the energy efficiency is typically the same or slightly increased [20]. Despite this increase, utilization of biodiesel has consistently shown a decrease in harmful emissions. Biodiesel generates little to no sulphur emissions [21], and considerable reductions in carbon monoxide and particulate matter [22]. Although, depending on the combustion conditions of the engine [23,24], both increased [25,26] and decreased [27] NO<sub>x</sub> emissions have been reported. Biodiesel has been also shown to decrease global warming potential and ozone layer depletion when compared to petrochemical diesel [28]. Khalife et al. [23] did a comprehensive review of additives to biodiesel blends on the performance of diesel engines. Their data made it clear that there is potential for utilization of biodiesel blends, whilst also highlighting that further work is required on engine performance. It is important to note, therefore, the need for adaptation and optimization of diesel engines, and the associated costs, for effective utilization in the mining industry.

Biodiesel comprises of fatty acid methyl esters (FAMES) derived from biological feedstocks, which are typically organized by generations. First-generation biodiesel is derived from food crops (e.g., sugarcane or canola) and second-generation from non-food bio-feedstocks (e.g., agricultural wastes or forestry). However, both have issues, including competing with food crops for arable land and low aerial productivity.

Micro- and macro-algae provide the principal bio-feedstock for third generation biodiesel. Photosynthetic microalgae have been the preferred feedstock as they can achieve up to 80% lipid content per dry weight of biomass in the extreme case [29], but more commonly in the 30–40% range [30]. They can be also grown year-round on non-arable land, use a variety of liquid media (e.g., freshwater, saltwater or wastewater) and importantly provide an opportunity to directly mitigate industrial CO<sub>2</sub> emissions [31,32], including those from ore smelting [33]. Furthermore, compared to first and second generation biodiesels, microalgae have an over 85% increased biodiesel areal production rate [34,35].

This paper uses a life cycle assessment (LCA) approach to model the impact of using a microalgae sourced biodiesel blend in four underground metal ore mine sites (Canada, Australia, Zambia and

Poland). The biodiesel was assumed to be produced from lipids extracted from acidophilic microalgae grown using ore smelter off-gas (6% CO<sub>2</sub>) as their carbon source. The intention was to assess the benefits of an integrated supply and use chain by taking into account location, operation and climate differences on four commonly assessed environmental impact potentials (global warming, eutrophication, acidification and human toxicity). These potentials are well defined categories that provide a basis for comparison within industries such as mining [36,37].

The LCA model (Fig. 1) developed compared emissions from fuel production (diesel or biodiesel), fuel transportation to the mine site, and overall emissions from mining operations, including from fuel use.

## 2. Materials and methods

### 2.1. Goal and scope

The initial goal was to estimate the maximum achievable biodiesel blend at each of the four mine sites based on how much could be produced from mitigating smelter CO<sub>2</sub> emissions (see Section 2.2). Once the highest biodiesel blend per site was determined, an LCA could be then conducted to describe and contrast the global warming, eutrophication, acidification, and human toxicity potentials of two scenarios. The first scenario was full petrochemical sourced diesel operation and the second using a biodiesel blend. To obtain this, production, transportation, and overall operations emissions for both scenarios were examined and compared.

Microalgae cultivated in captured CO<sub>2</sub>-rich off gas have shown favourable fixation rates in industries such as coal-fired power generation [38] and cement production [39]. Therefore, an important criterion for biomass cultivation was to utilize waste CO<sub>2</sub>

from associated ore smelting, which in many cases is carried out near the mine, thereby providing regional access to a CO<sub>2</sub> source to enhance microalgal production. Based on stoichiometric calculations, a kilogram of microalgae (dry weight) with a 50% carbon content can bio-fixate approximately 1.8 kg of CO<sub>2</sub>. A nickel ore smelter [33,40] which produces approximately 95,000 tonnes of matte and 760 Mm<sup>3</sup> of furnace off-gas annually, was used as a standard size and assumed to be located 10 km from each mine site to provide a basis for comparison. Each mine location was evaluated for microalgae growth under local climate conditions and utilizing smelter furnace off gas containing 6% CO<sub>2</sub> [33] as a source of carbon and, where needed, waste heat for maintaining bioreactor temperature.

#### 2.1.1. Mine site description

Four regionally distinct underground copper mines were used to compare the impact of both mine size and climatic variations on microalgae growth (Table 1). The mine sites selected are spread out over four continents and provide the study with a variety of environmental conditions, mine operations, production rates, fuel requirements, and primary electricity generation methods.

To quantify the potential for biodiesel as a transitional option towards the implementation of BEVs, and to allow for the fuel requirement in Table 1, the vehicle fleet at each mine site was examined. The results are summarized in Table 2.

While to accurately quantify the impact of electricity usage, a breakdown of regional electricity generation and average greenhouse gas (GHG) emissions factor for each region investigated is provided in Table 3.

#### 2.1.2. System boundaries

The base scenario involves petrochemical diesel production at the nearest refinery to the mine

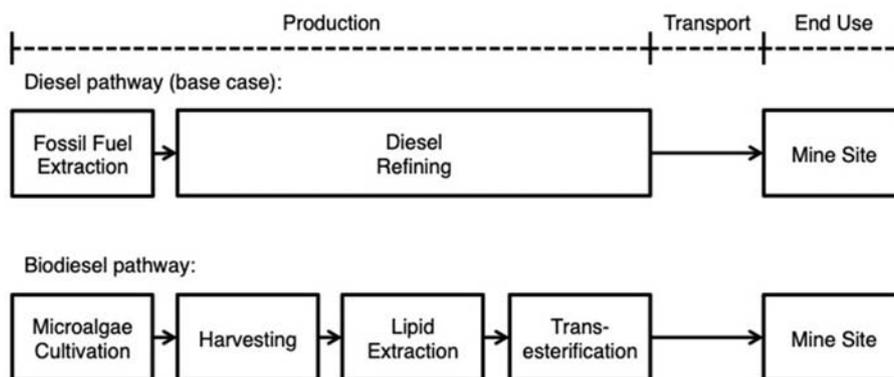


Fig. 1. Pathways considered by the LCA.

Table 1. The selected mine sites (adapted from [11]).

Mine site	Location	Production (Cu. tpa)	Calculated required fuel (m <sup>3</sup> pa)	Ambient temperature (High/Low)	Main electricity generation
A	Canada	6400	5321	24 °C/−23 °C	Hydropower (98%)
B	Australia	53,000	5150	35 °C/5 °C	Coal (80.8%)
C	Zambia	18,000	4742	34 °C/10 °C	Hydropower (85%)
D	Poland	74,000	24,720	25 °C/−3 °C	Coal (80%)

location, resulting in distances between 400 and 2300 km, transportation to the mine site, and use of the diesel (Fig. 2). The biodiesel scenario includes regional cultivation of microalgae (with smelter off-gas), subsequent microalgae harvesting, production of biodiesel (lipid extraction and transesterification), biodiesel transport to the mine site, and the end-use as biodiesel blend.

The microalgae cultivation facilities were selected based on a comparison of options, as shown in Table 4. The selected top-lit, covered microalgae production ponds operate at 1 m depth, providing a good areal production rate and allowing for increased residence time of applied CO<sub>2</sub> rich off-gas [45]. This design is based on previous models that used smelter furnace off-gas to both heat (when needed), agitate, and supply CO<sub>2</sub>, which showed that utilizing the 24 m<sup>3</sup>s<sup>−1</sup> of furnace off-gas (6% CO<sub>2</sub> on average) 180 tanks (50 m long, 5 wide and 1 m deep) could be supported [33,46]. The gas-lift design and off-gas application rate used in this model is based on extensive laboratory results [45,47,48]. The various stages from microalgae cultivation to biodiesel production are assumed to be carried out at the smelter site to avoid additional transportation.

The selection of an appropriate harvesting method of cultivated microalgae includes considerations of cost, biomass contamination, reusability of the cultivation media, processing time, scalability, recovery and concentration factor [51]. As such, several options are compared in Table 5, and based on the

requirements, a two-stage system consisting of submerged microfiltration followed by centrifugation was selected. The system requires 0.84 kWh m<sup>−3</sup> of culture processed [52]. The model was developed such that the harvesting system is run upon reaching a biomass concentration of 1 g/L, at which point 80% of the pond volume was harvested and the water recycled. The system is then replenished with the necessary water, nitrogen and phosphorus to account for the losses to the harvested concentrate.

Following harvesting, extraction is required to remove the lipid fraction as a feedstock for biodiesel production. To avoid additional dewatering and drying stages, the wet biomass processing method proposed by Sathish and Sims [55] was adopted. The method utilizes an eight stage process and uses inputs of sulphuric acid (2.45 kg kg<sup>−1</sup><sub>algae,dw</sub>), sodium hydroxide (2.00 kg kg<sup>−1</sup><sub>algae,dw</sub>), water (70 kg kg<sup>−1</sup><sub>algae,dw</sub>), and hexane (32.75 kg kg<sup>−1</sup><sub>algae,dw</sub>). It was assumed that the evaporated hexane at the end of the process can be recovered and recycled at an efficiency of 90%. Electricity requirements for heating, centrifugation, and evaporation were estimated to be 14.7 kWh kg<sup>−1</sup><sub>algae,dw</sub>.

The final stage of biodiesel production is transesterification, where the extracted lipids are reacted with methanol in the presence of a catalyst to produce methyl esters (biodiesel) and glycerol [56,57]. For this model a sodium hydroxide catalyst was utilized as an efficient and low cost catalyst [58]. An existing process for soy biodiesel production provided in the LCA software was adapted to the microalgal lipid input [59].

Table 2. Vehicle inventory (adapted from [11]).

Equipment	Mine site			
	A	B	C	D
Haulage Truck	8	10	10	30
LHD	10	13	12	43
Jumbo Drill	4	2	3	16
Production Drill	3	2	2	8
Bolters	8	5	6	33
Explosives Vehicle	3	4	4	19
Personnel Carrier	26	50	15	54
Miscellaneous <sup>a</sup>	55	30	50	83

<sup>a</sup> Miscellaneous includes minecats, forklifts, loaders, pickups, etc.

Table 3. Electricity generation breakdown of the four mine sites.

Electricity generation method	Mine site			
	A <sup>1</sup>	B <sup>2</sup>	C <sup>3</sup>	D <sup>4</sup>
Coal	<1%	81%	8%	80%
Natural gas	<1%	2%	7%	7%
Hydropower	97%	5%	85%	—
Solar	—	5.1%	—	—
Wind	2%	5.3%	—	13%
Biomass	<1%	1.6%	—	—
Intensity factor (g CO <sub>2</sub> kWh <sup>−1</sup> )	3.4	743.7	128.1	801.8

<sup>1</sup> [41], <sup>2</sup> [42], <sup>3</sup> [43], <sup>4</sup> [44].

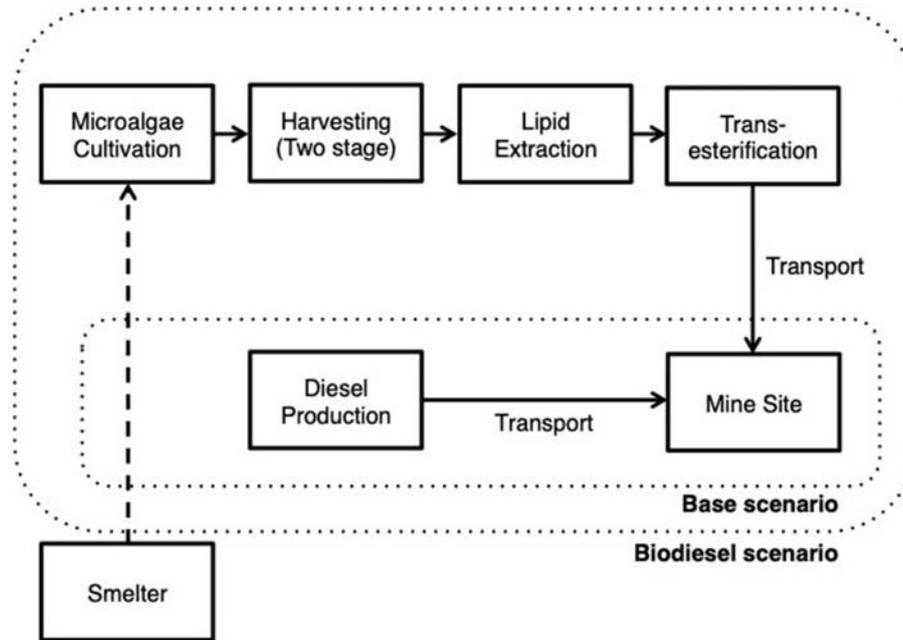


Fig. 2. General process overview with either fossil fuel diesel or biodiesel-blend operations.

## 2.2. Microalgae biodiesel production

The mine sites selected for evaluation represent a wide range of climates, as can be seen from average monthly temperatures, collected from [climate-data.org](https://climate-data.org), shown in Fig. 3. Another important locational and seasonal variable is solar irradiation, and these values were calculated using the ASHRAE Clear Sky Model [60], which is commonly used for engineering approximations [54]. Solar irradiation ( $I_h$ ,  $\text{W m}^{-2}$ ) was subsequently calculated using Equation (1):

$$I_h = (C + \sin\beta) \left( \frac{A}{e^{B/\sin\beta}} \right) \quad (1)$$

where  $A$  is the apparent solar irradiation ( $\text{W m}^{-2}$ ),  $B$  is the atmospheric extinction coefficient (unitless),  $C$  is the ratio of diffuse radiation on a horizontal surface to the direct normal irradiation (unitless) and  $\beta$  is the solar altitude angle (radians). Monthly average values of  $A$ ,  $B$ , and  $C$  were used, and  $\beta$  was calculated according to Equation (2) [61]:

$$\sin\beta = \sin\delta\sin\lambda + \cos\delta\cos\lambda\cos\omega \quad (2)$$

where  $\delta$  is the solar declination angle (radians),  $\lambda$  is the latitude (radians), and  $\omega$  is the hour angle (radians). Hourly values were calculated and averaged over a month for the growth model input. Comparing the model output to measured datasets available online provided an average monthly irradiation within 10% of the measured values (data not included).

Using the climatic information, as the major determining factor for microalgae growth rate the temperature of the microalgae ponds ( $50 \text{ m} \times 5 \text{ m} \times 1 \text{ m}$ ) was calculated, this took into account evaporative, convective, conductive heat losses, and heat addition through the application of off-gas and solar irradiation. For a detailed description of the model development refer to Laamanen et al. [33].

## 2.3. Microalgae selection

It is important to highlight that trace acidic gas components (mainly  $\text{SO}_2$ ) in the applied off gas

Table 4. Comparison between microalgae cultivation options.

Option	Areal volume ( $\text{m}^3 \text{ m}^{-2}$ )	Areal productivity ( $\text{g m}^{-2} \text{ day}^{-1}$ )	Relative Cost	Reference
Raceway pond	0.18	10	Low	[49]
Raceway pond	0.2	20	Low	[50]
Flat panel photobioreactor	0.7	42	High	[50]
Tubular photobioreactor	0.65	65	High	[50]
Deep pond (used in this assessment)	1	60	Medium	[45]

Table 5. Comparison between microalgae harvesting options.

Option	Recovery (%)	Concentration Factor (-)	Exiting Concentration (g L <sup>-1</sup> )	Energy requirements (kWh m <sup>-3</sup> )	Reference
Centrifugation (high recovery)	94	—	—	20	[53]
Centrifugation (low energy)	17	—	—	0.8	[53]
Electrolytic Flotation	52.2	52.8	29.03	4.96	[54]
Two stage (filtration-centrifugation) (used in this assessment)	95	55	22	0.84	[52]

would reduce the pH of the microalgae tanks down to pH 2.5–3, and to avoid significant additional costs for neutralization, typically through lime addition, we chose to utilize acidophilic microalgae [62].

The acidophilic species *Chlamydomonas acidophila* identified from the Tinto River in Spain [63] with optimal growth at pH 2.6–3 and 17.5 °C, can survive up to 27 °C [64]. Under culture conditions that will occur from sparging in smelter furnace off gas (pH 2.5 with 5% CO<sub>2</sub>), *C. acidophila* achieved production of 10 kg/m<sup>3</sup> of dry weight biomass per growth cycle [63], with a lipid content of 54.7% [65].

The minimum temperature acceptable level of growth was taken as 1.5 °C, which is based on an average of 10 microalgae species [66]. Microalgae growth can be calculated as a function of pond temperature using Equations (3) and (4) [66]:

$$\mu_{\max} = \begin{cases} 0 & \text{for } T_p < T_{\min} \\ \mu_{\text{opt}} \cdot \phi(T) & \text{for } T_{\min} < T_p < T_{\max} \\ 0 & \text{for } T_p > T_{\max} \end{cases} \quad (3)$$

where  $\mu_{\max}$  is the maximum specific growth rate at temperature  $T_p$  (day<sup>-1</sup>), and the temperature dependent growth rate can be calculate from:

$$\phi(T) = \frac{(T_p - T_{\max})(T_p - T_{\min})^2}{(T_{\text{opt}} - T_{\min}) [(T_{\text{opt}} - T_{\min})(T_p - T_{\text{opt}}) - (T_{\text{opt}} - T_{\max})(T_{\text{opt}} + T_{\min} - 2T_p)]} \quad (4)$$

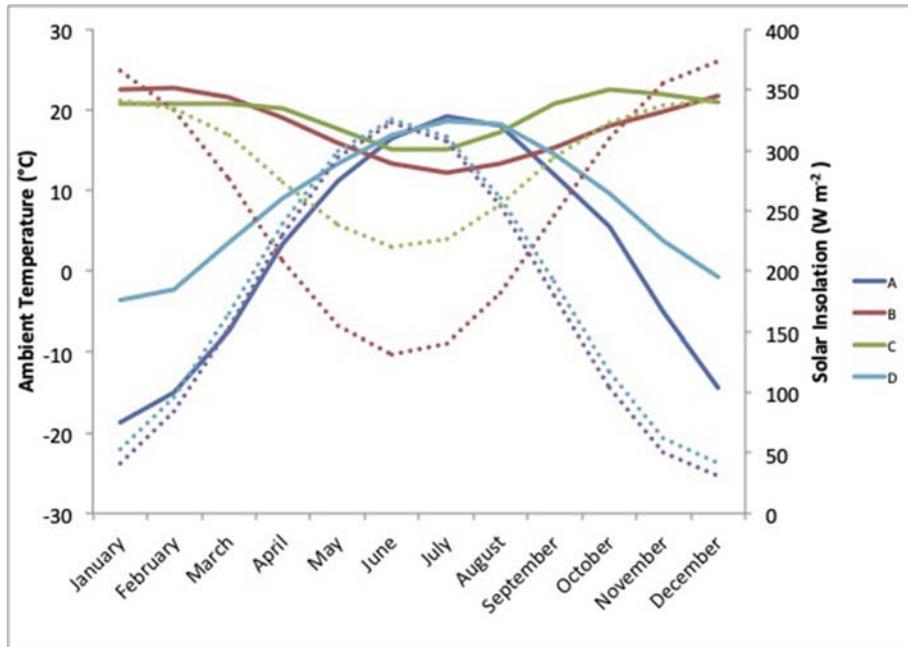


Fig. 3. Ambient air temperature (solid line) and solar insolation (dotted line) for the four mine sites A (Canada), B (Australia), C (Zambia), and D (Poland).

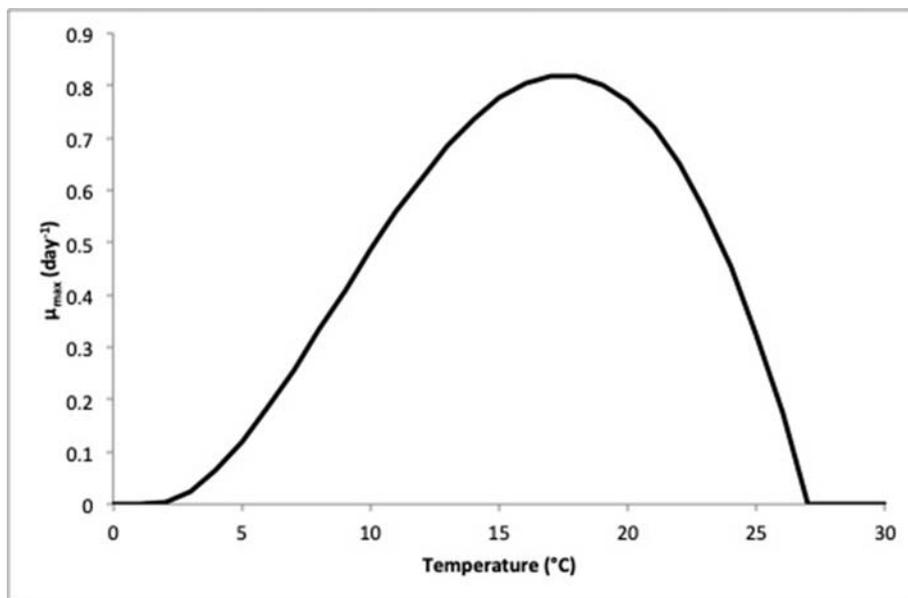


Fig. 4. The modelled temperature dependent specific growth rate of *C. acidophila*.

$T_p$  is the operating temperature of the pond, and  $T_{max}$ ,  $T_{min}$ , and  $T_{opt}$  are respectively the minimum, maximum, and optimal microalgae growth temperatures (°C). Growth rate as a function of temperature is shown in Fig. 4.

#### 2.4. Life cycle assessment (LCA) modelling

The LCA modeling was performed using the TRACI (Tool for the Reduction and Assessment of

Chemical and Other Environmental Impacts) 2.1 methodology within GaBi Solutions software [59]. The software was used to calculate emissions that contribute to global warming, acidification, eutrophication and human toxicity potentials, and was developed from one used to assess underground metal ore mining [11]. This model was verified by predicting CO<sub>2</sub> emissions to within  $\pm 5.6\%$  of those reported by the mines. The LCA model was

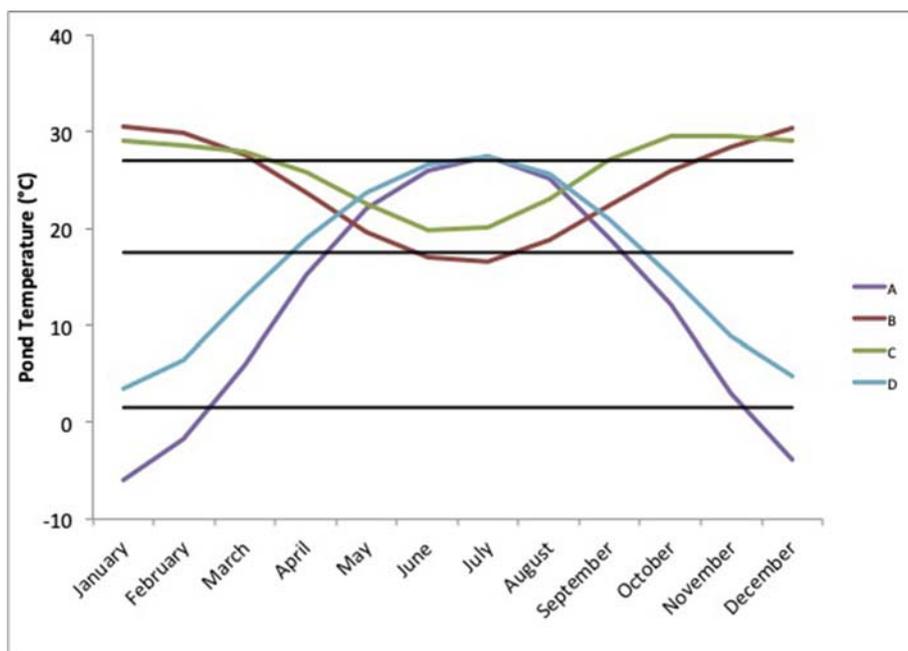


Fig. 5. Modelled microalgae cultivation pond temperatures at the four regional mine sites.

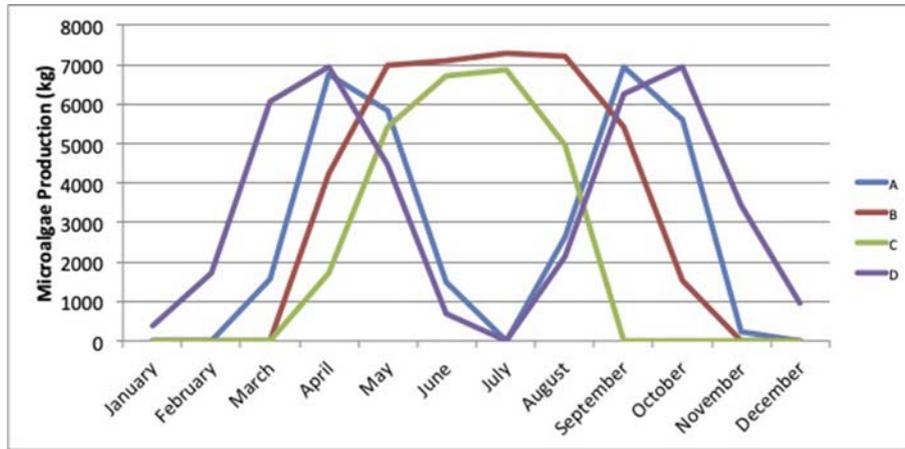


Fig. 6. Monthly microalgae production at the four regional smelter sites.

expanded to include production, transportation, and end-use of both types of diesel fuel.

### 3. Results and discussion

#### 3.1. Microalgae biodiesel production

The model was used to calculate the monthly pond temperature (Fig. 5) along with key temperatures for the selected microalgae growth (maximum (27 °C), optimum (17.5 °C) and minimum (1.5 °C).

The distribution of the heat transfer terms and their influence on estimated monthly temperature of the algae growth tanks show that despite having the ponds covered, surface heat losses are relatively high due to both convective ( $q_{conv}$ ) and evaporative ( $q_{evap}$ ) losses. With respect to heat addition, the gain from sparging in off gas ( $q_{offgas}$ ) is reasonably constant throughout the year, but solar energy has a significant influence on determining the operational temperature of the microalgae growth tanks (data not included).

Using the microalgae *C. acidophila*, the monthly temperatures can be used to estimate biomass production (Fig. 6). Values of zero productivity represent months where the temperature was either below the minimum temperature (winter of site A)

or above the maximum temperature (summer of sites B and C).

Site B (Australia) showed the highest biomass productivity in July (7275 kg of biomass produced in a month), whereas site D (Poland) could produce 11 months a year – coincidentally the result of these monthly variations were a very similar annual production between these sites. Site D would be able to produce 40.0 tonnes of microalgae (dry weight) per year while site B could produce 39.7 tonnes  $yr^{-1}$ . While site A (Canada, 31.1 tonnes  $yr^{-1}$ ) and site C (Zambia, 25.7 tonnes  $yr^{-1}$ ) were able to produce smaller quantities of microalgae per year based on the climates being too variable and hot, respectively.

Due to the elevated temperature the Zambian site (site C) shows the shortest growing season of five months. However, it is important to note that here is potential for improvement by bioprospecting for a regional microalgae species suited for the operational temperature profile, while also screening to ensure a high lipid productivity and an acidophilic or acid tolerant cultivation behaviour [62].

#### 3.2. Mine site biodiesel supply

Based on calculated annual microalgae production potential, the maximum biodiesel supply to

Table 6. Fuel requirements for the regional mine sites.

	Mine site			
	A	B	C	D
Annual ore production (t)	1,095,000	1,000,100	959,950	8,000,000
Diesel use (L/t ore)	4.86	5.15	4.94	3.09
Annual required diesel (m <sup>3</sup> )	5321.70	5150.50	4742.20	24,720
Annual biodiesel production (m <sup>3</sup> )	1737.20	2218.60	1434.50	2234.20
Average blend (%)	32.6	43.0	30.2	9.0

The relatively low blend achievable at site D (Poland), despite having the highest potential annual microalgae production, is due to an ore production rate about eight times greater than sites A, B, and C.

Table 7. The global warming potential (t CO<sub>2</sub> eq. yr<sup>-1</sup>) for the production of diesel and biodiesel for each site. Biodiesel blend operations represent the maximum biodiesel produced at each site.

Process	Mine site			
	A	B	C	D
Diesel operations (t CO <sub>2</sub> eq. yr <sup>-1</sup> )				
Diesel production	1889	2443	1747	26,678
Smelter off-gas (uncaptured)	8187	10,649	7296	11,020
Total	10,076	13,092	9043	37,698
Biodiesel operations (t CO <sub>2</sub> eq. yr <sup>-1</sup> )				
Utilizing maximum blend	B30	B40	B30	B9
Algae growth	21	1412	156	1560
Harvesting	59	3952	437	4369
Lipid extraction	674	45,475	5028	50,265
Biodiesel production	2248	3088	2004	3134
Diesel production	1289	1399	1192	10,076
Total	4291	55,326	8817	69,404

each mine site could be calculated. By using the total required fuel for each mine, based on diesel consumed per tonne of ore mined, the average biodiesel blend that could be utilized onsite was estimated (Table 6).

### 3.3. Environmental impacts

It was assumed that the smelter off-gas CO<sub>2</sub> from all four sites would be used at a rate of 1.8 gCO<sub>2</sub>/g<sub>biomass</sub> when microalgae are being produced. Whilst CO<sub>2</sub> consumption rates have not been reported for *C. acidophila*, *Euglena gracilis* and *Coccomyxa* sp., grown at low pH can consume 2.4–4.6 g of CO<sub>2</sub> per g of dry weight biomass [67]. As these values are well above the CO<sub>2</sub> consumption rate modelled in this study, the values for CO<sub>2</sub> capture are potentially underestimates for the maximum capture possible. The carbon capture from the smelter off-gas due to microalgae grown would result in potential mitigation of 8187 t CO<sub>2</sub> eq. yr<sup>-1</sup>, 10,649 t CO<sub>2</sub> eq. yr<sup>-1</sup>, 7296 t CO<sub>2</sub> eq. yr<sup>-1</sup>, and 11,020 t CO<sub>2</sub> eq. yr<sup>-1</sup> of global warming potential for

Table 8. The global warming potential (t CO<sub>2</sub> eq. yr<sup>-1</sup>) for transport of diesel and biodiesel for each regional mine site.

Process	Mine site			
	A	B	C	D
Refinery to mine (km)	835	700	2300	425
Diesel operations (t CO <sub>2</sub> eq. yr <sup>-1</sup> )				
Diesel transportation	5586	7076	20,900	88,286
Total	5586	7076	20,900	88,286
Biodiesel operations (t CO <sub>2</sub> eq. yr <sup>-1</sup> )				
Maximum available blend	B30	B40	B30	B9
Biodiesel transportation	76	106	1203	498
Diesel transportation	3813	4083	14,269	79,883
Total	3889	4189	15,472	80,381

the smelters associated with sites A, B, C, and D, respectively.

In addition to mitigation of CO<sub>2</sub> at the smelter, the global warming potential (t CO<sub>2</sub> eq.) associated with the production of each fuel type was analyzed. Emissions from the production of diesel fuel were calculated using the regional diesel production processes available within the LCA software. The associated impact of the diesel production also includes fuel transportation from the nearest refinery to the mine site, which ranged between 400 and 2300 km (Table 7). In Table 7, for comparison between diesel and biodiesel operations, the CO<sub>2</sub> eq. emissions released in the form of smelter off gas is equivalent to the amount that would be consumed with the production of biodiesel.

An import consideration is the advantage of regional biodiesel production and the associated reduction of emissions that are required to transport petrochemical diesel. Transportation emissions (Table 8) were calculated for petrochemical diesel based on the distance travelled to the nearest diesel refinery for each mine site. For the purposes of this study, biodiesel transportation was calculated based on a 10 km distance as the biodiesel due to location of the production plant on the smelter's property. This led to decreased CO<sub>2</sub> eq. emissions across all four mine sites for the transportation of fuel for on-site use.

Table 9 shows that the production of biodiesel and the use of a B30 blend at both mine sites A and C results in reduced impacts across all four emissions categories examined compared to the use of exclusively diesel fuel. The lipid extraction process continues to produce high levels of CO<sub>2</sub> eq. in areas that use fossil fuels for electric energy generation. Until these regions begin to transition to renewable energy generation methods, alternative processes for lipid extraction need to be further investigated to reduce emissions from biodiesel production at mine sites B and D. This finding is consistent with the study by Bharathan et al. [68] which showed that for BEV usage underground to be beneficial, from an overall global warming potential perspective, low carbon emitting regional electricity generation is required.

A decrease in human toxicity potential was reported for all four mine sites. While the human toxicity potential does not determine guidelines for ventilation in underground mines, the results suggest that there is an opportunity to decrease ventilation use, and therefore costs. Differences in emissions from biodiesel are not only restricted to the ratio of biodiesel to diesel [69], but also to engine temperature [17], load and speed [70].

Table 9. Summarized emissions of diesel and biodiesel operations from production, transport, and fuel use.

Category	Mine site			
	A	B	C	D
Global warming potential (t CO <sub>2</sub> eq. yr <sup>-1</sup> )				
Diesel operations	32,761	121,260	67,567	793,650
Biodiesel blend operations	25,472	148,866	59,783	797,045
Difference	-22.5%	+22.8%	-11.5%	+0.43%
Acidification potential (t SO <sub>2</sub> eq. yr <sup>-1</sup> )				
Diesel operations	328	1099	662	7400
Biodiesel blend operations	296	1388	536	7491
Difference	-9.7%	+26.3%	-18.9%	+1.2%
Eutrophication potential (t N eq. yr <sup>-1</sup> )				
Diesel operations	43.1	82.9	57.8	582.9
Biodiesel blend operations	40.5	105.4	55	595.1
Difference	-6.1%	+27.3%	-4.8%	+2.1%
Human toxicity potential (CTUh yr <sup>-1</sup> )				
Diesel operations	4.54	5.94	8.12	44.8
Biodiesel blend operations	3.80	5.43	6.4	43.2
Difference	-16.2%	-8.7%	-21.0%	-3.6%

The differences in emissions and varying regional regulations means specific testing at individual sites would need to be conducted to ensure all contaminants are below legal limits for long-term human working conditions. As such, while not assessed in this study, it could be expected that further decreases in energy consumption (and associated improvements in environmental impact) could be achieved through reduced ventilation requirements when biodiesel is used underground.

#### 4. Conclusions

An LCA was conducted to compare the global warming, acidification, eutrophication, and the human toxicity potentials of two different mining scenarios (diesel vs biodiesel blends) based in four regionally distinct underground metal ore mines. Our primary goal was to examine the possibility of producing biodiesel blend from microalgal biomass cultivated using smelter off gas (6% CO<sub>2</sub>).

From our findings, the cultivation of *C. acidophila* using smelter off gas as a CO<sub>2</sub> source was able to produce enough biodiesel annually to supply mine site A (Canada) and C (Zambia) with B30, mine site B (Australia) with B40, while mine site D (Poland) could use B9, due to its much higher ore production capacity.

Mine sites A (Canada) and C (Zambia), with their regional electricity generation coming largely from renewable sources, were capable of reducing overall emissions to their process by utilizing regionally produced microalgal biodiesel in a 30% blend

instead of pure diesel fuel in all four potentials examined. They showed reductions in global warming potential of 22.5% (A) and 11.5% (C), acidification potential of 9.1% (A) and 18.9% (C), eutrophication potential of 6.1% (A) and 4.8% (C), and human toxicity potential of 16.2% (A) and 21.0% (C). While the environmental impact was tied to regional electricity generation, all sites showed a decrease in human toxicity potential.

Although beyond the scope of this study, all sites could potentially benefit from reduced ventilation requirements through the use of biodiesel blends. That is, the requirement to remove emissions could be reduced through the use of biodiesel blends, but the overall requirements are determined by health and safety regulations that vary by location. Other underground operations, mine and ventilation system design, and climatic considerations will also influence requirements.

Overall, the utilization of microalgae biodiesel blends to replace pure petrochemical diesel represents a promising route for the mining industry to both transition to the use of BEVs and maximise its return on investment in existing machinery.

The outcomes of this study demonstrate the significant potential for utilizing regionally produced biodiesel underground. In further work, the described concept could focus on biodiesel use in other equipment (including utility vehicles and generators) and also consider different mining operations, in terms of ore type and mine design. This would provide valuable information to the industry to help it elucidate opportunities for an improved environmental footprint.

## Conflicts of interest

None declared.

## Ethical statement

The authors state that the research was conducted according to ethical standards.

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