An Integrated Water Curtain-Microalgal Culture System (WCMC) to Mitigate Air Emissions and Recover Nutrients from Animal Feeding Operations

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Abstract

Economically and technologically feasible air emission mitigation technologies are in high demand to sustain future animal agriculture. In this study, we designed an integrated Water Curtain-Microalgal Culture (WCMC) system to mitigate air emissions and recover nutrients to culture microalgae from Animal Feeding Operations (AFOs). The WCMC system included a water curtain, a windbreak wall and a raceway pond bioreactor. The water curtain was formed by continuously pumping water into a perforated water tank that flowed into the raceway pond bioreactor. The exhaust pollutants (NH₃ and particulate matter-PM) from a poultry house were dissolved and absorbed by the water droplets. Microalgal species were collected from local ponds and went through natural selection. *Desmodesmus* (*R. Chodata*) showed the best tolerances of temperature, nutrients, pH, and circulation shear force. The microalgal culture in the bioreactor was run in batch mode and the average productivity was 12.7 ± 2.9 g/m²/day. Exhaust ammonia (NH₃) and total suspended particle (TSP) concentrations were reduced by 74.9% and 89.2%, respectively. The harvested microalgal biomass had a protein content of 41.3%. The amino acid profile of microalgae demonstrated comparable quality to the WHO/FAO reference. Omega-3 fatty acids accounted for about 23% of total fat acids. Heavy metals (Pb, Cu,

Fe and Zn) did not exceed the tolerance levels. The adaptation of this new technology will reduce AFOs environmental impact, create a win-win situation for future animal agriculture and microalgal cultivation, and generate new alternative protein sources as food and feed supplements.

Keywords. Air emission mitigation, microalgal culture, water curtain, nutrient capture and reuse, wet spray scrubbers

Introduction

Animal feeding operations (AFOs) bring opportunities and economic growth to rural communities [1], though, extension of AFOs leads to some potential environmental issues, including odor and air pollutions. Major air emissions from AFOs include NH_3 , CO_2 , and particulate matter (PM). Approximately, 50% of the total anthropogenic NH_3 emissions in the U.S. are from animal agriculture [1]. Exhaust NH_3 and PM from AFOs contains major (N, P, S, and K) and minor (Fe, Zn, Cu, and Na) nutrients [2, 3]. Dry and wet deposition of these airborne nutrients could cause ecosystem eutrophication and acidification [1]. Mitigating air emissions is essential to sustain animal agricultural operations, particularly AFOs. Wet spray scrubbers are one of the most efficient approaches to mitigate air emissions [4-6]. Wet spray scrubbers utilize liquid droplets to capture gases and particulate matter (PM) and have minimum resistance to air flow. In spite of good mitigation efficiency of wet spray scrubbers, the effluent from the scrubbers is rich in nutrients, and disposal of the effluent limits their application in AFOs. Fu, et al. [7] demonstrated using reverse osmosis membrane to concentrate ammoniacal nitrogen from wet scrubber effluent and recycling permeate as feed water in the acid scrubber system. Hadlocon and Zhao [8] investigated the production of ammonium sulfate fertilizer from acid spray wet scrubbers effluents. Besides these physical and chemical approaches of nutrient

recovery, the effluent can also be used as nutrient-rich water to culture microalgae for value-added animal feed production, which would improve the economic feasibility of wet spay scrubbers in AFOs [9].

Microalgae have attracted considerable attention as potential feedstock for biofuel and animal feed production [10, 11]. Due to excellent nutrient compounds and digestibility of microalgae, about 30% of the current world microalgae production is used in animal feed application [11, 12]. A swine feed trial found that docosahexaenoic acid (DHA)-rich microalgae resulted in higher weight gain and feed conversion efficiency than control diet [13]. Evans, et al. [14] incorporated 16% microalgae into broiler starter diets and did not find any performance detriment. Ekmay, et al. [15] found weanling pigs and broiler chicks performed well with dietary inclusion of 10% and 15% defatted green microalgal biomass, respectively. Utilization of microalgae in aquaculture is another growing market, and they can be used directly in aquaculture feeds [11]. These nutritional and toxicological studies demonstrated that microalgal biomass could be used as a valuable feed supplement and substitute for convention protein sources. However, large-scale microalgae production is still not cost-competitive because of high demand on nutrients, water and energy [16-18]. Therefore, it is important to capture and recycle nutrients from different sources to sustain microalgal cultivation for biofuels and animal feed production. Reusing nutrients from agricultural waste streams could be an effective approach to address the nutrient issue of microalgal cultivation. In addition, nutrient recovery also provides a holistic solution to animal waste management [19-22].

Our previous study showed that microalgal cultivation was a promising technology to mitigate NH_3 and PM emissions from AFOs and the nutrients in the poultry house dust significantly enhanced the microalgal growth [9]. The objective of this study was to develop an

integrated Water Curtain–Microalgal Culture (WCMC) system for poultry operations that mitigates air emissions, captures and reuses nutrients to produce microalgal biomass as potential animal feedstock.

Materials and methods

Water Curtain-Microalgal Culture system (WCMC)

The WCMC system included a water curtain, a windbreak wall, a raceway pond bioreactor, and an exhaust air blower system (Figure 1). The water curtain was formed by continuously pumping water into a perforated water tank that flowed into the open pond bioreactor. Exhaust pollutants (such as NH_3 and PM) were dissolved and absorbed into water curtain droplets. The nutrient-rich effluent was used to culture microalgae. Two main products of the WCMC system are clean air and protein-rich microalgal biomass.

Water curtain and windbreak wall

The dimensions of the perforated water tank were $0.625 \text{ m} \times 0.476 \text{ m} \times 0.352 \text{ m}$ (L $\times$ W $\times$ H) with 30 holes (10 $\times$ 3 rows, diameter = 7.94 mm) (Figure 2). The water curtain flow rate was 16.0 L/min. The windbreak wall was 0.476 m $\times$ 0.400 m (L $\times$ H), and it was designed to reduce air flow through the water curtain to increase the exhaust air retention time. The exhaust air from a poultry house was delivered to the water curtain through a 10 m length and 0.102 m diameter PVC pipe with an air flow rate of $0.05 \text{ m}^3/\text{sec}$.

Figure 1. The integrated Water Curtain-Microalgal Culture system (WCMC)

(A) Schematics of WCMC and (B) the implemented system

Raceway pond bioreactor for microalgal culture

The raceway pond bioreactor for suspended microalgal culture was made of fiberglass with

a dimension of $2.44 \text{ m} \times 1.22 \text{ m} \times 0.41 \text{ m}$ ($L \times W \times H$) and the working volume of 0.91 m^3 . The raceway pond was driven by 4 aquarium pumps (Pentair Aquatics, Chino, CA) with a channel velocity of 0.25 m/s . The reactor was placed in a greenhouse ($2.05 \text{ m} \times 3.66 \text{ m} \times 2.0 \text{ m}$ ($W \times L \times H$)) with 4 vents.

Figure 2. Section view of the water curtain and windbreak wall

Microalgae cultivation

Strain selection and morphological identification

The selection of microalgal strains that could grow in real environmental conditions is a critical step in developing a reliable microalgal culture for utilizing the captured nutrients. The selected strains must also be robust enough to outcompete potential contaminated microbes of

bacteria, protozoa, and fungi. The parameters of temperature and nutrient were used to select the best adapted microalgae that predominate the culture. Water samples containing native microalgal species were collected from local ponds (Okemos, Michigan, U.S. Longitude: -84.5789, Latitude: 42.7803) in September 2012. The selection and screening of targeted microalgal strains included two steps: the collected water samples were first cultured on a shaker at 200 rpm for 3 d in the laboratory; the cultures were then moved to an outside greenhouse (temperature ranged from 2 °C to 20 °C) for 5 months. Wet scrubber effluent was used as a nutrient source. Microalgal species went through natural selection and the surviving species were used as the inoculum for the following microalgae cultivation.

Strain identification was based on morphologic properties of individual microalgae. Microalgal cells were photographed at 100x magnification using a Nikon Eclipse 50i microscope with the DS Camera Head DD-Fi1 (Nikon Instruments Inc., Melville, NY). The Nikon NIS Elements imaging software was used to process the images. The distribution of microalgal species was recorded based on cell counting.

Microalgae culture and harvesting

The microalgal inoculum was inoculated into the raceway pond bioreactor to carry out nutrient removal and microalgal biomass accumulation. The cultivation temperature ranged from 5°C to 30°C, and fluorescent lamps provided light intensity of 100 microeinstein (μE)/m²/sec from 0600 h to 2100 h. The microalgal culture in the bioreactor was run in batch mode and water was recycled after harvesting the microalgal biomass. There were total four batches of experiments from May, 2014 to August, 2014. Batch 1 (28 d) was the culture stabilizing period and microalgae were adapting to the new environment. Batches 2-4 were three replicates running for 15 d to 20 d. Microalgal biomass was harvested after each batch by pumping out 90 % of the

microalgal suspension medium. The remaining 10% of medium was served as inoculum for next batch cultivation. The microalgal suspension medium withdrawn from the reactor was naturally gravity settled for 3 d, then the top supernatant was collected and recycled back to the water curtain operations. The settled microalgal biomass was centrifuged at 988 g for 5 min to collect cell pellets and the pellets were freeze-dried for further analyses.

Microalgal density and growth performance

Microalgal suspension medium (25.0 ml) were collected and stored at 4 °C prior to microalgal density analyses during each day of the study. Total 149 samples were collected in 73 days of the cultivation. The microalgal biomass concentrations were monitored by measuring optical density (OD) at 750 nm (OD₇₅₀) (UV-2600/2700, Shimadzu Corporation, Japan) and then converted to mass concentrations (g/L) using a calibration curve (Figure 3). Microalgal specific growth rate was calculated by plotting the natural log of cell concentration over time.

$$\ln(x) = \mu * t + \ln(x_0) \quad (1)$$

$$t_d = \frac{\ln(2)}{\mu} \quad (2)$$

Where x is the cell concentration, t is the time (d), x₀ is the initial cell concentration, μ is the specific growth rate, and t_d is the doubling time (d) in the exponential phase.

Figure 3. The calibration curve of microalgal optical density at 750 nm (OD₇₅₀) and biomass concentrations (g/L)

Calculation of NH₃, CO₂, and Total Suspended Particle (TSP) mitigation efficiencies

Ammonia (NH₃) concentrations were measured daily at the WCMC inlet (exhaust air) of the poultry house and the WCMC outlet (cleaned air) of the greenhouse using Dräger tubers (range of 0.25-3 ppm and 5-70 ppm with $\pm 10\%$ precision, Dräger Safety Inc. Pittsburg, PA).

The NH₃ mitigation efficiency was defined as:

$$\eta_{NH_3} = \frac{Conc_{ExhNH_3} - Conc_{CleanNH_3}}{Conc_{ExhNH_3}} \times 100\% \quad (3)$$

Where

η_{NH_3} = NH₃ mitigation efficiency (%)

$Conc_{ExhNH_3}$ = NH₃ concentration in the exhaust air from the poultry house before the WCMC

(ppm)

$Conc_{CleanNH_3}$ = NH₃ concentration in the cleaned air after the WCMC (ppm)

Concentrations of CO₂ from the poultry house before and after the WCMC were measured using an INNOVA 1412 photoacoustic analyzer (5.1 ppm detection limit at 1,000 ppm range, Lumasense Technologies, Ballerup, Denmark). The CO₂ mitigation efficiency was defined as:

$$\eta_{CO_2} = \frac{Conc_{ExhCO_2} - Conc_{CleanCO_2}}{Conc_{ExhCO_2}} \times 100\% \quad (4)$$

Where

η_{CO_2} = CO₂ mitigation efficiency (%)

$Conc_{ExhCO_2}$ = CO₂ concentration in the exhaust air from the poultry house before the WCMC (ppm)

$Conc_{CleanCO_2}$ = CO₂ concentration in the cleaned air after the WCMC (ppm)

A filter-based method was used to determine total suspended particulate matter (PM_{TSP}) concentrations. Filter samples were collected at the WCMC inlet (exhaust air) of the poultry house and the WCMC outlet (cleaned air) of the greenhouse. Three samples were collected at the beginning, middle and end of each batch. The sampling system consisted of a pump, a flow meter, and a filter holder with a 46.2 mm diameter 2- μ m PTFE filter. The flow rate was 1.0 m³/hr and the sampling duration was 24 hr. The air volume for sampling was calculated based on time and air flow rate. The sampling filters were kept in plastic petri dishes during transportation and storage. The PM_{TSP} concentrations (mg/m³) were calculated using the sampling air volume (m³) to divide the collected TSP weight (mg).

The PM_{TSP} mitigation efficiency was calculated:

$$\eta_{TSP} = \frac{Con_{ExhTSP} - Con_{CleanTSP}}{Con_{ExhTSP}} \times 100\% \quad (5)$$

Where

η_{TSP} = TSP mitigation efficiency (%)

Con_{ExhTSP} = Exhaust air TSP concentrations from the poultry house before the WCMC (mg/m^3)

$Con_{CleanTSP}$ = Cleaned air TSP concentrations after the WCMC (mg/m^3).

Nutrient (NH_4^+ -N and NO_3^- -N) analyses

The concentration of ammonium (NH_4^+ -N) ions in aqueous medium was measured using ammonium ion-selective electrode (NH_4 -BTA, Vernier Software & Technology, Beaverton, OR). It was calibrated from 1 to 100 mg/L with the precision of $\pm 10\%$ of full scale using NH_3Cl standard solution. The concentration of nitrate (NO_3^- -N) ions in aqueous medium was measured using nitrate ion-selective electrode (NO_3 -BRA, Vernier Software & Technology, Beaverton, OR). It was calibrated from 1 to 100 mg/L with the precision of $\pm 10\%$ of full scale using NaNO_3 standard solutions.

Microalgal biomass composition analyses

Freeze-dried biomass was used for chemical analyses, which was conducted by the University of Missouri Agriculture Experiment Station Laboratory. The Kjeldahl method was used to determine nitrogen content in microalgae (TKN; AOAC Method 928.08, 2000). Microalgal amino acids profile was analyzed by an AOAC method (AOAC Method 982.30, 2006). A capillary gas-liquid chromatography was used to analyze fatty acids (AOAC official method 996.06). Microalgal energy and element content were analyzed using bomb calorimetry and microwave digestion followed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Statistical analyses

The PROC NLIN of SAS v. 9.4 (SAS Inst. Inc., Cary, NC) was used to simulate a microalgal growth curve. The PROC TTEST was used to conduct pair-wise comparison for NH₃, CO₂, and TSP mitigations.

Results and Discussion

Selection of microalgal strains

The original microalgal assemblage mainly consisted of 95% of *Rhizocloniu spp* and *Pediastrum* (Figure 4). *Rhizocloniu spp* is a filamentous microalgae with a cell diameter of 20 - 30 µm and cell length of 50 -140 µm, which can grow in freshwater, seawater, and brackish water [23]. *Pediastrum* is a genus of green microalgae and they are commonly growing in freshwater microhabitats, such as ponds, marshes, pools, and lakes [23]. In the first 3-month culture, *Rhizocloniu* and *Pediastrum* species significantly decreased to 20%, and *Desmodesmus* (*R. Chodata*) and *Scenedesmus* (*Chlorophyceae*) increased to 80% in the microalgal assemblage. *Desmodesmus* and *Scenedesmus* are among the most common genera of freshwater microalgae and they can grow under a wide range of environmental conditions [24]. After 5-month culture, *Desmodesmus* dominated the microalgal assemblage with the proportion of 99%. It has been reported that *Desmodesmus* is widely distributed and has better nutrient and temperature tolerance than other species [24]. In addition, *Desmodesmus* has small and non-flagellated cells that are more shear resistant, which alleviates the cell damage caused by circulating pumps.

Figure 4. Microalgal assemblage selection (microscopy photo 100×). (A) Original microalgal assemblage from local freshwater pond and (B) microalgal assemblage after 3-month cultivation using wet scrubber effluents

Microalgal growth performance

The growth curve of *Desmodusmus* is shown in Figure 5, which demonstrated a typical sigmoid growth. Microalgae biomass was harvested around 13 d when the microalgal population reached its maximum density. The average growth rate was 2.2 d^{-1} , which corresponded to the doubling time of 0.31 d. The microalgal growth curve can be described using the following logistic growth function with $\text{MSE}=0.04$.

$$y(t) = \frac{0.51}{1 + 3.99 \exp^{(-1.68 \times 10^6 \times t)}} \quad (6)$$

Where: $y(t)$ is the microalgal density at t (d).

The mean net biomass accumulation was $0.80 \pm 0.02 \text{ g/L}$ and the productivity was $12.7 \pm 2.9 \text{ g/m}^2/\text{day}$. The productivity was similar as our previous study ($11.2 \text{ g/m}^2/\text{day}$) [9]. Raceway pond bioreactors are the most common large-scale production system because they are relatively economical to build and operate. However, raceway pond bioreactors have a relative low productivity ranging from 0.02 to 0.2 g/L/day [25]. Slade and Bauen [26] summarized the data

from the literatures and concluded that the production of microalgal biomass in raceway pond bioreactors ranged from 10.0 to 20.0 g/m²/day.

Figure 5. Microalgal growth performance.

Points are mean values and vertical bars represent $\pm$ standard error (n=3)

Ammonia (NH₃), carbon dioxides (CO₂) and total suspended particle (TSP) mitigation

Concentrations of NH₃, CO₂, and TSP before and after water curtains are presented in Table

1. The inlet air was directly from the laying hen house, and NH₃ concentrations ranged from 1.04 to 4.90 ppm (Figure 6). These values were much lower than NH₃ concentrations from commercial facilities (20.0 ppm) [27]. Ammonia (NH₃) concentrations after the water curtain (outlet NH₃ concentrations) were significantly lower than inlet NH₃ concentrations ($p < 0.05$) (Figure 6). Apparently, 74.9% of the NH₃ in the inlet air were removed by the water curtain system. Total suspended particle (TSP) concentrations were also significantly reduced by the water curtain system. The mitigation efficiencies of TSP ranged from 75.0% to 95.0%. The absorbed TSP could provide essential nutrients for microalgae [9]. The CO₂ concentrations were

not significantly reduced due to the facts of the low water solubility of CO₂ (approximately 1.5 g CO₂/L water) and high air flow rate from the chicken house. The CO₂ concentrations in the outlet of the water curtain system were around 750 ppm, which were much higher than CO₂ concentrations in the atmosphere. Relatively high CO₂ concentrations could help CO₂ diffusion from air into the culture media especially at alkaline pH condition [28], and provide carbon source to enhance microalgal growth [29].

Table 1. Ammonia (NH₃), carbon dioxide (CO₂), and total suspended particles (TSP) concentrations at the inlet and outlet air of the water curtain system

Items	n	Before water curtain (ppm)		After water curtain (ppm)		Mitigation (%)	
		mean $\pm$ sd	min, max	mean $\pm$ sd	min, max	mean $\pm$ sd	min, max
NH ₃	67	3.31 $\pm$ 1.10	1.04, 4.90	0.79 $\pm$ 0.54	0.04, 1.94	74.9 $\pm$ 16.6	28.5, 98.5
CO ₂	8	821.4 $\pm$ 382.1	604, 1711	750 $\pm$ 374	497, 1600	9.42 $\pm$ 6.82	0.81, 18.7
TSP	9	27.1 $\pm$ 10.8	10.2, 40.3	2.91 $\pm$ 2.18	0.91, 7.80	89.2 $\pm$ 6.43	75.0, 95.0

Figure 6. NH₃ concentrations before (inlet) and after (outlet) the water curtain system. Points are mean values and vertical bars represent $\pm$ standard error (n=3).

Changes in NH_4^+ , NO_3^- , and pH of the culture media

Changes of NH_4^+ concentrations during the culture are shown in Figure 7. The amount of ammonium nitrogen ($\text{NH}_4^+\text{-N}$) in the culture media ($N_{\text{N-media}}$) was determined by three main processes (Eq. 7).

$$N_{\text{N-media}} = N_{\text{N-inlet}} - N_{\text{biomass}} - N_{\text{N-outlet}} \quad (7)$$

Where $N_{\text{N-inlet}}$ is the nitrogen absorbed from the inlet exhaust air (g/day), N_{biomass} is the nitrogen assimilation by microalgae (g/day), and $N_{\text{N-outlet}}$ is the nitrogen loss from the culture media (g/day). Transfer of ammonium nitrogen ($\text{NH}_4^+\text{-N}$) into the liquid phase is mainly governed by the ammonia gas-liquid equilibrium ($\text{NH}_3(\text{g}) \rightleftharpoons \text{NH}_3(\text{aq})$) and the ammonium-ammonia dissociation equilibrium ($\text{NH}_4^+(\text{aq}) \rightleftharpoons \text{NH}_3(\text{aq}) + \text{H}^+(\text{aq})$). Two important factors affecting $N_{\text{N-inlet}}$ are the droplet surface area available for NH_3 mass transfer and the time available for diffusion of NH_3 gas molecules into the liquid droplets. In addition, some $\text{NH}_4^+\text{-N}$ could be directly released from particle-phase as well [30]. Due to the large dilution at the beginning of the culture, both initial $\text{NH}_4^+\text{-N}$ and microalgal inoculum concentrations in the culture media were very low. $\text{NH}_4^+\text{-N}$ concentrations kept increasing during the culture period because the N input ($N_{\text{N-inlet}}$) was much greater than the assimilation by microalgae (N_{biomass}) due to low inoculum concentrations. Carbon limitation might also limit the N assimilation by biomass. After 13 d culture, microalgae reached to the maximus biomass concentrations, the growth rate was close to 0 d^{-1} , and N assimilation was ceased ($N_{\text{biomass}} \approx 0 \text{ g/day}$). A thermodynamic equilibrium was reached and the $\text{NH}_4^+\text{-N}$ concentrations leveled off at approximately 15 mg/L (Figure 7).

The NO_3^- concentrations of the culture media during batch cultures are shown in Figure 8, which are similar to the trend of the NH_4^+ concentrations. However, the source of NO_3^- was

different from NH_4^+ . The concentration of gas-phase NO_x ($\text{NO} + \text{NO}_2$) in the exhaust air from the animal facility were very low [1]. The NO_3^- was mainly from particle-phase NO_3^- in the exhaust air. It was reported that particle-phase NO_3^- in $\text{PM}_{2.5}$ from commercial laying hen facilities was approximately $0.63 \mu\text{g}/\text{m}^3$ [30]. Since changes of NO_3^- and NH_4^+ in the culture media were similar, microalgae did not demonstrate their preference on nitrogen sources (NH_4^+ vs. NO_3^-), which was similar to the observation of Dortch [31].

The pH of the culture media are shown in Figure 9. The pH was stable at approximately 9.6 after 4 d culture. The high pH is in favor of the formation of NH_3 . NH_3 is relatively toxic to microalgae and could impede microalgal growth. It has been reported that once the pH of culture media exceeded 8.0, microalgal photosynthesis could be inhibited at 28 mg/L of NH_3 in the culture media [32]. Since the NH_3 concentrations were relative low in our study, the inhibition of high pH was not observed. Indeed, it has also been reported that pH around 9 was in favor of *Desmodesnus* growth [33]. Good tolerance to high pH alleviates contamination issues caused by other microbes because most of microbes co-existing with microalgae prefer acidic environment. Considering that contamination is a key issue for large-scale raceway pond microalgal cultivation, selecting alkaline tolerant microalgae could be a very good solution to overcome it.

Figure 7. NH₄⁺ in the culture media during the batch culture period. Points are mean values and vertical bars represent $\pm$ standard error (n=3).

Figure 8. NO₃⁻ in the media during the batch culture period. Points are mean values and vertical bars represent $\pm$ standard error (n=3).

Figure 9. The culture media pH during the batch culture period. Points are mean values and vertical bars represent $\pm$ standard error (n=3).

Biomass analysis: protein, amino acids profile, fatty acids profile and heavy metals concentrations

The nutritional composition of *Desmodesmus* are listed in Table 2. *Desmodesmus* grown on the wet scrubber effluent accumulated 41.3% of crude protein and 1.91% of crude fat, and had 3,863 kcal/kg of energy content. It has been reported that under different culture conditions the crude protein of microalgae could range from 10% to 60% [12, 20, 34]. Due to relatively high nitrogen content in the culture media, the microalgae in this study had a higher crude protein content than other reported microalgae. The amino acid profile of *Desmodesmus* is shown in Table 3 and they were comparable with the WHO/FAO references of egg and soybean [12]. Total essential amino acids and conditional essential amino acids were 38.5 g/100g and 22.1 g/100g protein, respectively. Amino acid profile varied regarding different microalgal strains. For example, Boyd [34] reported lysine content of 13 species of freshwater microalgae ranged from 5.23 to 8.03 g/100 g protein. Becker [12] reported *Aphanizomenon sp* had 3.5 g lysine/100 g proteins and *Chlorella vulgaris* had 8.4 g lysine/100 g proteins. Several nutritional and

toxicological studies demonstrated that the microalgae biomass could be used as a valuable feed supplement or substitute for conventional protein sources [12, 15, 35, 36]. Trials in poultry feeds found green microalgae *Chlorella vulgaris* positively affected the laying hen performance, including eggs number and quality, as well as hatching performance [35]. Significantly higher growth rate and lower non-specific mortality rate for turkeys were observed with *Spirulina* as the diet supplement [37]. Swine and poultry feed trials using microalgae as the protein sources resulted in higher weight gain and feed conversion efficiency [15]. In the pet food market, microalgae not only promote pet health but also influence on the external appearance of the pet (shiny hair, beautiful feathers) [36]. According to the crude protein content and amino acid profile, *Desmodesmus* have comparable quality to conventional foods, therefore, they have high market potential as an alternate protein source of food supplement.

Fatty acids profile of *Desmodesmus* is shown in Table 4. Even though the crude fat in *Desmodesmus* biomass was only 1.91% (w/w), omega-3 fatty acids such as linolenic acid and eicosapentaenoic acid (EPA) are the main components that account for approximately 23% of total fatty acids. Omega-3 fatty acids have been proved as a nutraceutical supplement to prevent cardiovascular disorders and cancers [38]. Omega-3 oils have a high demand in both the human nutraceuticals and animal feed market [11].

Certain heavy metals in animal exhaust air can be potentially accumulated in microalgal biomass. Several heavy metals, including arsenic, lead, copper, iron and zinc, were reported in exhaust air of animal facilities [3]. The contents of these metals in the microalgal biomass were listed in Table 2. NRC [39] defined the maximum tolerable level (MTL) as the dietary level that, when fed for a limited period, will not impair animal performance and should not produce unsafe residues in human food derived from the animal. As shown in Table 2, none of heavy metals was

exceeded MTL [39]. However tolerance values for mineral vary with age and physiological conditions of the animal, and the amount of lead and arsenic should always be maintained as far below the MTL as feasible to minimize the contribution to the human diet.

The use of microalgal products in rations is new to many producers. Research and development have been conducted on some microalgae. However, the guidelines and regulations for their animal feed application have not been well developed. Factors including economics, storage and handling, nutrient variation, and food safety should be considered during the commercialization of such technologies.

Table 2. Nutritional composition and heavy metal concentrations of *Desmodium* biomass

Items	W/W % ^a	Heavy metal	mg/kg (ppm)	MTL (ppm) ^c
Dry matter	93.7	Arsenic (As)	2.4	50 ^d
CP ^b	41.3	Lead (Pb)	1.1	30
Crude fat	1.91	Copper (Cu)	54	250 ^e
Amino Acids	34.0	Iron (Fe)	448	1,000 ^f
ME, kcal/kg	3863	Zinc (Zn)	329	1,000 ^g

^aW/W%= grams per 100 grams of biomass, ^bCP (crude protein)= 6.25 x N%, ^cMTL= maximum tolerable level, ^dInorganic arsenic MTL for cattle, sheep, swine, poultry and horse, ^eMTL for swine, ^fMTL for cattle and poultry, ^gMTL for swine and poultry

Table 3. Amino acid profile of *Desmodium* as compared with conventional protein sources and the WHO/FAO reference pattern (g per 100 g protein)

Category	Amino acids	g per 100 g of sample	g per 100 g of proteins	WHO/FAO	Egg	Soybean
Essential ^a	histidine	0.60	1.65		2.4	2.6
	isoleucine	1.41	3.88	4.0	6.6	5.3
	leucine	3.02	8.32	7.0	8.8	7.7
	lysine	2.12	5.84	5.5	5.3	6.4
	methionine	0.76	2.09		3.2	1.2
	phenylalanine	1.84	5.07		5.8	5.0
	threonine	1.82	5.01		5.0	4.0
	tryptophan	0.27	0.74	1.0	1.7	1.4
	valine	2.15	5.92	5.0	7.2	5.3
	sum	14.0	38.5			
Conditional ^b	arginine	2.62	7.22		5.2	7.4
	cysteine	0.47	1.29		2.3	1.9
	glycine	2.08	5.73		4.2	4.5
	proline	1.58	4.35		4.2	5.3
	tyrosine	1.26	3.47		4.2	3.7
	sum	8.0	22.1			
Dispensable ^c	alanine	3.01	8.29		-	5.0
	aspartic Acid	3.20	8.81		11.0	1.3
	glutamic Acid	4.08	11.2		12.6	19.0

serine	1.45	3.99	6.9	5.8
sum	11.7	32.3		

^aAn essential amino acid or indispensable amino acid is an amino acid that cannot be synthesized de novo by the organism being considered, and therefore must be supplied in its diet. ^bConditional essential amino acid is an amino acid that its synthesis can be limited under special pathophysiological condition. ^cDispensable amino acid is an amino acid that can be synthesized de novo.

Table 4. Fatty acid profile of *Desmodemus*

Fatty acids	Percent of total fat acids
Myristic (14:0)	0.48
C15:0	1.29
Palmitic (16:0)	17.8
Palmitoleic (9c-16:1)	2.00
Margaric (17:0)	0.23
Stearic (18:0)	1.22
Elaidic (9t-18:1)	0.10
Oleic (9c-18:1)	15.0
Linoleic (18:2n6)	10.1
Linolenic (18:3n3)	18.4
Stearidonic (18:4n3)	3.81
Arachidic (20:0)	0.99
Gonodic (20:1n9)	0.56
EPA (20:5n3)	0.18
Behenoic (22:0)	0.22
Clupanodonic (22:5n3)	0.21
DHA (22:6n3)	0.05
Lignoceric (24:0)	0.26

Conclusions

Capturing and reusing nutrients in the exhaust air to culture microalgae can be a good solution to achieve both emission control and value-added bioproduct generation. This study developed an integrated Water Curtain-Microalgal Culture (WCMC) system to realize such concept. The WCMC had NH₃ and TSP mitigation efficiencies of 74.9% and 89.2%, respectively. The microalgal productivity was 12.7 ± 2.9 g/m²/day. The microalgal biomass had a protein content of 41.3%, and the amino acid profile has a quality comparable to egg and soybean. Omega-3 fatty acids accounted for about 23% of total fat acids. Heavy metals did not exceed MTLs. The WCMC system is a promising technology that not only mitigates NH₃ and PM emissions from AFOs, but also provides a holistic solution to animal nutrient management and creates a win-win situation for animal agriculture and microalgal refining.

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Graphical Abstract