LIFE CYCLE SUSTAINABILITY ASSESSMENT OF ENZYME-INDUCED CARBONATE PRECIPITATION (EICP) FOR FUGITIVE DUST CONTROL

A.J. Raymond[1], C. Purdy[1], T. Fox[2], A. Kendall[1], J.T. DeJong[1]*, E. Kavazanjian Jr.[3], M. Woolley[3], K. Martin[3]

[1] Department of Civil and Environmental Engineering, University of California, Davis, 1 Shields Avenue, Davis, California, USA

[2] Department of Mechanical Engineering, The University of Akron, 302 East Buchtel Avenue, Akron, Ohio, USA

[3] School of Sustainable Engineering and the Built Environment, Arizona State University, PO Box 875502, Tempe, Arizona, USA

*Corresponding author; e-mail: jdejong@ucdavis.edu

Abstract

Fugitive dust caused by infrastructure construction reduces air quality and may cause serious respiratory problems. Earthwork contractors apply dust control strategies to meet environmental regulations for dust mitigation. A life cycle sustainability assessment (LCSA) was performed to compare the impacts of two dust control methods: water application—currently considered the best available technology by industry—and enzyme-induced carbonate precipitation (EICP), a new bio-mediated technology being developed at Arizona State University. For each dust control method, indicators of resource depletion (e.g., primary energy and water consumption), climate change (e.g., global warming potential), acidification, eutrophication, respiratory inorganics, ozone depletion, and smog formation were evaluated. The system boundary of the LCSA included the raw materials extraction, materials and energy processing, transportation, and treatment phases of the life cycle for each method. The potential impacts associated with water application exceed those of EICP across all impact categories, except acidification, eutrophication, human health particulate, and ozone depletion potentials. The transportation phase is the primary contributor to impacts for water application due to the need for daily treatments. In contrast, most of the impacts of EICP stem from materials processing and EICP process emissions. In arid climates where runoff to surface or ground water is of little concern, EICP process emissions depend largely on the volatilization of ammonia following the application of EICP on the soil. With respect to the economic impacts of each method, water application costs nearly double EICP. A sensitivity analysis was performed to evaluate the effects of critical modeling assumptions, such as ammonia losses from volatilization and watering frequency. Due to its predicted impacts, EICP is potentially more sustainable than water application, particularly as watering frequency increases. With further development focused on preventing EICP process emissions and reducing production costs, EICP could become more viable for fugitive dust control.

Keywords:

Erosion; Fugitive dust control; Bio-mediated; Sustainable construction; Life cycle assessment

1 INTRODUCTION

Fugitive dust (i.e., wind-blown fine-grained soil) is a form of particle pollution that reduces air quality and increases the risk of serious health problems. When exposed soils are mechanically disturbed by natural or anthropogenic sources, particulate matter can become entrained in the air. Exposure to particle pollution has been linked to a variety of health problems, including premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, decreased lung function, aggravated asthma, and other respiratory symptoms (e.g., irritation, coughing or difficulty breathing) [CARB 2017].

The US Environmental Protection Agency (EPA) sets National Ambient Air Quality Standards (NAAQS) for six criteria air pollutants: particulate matter (i.e., PM_{10} and $PM_{2.5}$), photochemical oxidants (i.e., ozone), carbon monoxide, sulfur oxides, nitrogen oxides, and lead. Under the Clean Air Act, an area that does not meet the NAAQS is designated a 'nonattainment area.' There are several nonattainment areas in the US, particularly in arid and semiarid regions. As of November 2018, over 9.1 million Americans are living in areas with nonattainment status according to the PM_{10} NAAQS established in 1987 (Tab. 1). Similarly, over 23.2 million Americans live in $PM_{2.5}$ nonattainment zones [US EPA 2018].

Tab. 1: Nonattainment areas in the US and populations at risk [US EPA 2018].

NAAQS	No. of States with Areas in Nonattainment Status	No. of Counties with Areas in Nonattainment Status	2010 Population Living in Nonattainment Areas (million)
8-Hour Ozone (2015)	23	201	124.1
$PM_{2.5}$ (2012)	4	20	23.2
PM_{10} (1987)	9	29	9.1
Sulfur Dioxide (2010)	19	55	3.3
Lead (2008)	8	13	9.6
Carbon Monoxide (1971)[1]	--	--	--
Nitrogen Dioxide (1971)[2]	--	--	--
Across All Criteria Air Pollutants	38	--[3]	132.5

[1]All Carbon Monoxide nonattainment areas were redesignated to maintenance areas as of September 27, 2010.
[2]All Nitrogen Dioxide nonattainment areas were redesignated to maintenance areas as of September 22, 1998.
[3]No available data.

Common sources of fugitive dust include unpaved roads, agricultural activities, and construction operations [US EPA 1995]. In 2014, the Maricopa County Air Quality Department estimated annual PM_{10} emissions from all source categories in the Maricopa County Nonattainment Area in Arizona. The study found that construction and earthwork activities contributed approximately 4,700 tonnes per year or 15% of total annual PM_{10} emissions (Fig. 1) [MCAQD 2017].

Environmental agencies impose air pollution control regulations to limit fugitive dust emissions at active construction sites. For example, Maricopa County's Rule 310 is an EPA-approved regulation for regional PM_{10} emissions from 'dust-generating operations' (e.g., construction, demolition, earthwork, and vehicle track-out) [Maricopa County 2010]. Rule 310 requires earthwork contractors to apply dust control strategies to prevent, reduce, or mitigate fugitive dust emissions.

Conventional dust control methods include the application of water, salt, or synthetic polymers. However, these methods are either ineffective in arid climates, limited to short-term stabilization, or very expensive. Many existing methods also have adverse environmental impacts [US EPA 1995]. Research suggests that bio-cementation of surficial soils using carbonate precipitation may provide an alternative and more sustainable method for fugitive dust control [Hamdan 2016].

This paper presents the results of a life cycle sustainability assessment (LCSA) that evaluates and compares the impacts of two dust control methods: water application—currently considered the best available technology by industry—and enzyme-induced carbonate precipitation (EICP), a new bio-mediated technology being developed at Arizona State University (ASU). First, background information on each dust control strategy is presented. Details regarding the methods, models, and data used in the study are then described. The results obtained for several indicators of sustainability are presented for each life cycle stage. A sensitivity analysis is performed to understand the influence of critical modeling assumptions on the LCSA results. Finally, the implications of the study's results are discussed.

2 BACKGROUND

In this section, the dust control methods under investigation in this study are described.

2.1 Water application

Water application—or watering—is the most common practice for fugitive dust mitigation at disturbed soil sites

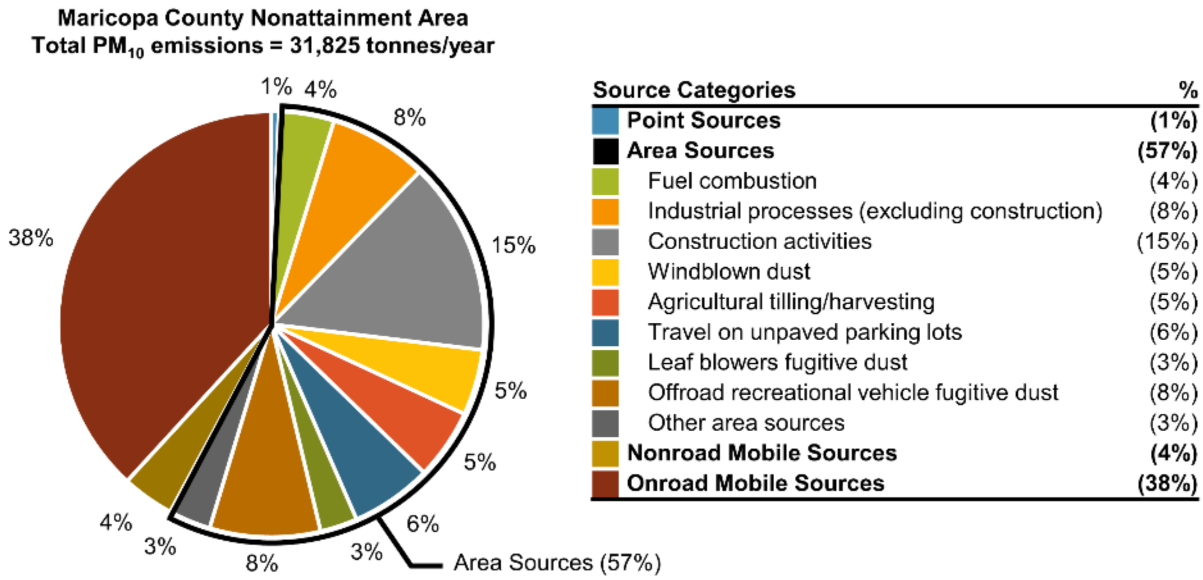

Fig. 1: 2014 PM_{10} emissions inventory for the Maricopa County Nonattainment Area [MCAQD 2017].

[US EPA 1995]. Watering works by increasing the weight of soil particles (i.e., through adsorption of water to particle surfaces) and agglomerating particles together by capillary action, thereby reducing particle detachment and subsequent entrainment in the air. Watering during construction activities can reduce PM_{10} emissions by 10% to 74% and typically costs anywhere between $160 and $1,360 per day [WRAP 2006].

Watering is an effective, though temporary, dust control method and often requires multiple applications. Many guidelines for effective watering recommend a minimum of two applications per day. However, more frequent applications may be needed to adequately mitigate fugitive dust emissions (depending on temperature, humidity, wind speed, soil characteristics, etc.) [ADOT 2010]. In 2001, the Midwest Research Institute found that by increasing the frequency of water applications during construction activities from a 3.2- to 2.1-hour watering interval, PM_{10} control efficiency was increased from 61% to 74% [WRAP 2006]. This suggests that as many as five or more applications per day may be required for some projects.

The volume of water required per application also depends on many factors, including the type of construction activity and the soil characteristics onsite. Trenching or excavation operations typically require watering to the planned depth of the cuts, whereas other activities only require surficial wetting (of the top 1 to 2 cm of soil) to prevent most dust emissions [US EPA 2001; ADOT 2010]. However, even surface watering can result in high water demand. For example, dry soil with a porosity between 43% and 58% will require approximately 4 L of water per square meter to achieve a surface moisture content between 15% and 36%, a range that has been found to sufficiently reduce PM_{10} emissions [US EPA 2001]. Furthermore, watering is labor intensive, and frequent applications can substantially increase project costs.

2.2 Enzyme-induced carbonate precipitation

Enzyme-induced carbonate precipitation (EICP) is a bio-mediated process being leveraged by researchers at ASU as a new technology for fugitive dust control. The EICP technology consists of a spray-on solution that, through a chemical reaction, precipitates calcium carbonate ($CaCO_3$) on soil particle surfaces and at particle contacts, thereby cementing the soil and creating an erosion-resistant crust.

The EICP reaction is made possible by the urease enzyme (urea amidohydrolase), which, in the presence of urea, can catalyze a hydrolysis reaction that results in the production of ammonia and carbonic acid (Eq. 1). When the solution pH is not highly alkaline, ammonia will participate in an equilibrium reaction with water, producing ammonium and hydroxide ions (Eq. 2). The hydroxide ions increase solution pH, which promotes the deprotonation of carbonic acid to form bicarbonate and carbonate ions (Eq. 3). As carbonate ions become increasingly available, the addition of calcium ions may supersaturate the aqueous solution with respect to calcium carbonate and initiate precipitation (Eq. 4) [Hamdan 2016; Gomez 2018].

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_3 + H_2CO_3 \quad (1)$$

$$NH_3 + H_2O \rightleftarrows NH_4^+ + OH^- \quad (2)$$

$$H_2CO_3 \rightleftarrows HCO_3^- + H^+ \rightleftarrows CO_3^{-2} + 2H^+ \quad (3)$$

$$Ca^{+2} + CO_3^{-2} \rightleftarrows CaCO_3 \quad (4)$$

Hamdan and Kavazanjian [2016] conducted wind tunnel experiments to assess the viability of EICP for surficial stabilization of soils. The testing program quantified the erosion resistance of treated soil specimens by measuring soil particle threshold detachment velocity (TDV), or the wind velocity at which soil particles become entrained in the air. The TDVs of three soil types were evaluated for specimens of untreated soil (control), wetted soil, soil treated with a salt solution (a common practice for dust control in the mining industry), and EICP-treated soil. The concentrations of calcium chloride and urea in the EICP solution formulation were varied to establish the solution strength required to yield a TDV comparable to that of the wetted soil. In most cases, the TDVs of the specimens treated with EICP solution concentrations of 0.4 M calcium chloride and 0.6 M urea or greater exceeded the TDV of wetted soil, which varied from 22 m/s to 23 m/s [Hamdan 2016].

More recently, a durability analysis was conducted at ASU using an accelerated weathering chamber to evaluate the impacts of exposure to the sun and high temperatures on the ability of EICP to mitigate fugitive dust. Results showed that at 6.5 months of exposure to conditions representative of an Arizona summer, the EICP crust was not significantly degraded and a TDV greater than 24 m/s was maintained [M. Woolley, personal communication, March 12, 2018]. The outcomes of the wind tunnel testing and durability analysis demonstrate the potential for EICP to provide improved performance relative to an existing business-as-usual method (i.e., watering) for dust control.

3 METHODS AND MATERIALS

3.1 Goal and scope definition

The goal of this study was to perform a LCSA to evaluate and compare the environmental, economic, and social impacts of EICP against those of watering for mitigation of fugitive dust. Typically, LCSA integrates environmental life cycle assessment, life cycle costing, and social life cycle assessment. However, indicators of social impacts are less developed and not as widely used [Neugebauer 2015]. In this study, the social cost of carbon is quantified and used to represent the potential social impacts of each dust control method.

An attributional, process-based life cycle assessment (LCA) was performed to understand the environmental impacts of EICP versus water application for dust control. The functional unit for comparing the two systems is 1 acre (4047 m^2) of land treated to mitigate fugitive dust (TDV ≥ 22 m/s) over a period of two weeks. The project site was assumed to be located in Maricopa County, Arizona. The LCSA results are normalized with respect to the functional unit.

System description and boundaries

The following processes are quantified over the life cycle of each dust control strategy (Fig. 2): raw materials extraction, materials processing and transportation, energy (e.g., diesel and electricity) production, vehicle/equipment mobilization and use, and onsite operations. Some processes (e.g., the transportation of jack beans from the field to a processing plant, manufacturing of vehicles and equipment, and management of any waste generated onsite) were not included in the scope of the study.

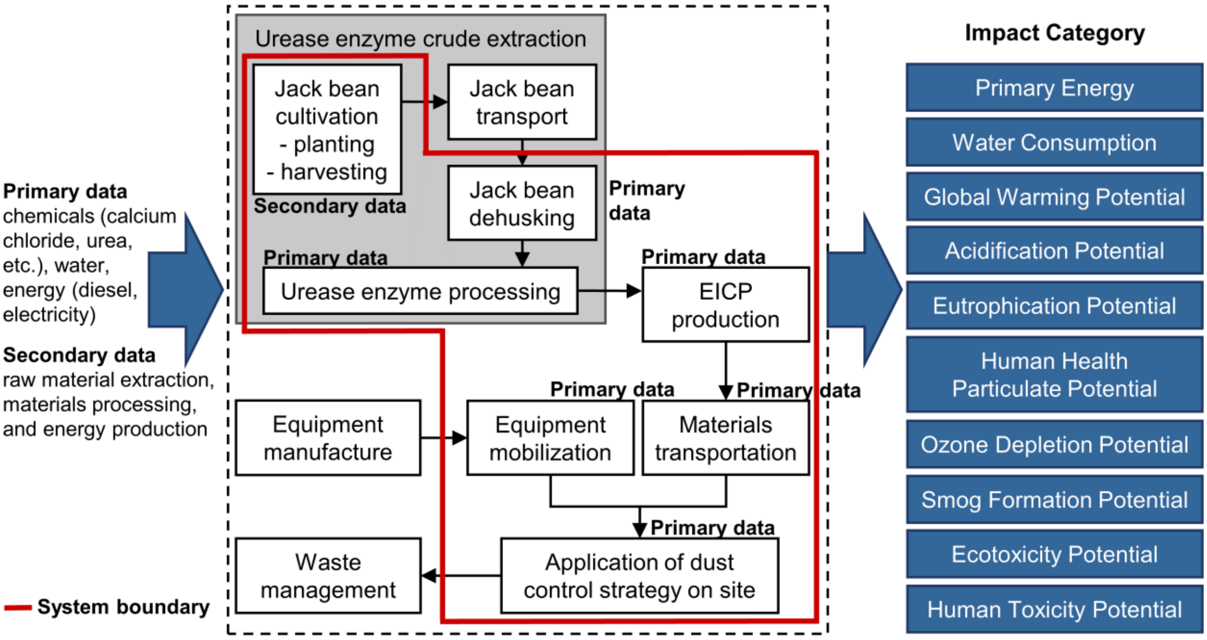

Fig. 2: Flow diagram and system boundary for dust control via EICP. Primary data refers to data collected from ASU researchers; secondary data refers to data obtained from published literature or reference LCI databases.

3.2 Life cycle inventory

A life cycle inventory (LCI) was performed to catalog the relevant inputs (e.g., energy and raw materials) and outputs (e.g., emissions to air, water, and soil, solid wastes, coproducts, or other releases) associated with each dust control method over its life cycle [ISO 2006].

Primary data for modeling the foreground system

Primary data for the materials required for each dust control strategy were collected based upon the research conducted at ASU. Secondary data from published literature were supplemented where necessary. For watering, it was assumed that daily applications of approximately 16,500 L of water per acre were required. Dust control through EICP required only one application (4,930 L of solution) per functional unit. In the EICP solution formulation, the reaction is catalyzed using a plant-derived urease from jack beans. In this study, crude extraction of the urease enzyme from jack beans was modeled using a procedure developed at ASU. Some data for EICP production (e.g., specific material quantities) are subject to a nondisclosure agreement and not provided in this paper.

Transportation modeling

Transportation modeling was required to estimate fuel use and associated emissions (e.g., from fuel production and consumption) during the materials transportation, equipment mobilization, and onsite operations phases of the life cycle. The distance for transporting materials and equipment to the project site was assumed to be 100 miles (161 km) roundtrip. Onsite operations required vehicles to travel approximately 2,090 ft (637 m) per application. Two vehicles were selected to model the necessary transportation to site and subsequent application of each dust control method onsite:

- a HINO 338, with a capacity of 7,571 L and a gross vehicle weight ratio (GVWR) of 14,969 kg; and
- a Freightliner M2-106, with a capacity of 15,142 L and a GVWR of 26,308 kg [Herc Rentals Inc. 2018].

MOVES2014b, the latest version of the Motor Vehicle Emission Simulator (MOVES) developed by the US EPA, was used to create emissions inventories for onroad motor vehicles and nonroad equipment. MOVES calculates the energy consumption and emissions (including criteria air pollutants, greenhouse gases, and select air toxics) associated with mobile sources. Required user inputs include vehicle type, time period, geographical area, pollutants, vehicle operating characteristics, and road type to be modeled. In this study, national level emissions rates were allocated to the county level for Maricopa County and averaged across all road types for the months of July and August 2018. A 'medium heavy duty' vehicle (8,845 kg < GVWR ≤ 14,969 kg) was selected to model the HINO 338, and a 'heavy heavy duty' vehicle (GVWR > 14,969 kg) was selected for the Freightliner M2-106. Emissions for both vehicle types were calculated at two distinct speed bins:

- 52.5 mph ≤ speed < 57.5 mph (used to model materials transportation and equipment mobilization); and
- 2.5 mph ≤ speed < 7.5 mph (used to model onsite operations).

EICP process emissions

Due to the high nitrogen (N) content of urea (46% N), its use (e.g., in EICP for dust control or as an agricultural fertilizer) contributes to the acceleration of the global N cycle. When applied to the soil surface, urea is susceptible to:

- ammonia (NH_3) volatilization;
- nitrous oxide (N_2O), nitric oxide (NO), and nitrogen gas (N_2) emissions through the aerobic and anaerobic processes that occur in soils; and
- leaching and runoff of N, mainly as nitrate (NO_3^-) [Klein 2006].

The emissions resulting from the application of EICP on the soil (i.e., EICP process emissions) were estimated following the recommendations presented in Chapter 11 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and using values from published literature [Bouwman 2002; Holcomb 2011]. In the baseline study, 10% of the applied N was assumed to volatilize as NH_3 [Klein 2006]. Direct N_2O and NO emissions due to nitrification and denitrification of the urea in the soil were assumed to be 1.1% and 0.7% of applied N, respectively [Bouwman 2002]. No data were available to estimate N_2 emissions. Indirect N_2O emissions (from volatilization and subsequent redeposition of NH_3 to soil and water) were assumed to be 1% of volatilized NH_3 [Klein 2006]. It was assumed that no emissions were released via leaching or runoff of NO_3^- due to the arid climate of the project site.

Secondary data for background processes

Secondary LCI data were used to quantify the energy and material inputs as well as emissions for a variety of background processes, including the production of chemicals (e.g., calcium chloride and urea), water, diesel, electricity, and other inputs (e.g., jack beans, powdered nonfat milk, cheesecloth, and glass wool). No LCI data were available for jack bean production; therefore, an LCI dataset for soybeans was used as a surrogate. Most LCI data were collected from published academic literature, the GaBi Professional database (last updated in 2018), the ecoinvent database (last updated in 2018), and the National Renewable Energy Laboratory (NREL) US LCI Integrated database (last updated in 2012) accessed through the GaBi ts 8 software [ecoinvent 2018; thinkstep 2018].

US data were used where available and supplemented with European datasets where necessary, most notably for calcium chloride production. In the US, calcium chloride is produced by refining natural brines; however, no LCI data were available for this process. Instead, calcium chloride derived from the Solvay process (i.e., a major industrial process for producing soda ash) was modeled. The use of this dataset is likely to overestimate impacts from calcium chloride production.

3.3 Life cycle impact assessment

A life cycle impact assessment (LCIA) was performed to evaluate the potential environmental and human health impacts of each dust control strategy throughout its life cycle [ISO 2006]. In the LCIA, the LCI data were translated into indicators of resource depletion (e.g., primary energy and water consumption), climate change (e.g., global warming potential), acidification, eutrophication, human health impacts (e.g., from respiratory inorganics), ozone depletion, and smog formation. Indicators of ecotoxicity as well as other human health impacts (e.g., from carcinogens and noncarcinogens) were also evaluated; however, the results of these indicators are not provided in this paper.

The indicator values were modeled using the characterization factors provided in version 2.1 of the tool for the reduction and assessment of chemical and other environmental impacts (TRACI). TRACI is a midpoint level LCIA method that was developed by the US EPA, specifically for applications representing potential effects in the US [Bare 2003]. The 100-year global warming potential (GWP) values in TRACI were updated with those published in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Myhre 2013].

3.4 Life cycle costing

A life cycle cost analysis (LCCA) was performed to evaluate the direct monetary costs involved with the dust control methods over the equivalent life cycle illustrated in Fig. 2. Data were obtained from Fisher Scientific International, Inc. and Herc Rentals Inc. to model the costs associated with chemicals (e.g., calcium chloride and urea) use and vehicle/equipment rentals. The unit cost of diesel was assumed to be $3.00 per gallon. Water was priced at $0.006 per gallon [WIFA 2017]. Crude extraction of the urease enzyme was estimated to cost $0.27 per mL [K. Martin, personal communication, March 12, 2018].

3.5 Social cost of carbon

In addition to life cycle costing, the social cost of carbon (SCC) associated with each dust control strategy was computed. The SCC is 'an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year' [IWG on Social Cost of Greenhouse Gases 2015]. The SCC includes the impacts to agricultural productivity, human health, property damages from flood risk, and the value of the ecosystem as a result of climate change. Three integrated assessment models (IAMs) are used to estimate the SCC: the Climate Framework for Uncertainty, Negotiation, and Distribution model; the Dynamic Integrated Climate and Economy model; and the Policy Analysis of the Greenhouse Effect model. These IAMs combine climate processes, economic growth, and feedbacks between the climate and the global economy to translate climate impacts to economic damages. Variability between the models arises due to simplifying assumptions regarding the economic value of greenhouse gas (GHG) emissions [IWG on Social Cost of Greenhouse Gases 2015].

Due to uncertainty within the models, the Interagency Working Group provides four estimates for the SCC for any given discount year (i.e., the year pollutants are emitted). Three values are based on the average SCC from the three IAMs at discount rates of 2.5%, 3%, and 5%. The fourth estimate, the 95th percentile value of the average SCC at a 3% discount rate, represents higher-than-expected impacts from climate change [IWG on Social Cost of Greenhouse Gases 2015]. In this study, the SCC value for an average discount rate of 3% in 2018 was used.

3.6 Sensitivity analysis

A sensitivity analysis was performed to evaluate how uncertain and independent input variables affect the uncertainty in the outputs (i.e., the LCSA results) for each dust control method. Sensitivity to the following modeling assumptions was investigated:

4. The parameters associated with the emissions to air and water of nitrogen compounds (NH_3, N_2O (direct and indirect), and NO_3^-) caused by application of EICP.
5. The number of water applications per day.

NH_3 volatilization, a critical and uncertain variable in the EICP model, is influenced by various soil properties (e.g., pH, moisture content, texture, and cation exchange capacity) as well as external factors, such as temperature and wind speed [Fleisher 1987]. NH_3 volatilization from urea typically ranges from 3% to 30% of applied N [Klein 2006]. However, NH_3 losses over 80% have been reported in the literature [Holcomb 2011]. In this study, NH_3 losses were varied between 10% (baseline) and 80% of applied N. N_2O and NO_3^- emissions were also varied in the sensitivity analysis; however, the results for these parameters are not included in this paper.

Watering frequency was varied between 1 (baseline) and 5 applications per day. The upper bound was established in accordance with the recommendations of the Arizona Department of Transportation, which propose watering the soil every two hours to ensure compliance with Rule 310 [ADOT 2010].

4 RESULTS AND DISCUSSION

4.1 Baseline study

The results of the baseline study are presented in Fig. 3. The baseline study found that for the given treatment area of 1 acre, the potential impacts associated with water application exceed those of EICP for primary energy use (by a factor of about 3.5), water consumption (40), global warming potential (3.0), smog formation potential (5.0), project cost (1.9), and social cost of carbon (3.0). For the remaining indicators (i.e., acidification, eutrophication, human health particulate, and ozone depletion), the potential impacts of EICP are greater than those of watering by factors of 1.8, 2.1, 1.6, and 58,000, respectively. However, the ozone depletion potentials of EICP and water application are very small (approximately 1.2 × 10^{-5} kg CFC 11 eq. and 2.0 × 10^{-10} kg CFC 11 eq., respectively) and are considered negligible.

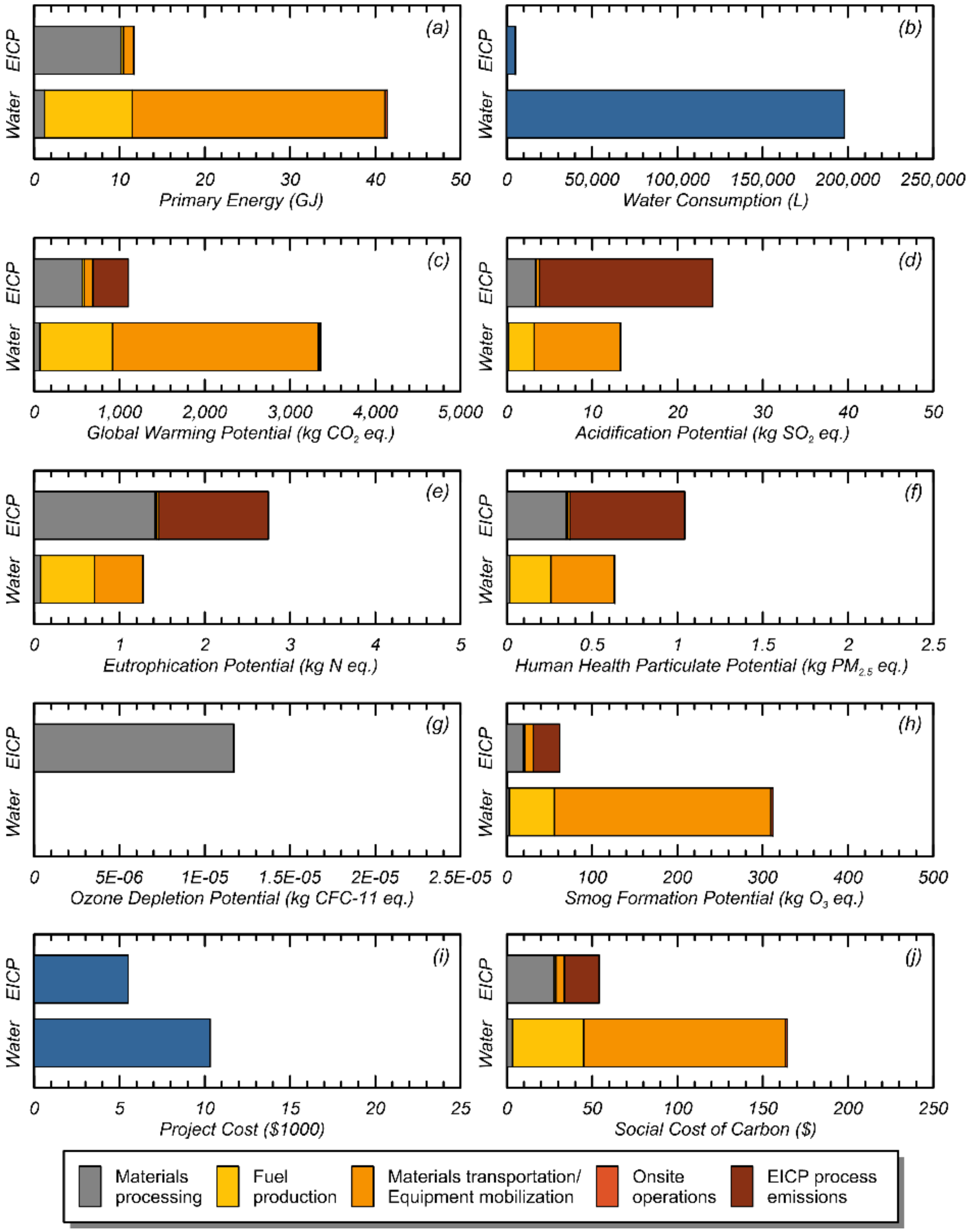

Fig. 3: Results of the baseline study, which compares EICP and water application for fugitive dust control (TDV ≥ 22 m/s) of 1 acre of land over a period of two weeks. The results are presented for each impact category and for all life cycle stages considered.

Tab. 2: Results of the sensitivity of potential impacts from EICP to changing ammonia losses via volatilization.

NH_3 Volatilization (% applied N)	100-year Global Warming Potential (kg CO_2 eq.)	Acidification Potential (kg SO_2 eq.)	Eutrophication Potential (kg N eq.)	Human Health Particulate Potential (kg $PM_{2.5}$ eq.)
10 (baseline)	1,103	24	2.7	1.0
20	1,138	43	3.9	1.7
30	1,172	62	5.1	2.4
40	1,207	81	6.3	3.1
50	1,241	100	7.5	3.7
60	1,276	119	8.8	4.4
70	1,310	138	10.0	5.1
80	1,345	157	11.2	5.8

Tab. 3: Results of the sensitivity of potential impacts from water application to changing watering frequency.

No. of Water Applications (per day)	100-year Global Warming Potential (kg CO_2 eq.)	Acidification Potential (kg SO_2 eq.)	Eutrophication Potential (kg N eq.)	Human Health Particulate Potential (kg $PM_{2.5}$ eq.)
1 (baseline)	3,356	13	1.3	0.6
5	10,865	44	4.5	2.1

The transportation-related phases (i.e., fuel production, materials transportation/equipment mobilization, and onsite operations) are the primary contributors to impacts for water application due to the need for daily treatments. In contrast, most of the impacts of EICP stem from materials processing and EICP process emissions. In arid climates where runoff to surface or ground water is of little concern, EICP process emissions depend largely on the volatilization of ammonia following the application of EICP on the soil. Between 38% and 84% of the global warming, acidification, eutrophication, human health particulate, and smog formation potentials are attributable to EICP process emissions.

With respect to economic impacts, total water application costs are nearly double that of EICP application. The project cost of watering stems mainly from truck rental costs (84%). For EICP, the cost of the urease enzyme is the highest contributor to overall project cost (59%). Approximately $4,800 of savings are realized per acre of EICP treatment over water application for dust control. However, durability analysis of EICP suggests the crust can remain resilient against fugitive dust emissions for much longer than two weeks if it is not disturbed. If, instead, the crust remains intact for one month, potential savings increase to over $15,100 per acre.

4.2 Sensitivity analysis

The results of the sensitivity analysis on the effects of changing NH_3 losses from volatilization and watering frequency are presented in Tab. 2 and Tab. 3, respectively. Only the indicator values for global warming potential, acidification potential, eutrophication potential, and human health particulate potential are presented. This is because NH_3 losses are independent of the other indicators (i.e., primary energy, water consumption, ozone depletion potential, smog formation potential, and project cost). Additionally, changing the watering frequency to five applications per day increased the magnitudes of all indicators (including those not presented) by a factor of about 3.5 (±0.3). On average, a 10% increase in NH_3 volatilization increased the total global warming, acidification, eutrophication, and human health particulate potentials of EICP by factors of 1.03, 1.32, 1.23, and 1.29, respectively.

4.3 Discussion

Given the results of the baseline study, the use of EICP for dust control has the potential to reduce water consumption by nearly 193,000 L and decrease GHG emissions by about 2,300 kg CO_2 eq. per acre. This translates to approximately $110 of savings from reduced GHG emissions. The sensitivity analysis indicates that increased savings may be realized with the use of EICP over water application as watering frequency increases.

A watering program that consists of five applications per day is likely to be more representative of real field conditions during construction activities in arid and semiarid regions, particularly during the summer, due to its compliance with Rule 310. Therefore, if NH_3 losses are equal to or less than 20%, the potential impacts associated with five water applications per day would exceed those of EICP across all impact categories (except ozone depletion, where the potential impacts of both methods are negligible). The use of EICP for dust control would lower project costs by about $29,300 per acre. Furthermore, EICP use would decrease water consumption by 985,000 L and GHG emissions by 9,700 kg CO_2 eq. per acre compared to water application. As a result, a social damage cost of nearly $500 would be avoided.

Limitations and future work

The results of this LCSA are specific to the described project site in Maricopa County and may not be representative of other sites (i.e., predicted impacts may vary for different soil types and climates). Additional research is required to understand the sensitivity of the results to project location and other potentially important modeling assumptions (e.g., materials transportation and equipment mobilization distances).

5 SUMMARY

Fugitive dust caused by infrastructure construction reduces air quality and may cause serious respiratory problems. Earthwork contractors apply dust control strategies to meet environmental regulations for dust mitigation. EICP is a bio-mediated process being leveraged in the development of a new dust control method. Prior research has demonstrated the feasibility of EICP for surficial stabilization of erosion-susceptible soils. However, the potential environmental, economic, and social impacts of EICP relative to existing business-as-usual methods (e.g., watering) for dust control have not been considered in the literature.

This paper summarizes the results of a LCSA that was performed to evaluate and compare the impacts of EICP against those of conventional water application for fugitive dust control of a 1-acre site in Maricopa County, Arizona. Due to its predicted impacts, EICP is potentially more sustainable than watering, particularly as the frequency of water applications increases to meet dust control regulations. Compared to watering, the application of EICP for dust control reduces water and fuel requirements substantially, resulting in lower environmental impacts and associated costs. With further development focused on preventing EICP process emissions (e.g., NH_3 volatilization) and reducing costs associated with crude extraction of the urease enzyme, EICP could become more viable as a method for fugitive dust control.

6 ACKNOWLEDGMENTS

This material is based upon work supported by the Engineering Research Center Program of the National Science Foundation (NSF) under NSF Cooperative Agreement EEC-1449501. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the NSF.

7 REFERENCES

[CARB 2017] California Air Resources Board (CARB); Inhalable particulate matter and health ($PM_{2.5}$ and PM_{10}). 2017. https://www.arb.ca.gov/research/aaqs/common-pollutants/pm/pm.htm.

[US EPA 2018] US EPA; Nonattainment areas for criteria pollutants (Green Book). 2018. https://www.epa.gov/green-book.

[US EPA 1995] United States Environmental Protection Agency (US EPA); Chapter 13.2: Fugitive dust sources. In AP 42, Fifth edition, Compilation of air pollutant emissions factors, Volume I: Stationary point and area sources. 1995.

[MCAQD 2017] Maricopa County Air Quality Department (MCAQD); 2014 periodic emissions inventory for PM_{10}. Maricopa County, Arizona: 2017.

[Maricopa County 2010] Maricopa County; Rule 310: Fugitive dust from dust-generating operations. 2010.

[Hamdan 2016] Hamdan, N.; Kavazanjian, E. Jr.; Enzyme-induced carbonate mineral precipitation for fugitive dust control. Géotechnique, 2016, 66, 7, 546-555.

[WRAP 2006] Western Regional Air Partnership (WRAP); WRAP fugitive dust handbook. WGA Contract No. 30204-111. Denver, Colorado: Western Governors' Association, 2006.

[ADOT 2010] Arizona Department of Transportation (ADOT); Quick reference dust control guide. Blue Skies Campaign. 2010.

[US EPA 2001] US EPA; Particulate emission measurements from controlled construction activities. EPA/600/R-01/031. 2001.

[Gomez 2018] Gomez, M.G.; Graddy, C.M.R.; DeJong, J.T.; Nelson, D.C. et al.; Stimulation of native microorganisms for biocementation in samples recovered from field-scale treatment depths. Journal of Geotechnical and Geoenvironmental Engineering, 2018, 144, 1, 04017098.

[Neugebauer 2015] Neugebauer, S.; Martinez-Blanco, J.; Scheumann, R.; Finkbeiner, M.; Enhancing the practical implementation of life cycle sustainability assessment – proposal of a tiered approach. Journal of Cleaner Production, 2015, 102, 165-176.

[ISO 2006] International Organization for Standardization (ISO); Environmental management – life cycle assessment – principles and framework. ISO 14040:2006. Geneva, Switzerland: ISO, 2006.

[Herc Rentals Inc. 2018] Herc Rentals Inc.; Water trucks. 2018. https://www.hercrentals.com/us/rentals/trucks-trailers/commercial-trucks/water-trucks.html.

[Klein 2006] Klein, C.D.; Novoa, R.S.A.; Ogle, S.; Smith, K.A. et al.; Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. In 2016 IPCC Guidelines for National Greenhouse Gas Inventories.

[Bouwman 2002] Bouwman, A.F.; Boumans, L.J.M.; Batjes, N.H.; Modeling global annual N_2O and NO emissions from fertilized fields. Global Biogeochemical Cycles, 2002, 16, 4, 28.

[Holcomb 2011] Holcomb, J.C.; Sullivan, D.M.; Horneck, D.A.; Clough, G.H.; Effect of irrigation rate on ammonia volatilization. Soil Science Society of America Journal, November 2011, 75, 6, 2341-2347.

[ecoinvent 2018] ecoinvent; ecoinvent 3.5. Zurich, Switzerland. 2018. https://www.ecoinvent.org/database/ecoinvent-35/ecoinvent-35.html.

[thinkstep 2018] thinkstep; GaBi ts 8: System software and databases for life cycle engineering. Leinfelden-Echterdingen, Germany. 2018.

[Bare 2003] Bare, J.C.; Norris, G.A.; Pennington, D.W.; McKone, T.; The tool for the reduction and assessment of chemical and other environmental impacts. Journal of Industrial Ecology, 2003, 6, 3, 49-78.

[Myhre 2013] Myhre, G.; Shindell, D.; Bréon, F.M.; Collins, W. et al.; Anthropogenic and natural radiative forcing. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 659-740.

[WIFA 2017] Water Infrastructure Finance Authority of Arizona (WIFA); Environmental Finance Center (EFC) at the University of North Carolina, Chapel Hill; 2017 Arizona water & wastewater rates report. 2017.

[IWG on Social Cost of Greenhouse Gases 2015] Interagency Working Group (IWG) on Social Cost of Greenhouse Gases; Technical update of the social cost of carbon for regulatory impact analysis under Executive Order 12866. 2015. US Government.

[Fleisher 1987] Fleisher, Z.; Kenig, A.; Ravina, I.; Hagin, J.; Model of ammonia volatilization from calcareous soils. Plant and Soil, 1987, 103, 2, 205-212.