Impact of Heavy Metals from Flue Gas Integration with Microalgae Production

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ABSTRACT

Integration of microalgae cultivation with coal-based flue gas is a widely proposed approach to supply carbon dioxide (CO₂). The utilization of coal derived CO₂ in microalgae growth systems will introduce heavy metals (toxic metals and metalloids), originally present in coal, into the cultivation system. This study evaluates the effect of 10 heavy metals (As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Se and Zn) at four different concentrations on the growth and lipid yield of microalgae, *Scenedesmus obliquus*. Results show at the baseline heavy metal concentration of 1X, corresponding to the concentrations expected from a coal fired power plant, a 12% higher biomass and 61% higher lipid yield when compared to a control containing no heavy metals. Higher concentrations of heavy metals, twofold (2X), fivefold (5X) and tenfold (10X), are shown to inhibit both growth and lipid production. Analysis shows most heavy metals added to the culture were mainly sorbed to biomass with Hg mostly lost to the environment. Discussion focuses on how flue gas-derived heavy metals could result in both positive and negative outcomes for biomass and biodiesel production and the environmental implications of a commercial microalgae growth system that utilizes coal based flue gas as a CO₂ source.

KEYWORDS

Flue gas, heavy metals, lipid accumulation, biodiesel, microalgae, *Scenedesmus obliquus*.

1. INTRODUCTION

A large portion of the carbon dioxide (CO₂) being emitted in the US is attributed to energy production, with fossil fuel combustion plants accounting for 78% of the US global warming potential [1]. Carbon emissions are expected to continue to increase as global energy demand grows with the majority of global electrical energy still being derived from the combustion of coal as it is an abundant and economical energy source [2]. One approach to reduce the environmental impact of coal based power production is the integration of flue gas with microalgae cultivation for the transformation to biomass-derived liquid fuel [3, 4]. Such microalgal-based systems require a concentrated CO₂ source as a nutrient for accelerated biological growth. Compared to traditional terrestrial bioenergy oil crops, microalgae have a current near term potential of 46.8 m³·ha⁻¹·yr⁻¹ oil, which is substantially higher than palm (5.9 m³·ha⁻¹·yr⁻¹ oil), rapeseed/canola (1.2 m³·ha⁻¹·yr⁻¹ oil), soybean (0.4 m³·ha⁻¹·yr⁻¹ oil) and corn (0.2 m³·ha⁻¹·yr⁻¹ oil) [5]. High productivity combined with the advantages of year round cultivation, use of non-agricultural land, integration with wastewater treatment, and use of low quality water give microalgae a competitive advantage over other terrestrial crops [6-8]. These advantages have led to increased interest in using microalgae as a feedstock for biofuel production with a variety of lifecycle, techno-economic and resource assessments assuming a seamless integration of point source CO₂ such as flue gas from coal fired power plants as a carbon source for microalgae cultivation [9-11]. These assessments have not fully considered the implications of integrating coal based CO₂ with growth systems in terms of environmental impact.

It is well known that heavy metals naturally present in coal are volatilized during coal combustion and are released along with the flue gas to the atmosphere, even after passing through cleaning devices [12-14]. The utilization of flue gas into algal cultivation systems will ultimately introduce these contaminants (note that the term heavy metals is widely used in literature to refer toxic metals and metalloids; in this study 10 inorganic contaminants of interest will be referred as heavy metals) [15-17]. Heavy metals are a concern for the

microalgae cultivation industry due to their adverse effects on human health in the form of carcinogenic, teratogenic and mutagenic effects as well as their potential toxicity to microalgae [3, 18]. Further, heavy metals sorption in microalgae biomass has the potential to limit its end use [19, 20]. Adsorption of heavy metals by microalgae has previously been studied, but with short time periods (typically 20 – 300 minutes), low pH (usually from 1 – 6.5) and at doses that are several times higher than what would be expected from flue gas integration [21-24]. These primary experimental assumptions are not applicable to commercial production of microalgae biomass for biofuel. Other studies have evaluated long term toxicity effects of heavy metals, but at concentrations that are again higher than the concentrations that would be seen with flue gas and are focused on assessing either the effects on growth or the effect on lipids [20, 25, 26]. Short and long term studies conducted are either mono-metal or include only a couple metals in multi-metal systems, whereas flue gas has been shown to have a large number of heavy metals [27]. A selected number of studies evaluating the feasibility of using point source CO₂ to cultivate microalgae measured heavy metals present in the biomass, however presented results were limited to the effects of heavy metals on biomass productivity [15-17]. A review of the literature highlights the need to better understand the impacts of multiple heavy metals on microalgae growth and lipid productivity for systems designed for the production of lipid rich microalgae biomass, including the end fate of the heavy metals that are sorbed from the integration of coal-based flue gas with cultivation.

This study experimentally evaluates the impact and fate of 10 heavy metals present in coal-based flue gas on microalgal growth and lipid production. *Scenedesmus obliquus* was cultivated in the presence of As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Se and Zn followed by analytical quantification of growth, lipid productivity, and heavy metals in the biomass and in the growth medium. Multiple metal concentrations named 1X, 2X, 5X and 10X were evaluated with the baseline concentration of 1X corresponding to the expected concentration in a commercial microalgae production facility that utilizes flue gas from a coal fired power plant. The higher concentrations (2X – 10X) are indicative of accumulation of heavy metals resulting from medium recycling to help reduce the production costs. Growth experiments were performed in photobioreactors (PBR) in triplicate. Results reveal the impact of heavy metals on biomass and lipid yield, the effect of the various metal

concentrations on productivity, and the environmental impact of biofuel derived from heavy metal contaminated microalgae biomass.

2. MATERIALS AND METHODS

The following section describes the cultivation system, the heavy metal concentrations introduced to the cultivation system to represent integration with coal flue gas, and the analytical procedure used to quantify growth, lipid yield, and heavy metal concentrations.

2.1. Organism, culture conditions, and inoculation protocols

2.1.1. Microalgae strain and growth media

Scenedesmus obliquus, obtained from the algal research group at Arizona Public Service (APS), was used in this study. The medium recipe used for the production of inoculums and experimental growth studies consisted of: NaNO_3 (11.8 mM), K_2HPO_4 (1.1 mM), $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ (2.0×10^{-1} mM), $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ (1.7×10^{-1} mM), $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ (1.1×10^{-1} mM), H_3BO_3 (1.8×10^{-1} mM), $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ (3.0×10^{-3} mM), $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ (3.0×10^{-7} mM), $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$ (2.4×10^{-4} mM), $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$ (2.4×10^{-4} mM), $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ (1.2×10^{-4} mM), $\text{Na}_2\text{EDTA} \cdot 2\text{H}_2\text{O}$ (3.2×10^{-2} mM) and $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (1.6×10^{-2} mM). Reagents used for the preparation of the medium were of analytical grade. Prior to inoculation, the medium was autoclaved at 121°C for 45 minutes. A mixture of $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ + $\text{Na}_2\text{EDTA} \cdot 2\text{H}_2\text{O}$ was autoclaved separately in order to minimize iron precipitation and was added to the medium afterwards with the pH of the final medium adjusted to 7.0 through the addition of HCl. Inoculum was generated through the growth of *S. obliquus* in Petri-dishes followed by the inoculation of 100 mL flasks and then cultivated in 3 L PBRs and grown for 7 days under continuous fluorescent light and at pH 7 until the biomass density reached approximately $2.5 \text{ g} \cdot \text{L}^{-1}$ dry weight (DW).

2.1.2. PBR configuration, mixing and pH

The PBRs used in this work were borosilicate glass tube reactors 4.5 cm in diameter and 80 cm in height with a microalgal culture capacity of 1.1 L. The PBR system consisted of 15 individual reactors all illuminated

with T12 fluorescent lights corresponding to a photosynthetically active radiation (PAR) of $200 \mu\text{mol photon}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ operated on a 12 hour light: 12 hour dark cycle. Mixing within the PBRs was accomplished by sparging air introduced at the bottom of the PBR through a glass capillary tube at a rate of 2.3×10^{-2} volume of air per volume of culture per minute. Introduction of CO_2 to the sparged air was used to maintain the PBR pH at 7.0 as needed. Detailed pictures of the growth system are presented in the Supporting Information (SI). Prior to inoculation, the PBRs were soaked for 12 hours in 10% HNO_3 solution and rinsed three times with deionized water (resistivity $17.7 \text{ megohm}\cdot\text{cm}$) to remove any heavy metal contamination. Prior to inoculation the individual PBRs were sterilized by autoclaving at 120°C for 30 minutes.

Washed microalgal inoculum was added to the PBRs until an initial density of $0.8 \text{ g}\cdot\text{L}^{-1}$ was achieved. Growth measurements were taken during the experiment by measuring optical density (OD) at 750 nm, which was correlated with total suspended solids in $\text{g}\cdot\text{L}^{-1}$ ($R^2 = 0.997$). Evaporation rates were measured and concentrations were adjusted.

2.2. Metal concentrations

Ten heavy metals (As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Se and Zn) were used in this study based on metals composition in coal derived flue gas [27]. Heavy metal sources and their concentrations are listed in Table 1 and are henceforth referred to as 1X, 2X, 5X and 10X concentrations. The baseline concentration of 1X was determined based on the worst case scenario for the transfer of heavy metals from coal based flue gas and represents the highest end concentration that microalgae might be exposed from flue gas integration without medium recycling. Base assumptions include a 4% CO_2 uptake efficiency, power plant air filtration efficiency of 99% corresponding to 1% fly ash introduced into the reactor system, and heavy metal transfer from fly ash to growth media (detailed calculations are presented in the SI) [28-30]. Concentrations 2X, 5X and 10X represent the potential accumulation of heavy metals with continual recycling of the medium. Stock solutions of each heavy metal salt were prepared individually at 1000X concentration and were sterilized by filtration through sterile $0.2 \mu\text{m}$ syringe filter prior to addition to growth media.

Table 1. Heavy metals and their concentrations added to the growth medium with the baseline concentration of 1X corresponding to the expected concentrations for coal fired flue gas

Heavy metal	Metal source	Concentration (μM)			
		1X	2X	5X	10X
As	NaAsO ₂	1.04	2.08	5.21	10.4
Cd	CdCl ₂	0.13	0.27	0.67	1.33
Co	CoCl ₂ .6H ₂ O	0.27	0.54	1.36	2.72
Cr	Na ₂ Cr ₂ O ₇ .2H ₂ O	2.50	5.00	12.5	25.0
Cu	CuCl ₂ .2H ₂ O	2.06	4.12	10.3	20.6
Hg	HgCl ₂	0.05	0.10	0.25	0.50
Ni	NiCl ₂ .6H ₂ O	4.33	8.66	21.6	43.3
Pb	PbCl ₂	0.26	0.53	1.32	2.63
Se	Na ₂ SeO ₃	0.13	0.25	0.63	1.27
Zn	ZnCl ₂	6.73	13.5	33.6	67.3

2.3. Sampling protocols

Immediately after the PBRs were inoculated the following samples were collected: 3 mL of sample for analysis of OD and pH, 45 mL of sample for lipid content, 25 mL sample for Hg analysis, and 12 mL of sample for the other heavy metals analysis. Samples for lipid analysis were immediately centrifuged (SorvallTM RC 6 Plus) at 3900 RPM for 5 minutes and the pellet was preserved at -80°C. Samples for heavy metal analysis were divided into 2 portions: 1) 5 ml was used for analysis of total heavy metal concentration in the microalgal suspension (10 mL in the case of Hg), and 2) the remaining sample was centrifuged (SorvallTM RC 6 Plus) at 7500 RPM for 3 minutes and the supernatant was analyzed for heavy metal concentration and is reported as heavy metal concentration in the medium. Samples for metal analysis were acidified immediately after collection followed by acid digestion (Standard Methods 3030E [31], EPA 7470A [32] and EPA 7471A [33]). The digested samples were then transferred to volumetric flasks and adjusted to a known volume and acidity by

addition of E-pure deionized water and nitric acid in order to match the acidity of the calibration standards.

Acids and reagents used for sample digestion and heavy metal analysis were of trace metal grade suitable for Hg analysis.

2.4. Analytical procedure

2.4.1. Heavy metal analysis

Analysis of all heavy metals except Hg was done by Inductively Coupled Plasma Mass Spectrometry (ICP-MS Agilent 7500 Series), whereas analysis of Hg was done by Cold Vapor Atomic Absorption Spectrometry (CV-AAS, PerkinElmer Analyst 800). ICP-MS and CV-AAS heavy metal standard solutions used to generate the calibration curves were purchased from Fisher Scientific and Inorganic Ventures. In order to reduce matrix interference due to acidity variation during sample dilution, an appropriate volume of nitric acid was added during dilution to ensure that sample acidity matched the acidity of the ICP-MS calibration standards. In addition to the experimental samples, reagent blank, laboratory-fortified blank, laboratory-fortified matrix and laboratory-fortified matrix duplicate samples were analyzed to assure quality data.

2.4.2. Lipid transesterification and FAME analysis

Lipids in microalgae were quantified through transesterification of lipids into fatty acid methyl esters (FAME). *In situ* transesterification, a method that combines oil extraction followed by transesterification in a single reaction vessel was used. Frozen microalgal pellets from 45 mL samples were freeze-dried and ground into a powder using a mortar and pestle. A subsample of 24 mg of dried microalgae was transferred into a crimp top gas chromatograph vial containing 0.5 mL acidified methanol (5% H₂SO₄) and was digested for 90 min at 90°C. After digestion, the vial was centrifuged and the acidified methanol containing the FAME was transferred into a 5 mL serum bottle containing 4 mL hexane. Complete recovery of FAMES was achieved by rinsing the biomass with additional 1 mL hexane. The sealed serum bottle was then immersed in a water bath at 90°C for 15 min and cooled down to allow phase separation. The upper phase containing the hexane-FAME was pipetted

out and analyzed by gas chromatograph (Agilent Technologies 7890A) using methyl ester standards purchased from Sigma-Aldrich.

2.5. Statistical analysis

Data from triplicate experiments are presented as mean $\pm$ one standard deviation. Statistical comparison of means to find the differences between treatments were done using Analysis of Variance (ANOVA) at 95% confidence interval. For multiple comparison of temporal data collected along the growth period, Dunnett's technique was applied using a 95% confidence interval.

3. RESULTS AND DISCUSSIONS

3.1. Effect of heavy metals on microalgae grown for biomass and lipid production

Microalgal growth in the presence of heavy metals (baseline 1X, 2X, 5X, and 10X) was determined and compared to a control, Figure 1. Heavy metals at 1X concentration had a positive effect on growth with an increase in biomass production of 12% compared to the control over the course of the 24 day growth experiment. Heavy metal concentrations of 2X, 5X and 10X had progressively larger negative impacts on microalgae productivity. Compared to the control, the final biomass content decreased by 20%, 56%, and 72% for the 2X, 5X, and 10X heavy metal concentrations, respectively. A non-recoverable decline in growth is observed at day 8 for the 5X and 10X heavy metal concentrations indicating these levels of heavy metals are detrimental to the system. Growth in the 2X system was negatively impacted over the course of the experimentation, however, the density of the culture continued to increase but at a lower rate as compared to the control.

Figure 1. Time course of *S. obliquus* growth in the absence (control) or presence of 1X, 2X, 5X and 10X heavy metal concentrations. Data points are presented as mean +/- one standard deviation of triplicate reactors.

Lipid content as determined through FAME analysis was collected periodically over the course of the growth period for the control and for each of the 4 different heavy metal concentrations with results presented in Figure 2. Heavy metals at concentrations of 5X and 10X statistically decreased (52%) total lipid content, while the 2X concentration were shown to not have a statistical effect on lipid concentrations (ANOVA, $p < 0.05$). However, the baseline concentration of 1X was shown to statistically increase the lipid yield by 61% at the conclusion of the growth period (ANOVA, $p < 0.05$). Increase in lipid content and culture density can be triggered through a number of stressors including but not limited to nutrient, light, salinity, and temperature. The results suggest that heavy metals from flue gas at the baseline concentrations are acting as a stressor at a level that increases biomass and lipid yields.

Figure 2. Time course of lipid (FAME) yield in the absence (control) or presence of 1X, 2X, 5X and 10X heavy metal concentrations. Data points are presented as mean +/- one standard deviation of triplicate reactors.

The final biomass and FAME productivities at the end of the 24 day growth period were condensed into dose response curves, Figure 3. Results show that for both biomass and lipid production there is an optimum metal concentration that improves yield. Two zones are identified based on the data presented in Figure 3, (1) favorable zone corresponding to improved yield, and (2) unfavorable zone where metals were detrimental to productivity.

Figure 3. Dose response curve for *S. obliquus* for different initial heavy metal concentrations at the end of growth experimentation. (A) Microalgal growth and (B) FAME yield. Data points are presented as mean +/- one standard deviation of triplicate reactors.

The favorable zone (zone 1) exists at and around metal concentrations of 1X and corresponds to higher biomass and FAME production. In this zone, heavy metals could have enhanced lipid yields due to stress-induced lipid accumulation [34-37]. Heavy metals are stressors that can lead to cellular oxidative stress due to the exacerbated production of byproducts of aerobic metabolism such as reactive oxygen species (ROS) [35, 38-40]. It has been suggested that under increasing stress, microalgae produce larger amounts of lipids as a

protective mechanism against ROS, where over-produced cytoplasmic lipid droplets serve as a sink to sequester ROS-scavenger molecules, thus accelerating the biosynthesis of such scavenger molecules [36, 37]. Heavy metals used in these experiments could have directly caused stress due to the stress mechanism explained above either through the catalysis of the generation of ROS molecules by redox-active Co(II), Cr(VI), Cu(II) and Cd(II); or through the consumption of the antioxidant pool (ROS-scavenger molecules) by non-redox-active As(III), Zn(II) and Pb(II); with all of these heavy metals used in this study [40-42].

Increase in growth when microalgae is exposed to very low levels of contaminants (as is the case in zone 1) has also been related to the microalgae adaptation to heavy metal stress levels producing an overcompensation effect generated by the homeostatic regulatory system in the microalgae that leads to the activation of metabolic and antioxidant production mechanisms to overcome toxicity (also called hormetic effect) [43]. For example, increase in growth for *Selenastrum capricornutum* and *Euglena gracilis* exposed to heavy metals (Zn, Cd or Pb) was documented to be a manifestation of hormesis [42, 43]. Furthermore, some heavy metals could have enhanced microalgal growth by acting as a nutrient, thus providing an additional nutrient source to the already existing sources in the medium. For example, Cu and Zn are cofactors in enzymes and are essential for DNA synthesis, photosynthetic electron transport and mitochondrial and chloroplast functions [42]. Nitrogen concentration in the medium was monitored over the course of the growth experiments. Enhanced nitrogen uptake with respect to the control was observed in the 1X, 2X and 5X heavy metal experiments. Further details are presented in the SI.

Growth inhibition observed in the unfavorable zone 2 could be explained as some combination of disruption of cell division, inactivation of proteins, disorganization of chloroplast and mitochondrial structures, chloroplast envelop rupture, deterioration of membrane integrity and even lysis known to be produced by heavy metals [20, 42, 44]. The reduced FAME yield could result after heavy metal damage to the chloroplast and disturbance of the endoplasmic reticulum (organelles involved in CO₂ fixation and lipid synthesis) known to occur as a result of excessive heavy metal induced stress [42, 44-46]. Even though these observations are a result of heavy metal concentration and strain specificity, the authors speculate that non-nutrient heavy metals

As, Cd, Cr, Hg, Ni and Pb played major roles in these results due to their reported toxicity to microalgae [20, 45, 47]. However, nutrient metals (e.g. Cu, Zn) could also be contributing to toxicity when present at higher concentrations than the optimal [25, 42, 47].

The results from this study show that heavy metals at the baseline concentrations have a positive impact on biomass and lipid production. Increasing levels of heavy metals to 2X concentrations and beyond negatively impact yields. The study of mechanisms enhancing lipid and biomass yields should be addressed in future work as this can be economically beneficial to the nascent algal-based biodiesel industry.

3.2. Distribution of heavy metals

Heavy metals added to the medium partitioned into three broad compartments that can be operationally defined based on microalgae production and potential end products: (1) medium, (2) harvested microalgal biomass, and (3) external environment. Figure 4 shows the relative percentages of heavy metal distribution for three concentrations, measured for 1X, 5X, and 10X, in the defined compartments at the conclusion of the 24 day growth period. At the baseline concentration of heavy metals, biomass serves as the major sink for 9 of the 10 heavy metals (except Hg). Increased starting concentrations of heavy metals, 5X and 10X, resulted in higher accumulation of all the heavy metals in the biomass except As and Hg. Two of the ten metals, Hg and Se, were shown to be partially lost from the cultivation system at all three experimental conditions, suggesting volatilization as demonstrated by several authors [48-55]. On average, 87% Hg and 21% Se was lost from the microalgal suspension for 1X, 93% Hg and 16% Se for 5X, and 94% Hg and 22% Se for 10X. The distribution of metals in the experimental systems shows the majority of the metals are associated with the biomass with As in biomass reaching an upper limit and Hg and Se susceptible to volatilization at all concentrations. The As removal by the microalgae is shown to be limited independent of the initial concentration. Accumulation of As in medium is likely to occur after several recycles, with the concentration in the medium expected to exceed the maximum As concentration in irrigation water recommended by the Food & Agriculture Organization of the United Nations [57] ($100 \mu\text{g}\cdot\text{L}^{-1}$) after 3 recycle events (see calculation in the SI). Remediation of As can be

achieved using current water treatment technologies (see SI), however additional treatment will impact the economics of the system.

Figure 4. Fractional distribution of heavy metals (100% corresponding to starting concentrations) in relative percentages of 10 heavy metals in the medium, biomass and lost to external environment after

the 24 day study period for 1X, 5X and 10X initial heavy metal concentration. Data represent mean of triplicate reactors.

3.3. Global impact of flue gas use in microalgae cultivation

Several implications for the microalgal-based biofuel industry may be suggested if the results of this study are extrapolated to a commercial scale. The effect of heavy metals on biomass and lipid yields will have repercussions to the carbon capture efficiency and the techno-economics of products and byproducts. Reduced biomass production resulting from excessive heavy metal stress (unfavorable zone) will reduce the carbon capture efficiency and therefore limit the plant CO₂ remedial capacity. Beyond carbon capture, the integration of microalgae growth with coal based flue gas provides an environmental service to retain heavy metals from flue gas emissions that otherwise would migrate from the power plant and settle in water bodies and soils. Heavy metals in the atmosphere pose a serious threat to the environment and human health due to its un-informed and un-intentional inhalation and contact. Microalgal biomass serves as the major sink for heavy metals, the airborne heavy metals fraction will be concentrated in the microalgal biomass and its management will be easier considering its lower volumes.

A widely proposed use for biomass grown with flue gas is biofuel feedstock. Using flue gas to grow *S. obliquus* may not present a negative effect on lipid yields as long as the levels are restricted to favorable concentrations. At low concentrations, heavy metals are shown to enhance growth and seem to constitute an additional stressor to increase lipid accumulation. However, the accumulation of heavy metals in the biomass could restrict the end products. Potential transfer of heavy metals from biomass to biodiesel could present challenges to biodiesel storage (as Pb, Ni, Zn, Co, and Cu, present in flue gas, accelerate FAME oxidation [58]) and airborne pollutant production (ignition of heavy-metal-containing diesel has been linked to negative health effects [59]). Feed for animal and feedstock for anaerobic digestion are popular uses proposed for harvested microalgal biomass and lipid extracted biomass that improve the economic feasibility and energetics of the microalgae-to-biofuel process [11]. However, it should be noted that heavy metals in these products can be toxic to livestock and can inhibit the biogas producing microbial community limiting the use of whole

microalgae and lipid-extracted biomass [60]. Given the important impact of heavy metals onto biodiesel, the amount of heavy metals in the final biofuel product and by-products must be quantified in future research for accurate assessment of the full impact of the integration of flue gas with microalgae cultivation.

CONCLUSIONS

Heavy metals did affect biomass growth and lipid accumulation in microalgae. At concentrations estimated to be the maximum delivered from coal-based flue gas (1X), microalgae responded to the stress with higher growth and larger lipid accumulation, while at higher heavy metal concentrations (2X, 5X and 10X) growth and lipids were inhibited. Integration of microalgal cultivation with carbon capture from flue gas will have to deal with heavy metals redistributed in the biomass, the medium and possibly the by-products. *Scenedesmus obliquus* had a large capacity for sorption of nine of the ten heavy metals studied, even after strong growth inhibition at 10X concentration. On average 87% Hg and 21% Se were lost from the microalgal suspension at 1X, 93% Hg and 16% Se at 5X, and 94% Hg and 22% Se at 10X; while the other elements were mostly associated with the biomass.

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Graphical abstract