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Constructed wetlands for resource recovery in developing countries

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ABSTRACT

Constructed wetlands (CW) are effective in treating wastewater, particularly in settings that require low technology and low maintenance as operational constraints. Biomass harvested from CW can be used as a renewable energy source and treated effluent can provide irrigation for agricultural uses. Biomass yields for four selected wetland plants in CW, namely *Phragmites* spp., *Typha* spp., *A. donax,* and *C. papyrus*, ranged from an average of about 1500 g of dry mass per square meter (g/m^2) for *Typha spp.*, up to 6000 g/m^2 for *A. donax*. The energy yield for direct combustion of these plants occupied a narrow range, averaging about 18 megajoules per kilogram of dry mass (MJ/kg) for all plant types, a comparable amount to *Acacia spp*. Methane yields varied from about 170–360 L of methane (normalised to standard conditions) per kilogram of dry mass (LN/kg). 1 m^2 of CW planted with *A. donax* can produce on average 110 MJ through direct combustion or 1660 L of methane from biogas production. In a village of 200 people the biomass from a CW planted with *Typha* spp. can reduce cooking fuel needs by 4–55% and therefore save up to 12 ha of forest per year. The water footprint of these plants was measured as the percent loss in water in the CW from evapotranspiration (ET). Under a fixed set of assumptions on climate and operation, the water used through ET, the CW could deliver from 64% to 76% of the influent water for subsequent use. In summary, CW have the potential to offset energy and irrigation needs at scales ranging from small communities to peri-urban areas. Constructed wetlands used to treat wastewater have the potential to provide a sustainable bioenergy source without placing burdens on water resources or displacing other food or energy crops.

1. Introduction

Globally 80% of all wastewater is discharged into the environment without treatment and 1 billion people still practice open defecation [1]. Wastewater treatment embodies aspects that include human health, ecosystem stability, energy, and greenhouse gas (GHG) emissions. Municipal-scale wastewater treatment plants are highly efficient regarding the physical space they occupy and the amount of carbon that can be removed per unit cost. However, they are also expensive, complex, centralised, and require vast amounts of energy and trained personnel to operate and maintain them [2].

Traditional wastewater treatment is a significant consumer of energy. In the United States, wastewater treatment accounts for about three per cent of the national electricity load [3]. Municipal wastewater treatment plants consume up to 2.2 MJ per cubic meter of water treated [2]. Many facilities in industrialised regions produce methane through sludge digestion that is either used as a heat source within the treatment plant, is used for some other renewable energy purpose, or is flared and wasted [2].

Constructed wetlands (CW) provide a low-cost, low-maintenance alternative to traditional wastewater treatment and have been widely used in both centralised and decentralised systems [4]. This nature-based solution treats varying types of wastewater through biological and physical processes in the root zones of wetland macrophytes [5]. The physical space necessary for CW is larger than that for other technologies [6], but comparable to other more traditional low-technology alternatives. For example to treat domestic-strength wastewater using CW in a temperate climate would require an area of 2–7 m^2/

List of abbreviations: ABP, Anaerobic Biogasification Potential; BMP, Biochemical Methane Potential; BOD, Biochemical Oxygen Demand; CW, Constructed Wetlands; ET, Evapotranspiration; FW, Free-Water; GHG, Greenhouse Gas; HBT, Hohenheim Biogas Yield Test; HHV, High-Heating Value; HLR, Hydraulic Loading Rate; LB, Laboratory Bioreactor; LHV, Low-Heating Value; SMP, Specific Methane Production; SSF-H, [sub-surface] horizontal flow; SSF-V, sub-surface vertical flow

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Nomenclature

A	Area, m^2
BOD	Biochemical Oxygen Demand, mg/l
CH_4	Methane
CO	Carbon monoxide
EJ	Exajoules, 10^{18} J
ET	Evapotranspiration, mm
ET_C	Evapotranspiration crop, mm
GJ	Gigajoules, 10^3 J
ha	Hectares
HHV	High-heating value, MJ/kg
HLR	Hydraulic loading rate, mm^3/day
LHV	Low-heating value, MJ/kg
LN	Litres of methane (normalised to standard conditions)
MJ	Megajoules, 10^6 J
P	Precipitation, mm
PE	Population equivalent
P_S	Sample mass, mol
Q_I	Inflow of wetland, L
Q_O	Outflow of wetland, L
SMP	Specific Methane Production, L/kg-VS
WC	Biomass, g
ΔH_V	Heat of vaporisation of water, kJ mol
Pb	Lead

person [7], while a non-aerated facultative lagoon would require 2–5 m^2/person and 0.2–0.5 m^2/person for an aerated lagoon [6]. Wetland systems still occupy a larger area than lagoon systems but provide additional ecosystem services, including aesthetics, biodiversity, wildlife refugia, and nutrient capture for reuse [8]. However, perhaps the most significant benefits of CW for wastewater treatment may be their capability to offset GHG emissions and to produce energy (*e.g.*, [9]). CWs as wastewater treatment systems require far less energy to treat wastewater (6.8% of the energy demand of a traditional activated sludge plant [10]), and have the potential to be net suppliers of energy and contribute to the bioenergy portfolios of countries.

1.1. Bioenergy production: compounded benefits through the use of constructed wetlands?

The production of bioenergy to reduce reliance on fossil fuels has been controversial. Biomass energy, as a source of renewable energy, has the potential to contribute up to 50 EJ, or about ten per cent, to the global energy supply by 2035 [11]. However, the primary source of biomass for this energy would be terrestrial energy crops [11]. The debate is usually centred around the use of arable land to meet energy security needs at the expense of food security [12]. Additionally, the water demands to grow energy crops are significant and may be prohibitive and threaten water security in water-scarce regions [13].

Other competing uses for bioenergy resources include wood for forest products and protection of biodiversity [14]. Bioenergy has the potential to make significant improvements in the quality of life and the stability of ecosystems in developing countries. About 3 billion people in developing countries rely on solid fuels for cooking (Fig. 1). Wood is the fuel source for 42% of this population and results in deforestation, soil erosion, and other ecosystem disturbances [15]. In Sub-Saharan Africa, where the per capita wood and charcoal consumption is the highest globally, wood fuel consumption in 2011 was at an average of 0.69 m^3/year [16].

Replacement of solid fuels with biogas for cooking can improve indoor air quality and lead to improved health through decreased exposure to airborne particulates and carbon monoxide (CO) [19]. Although biogas generation requires more infrastructure and processing than direct combustion, small-scale biogas facilities are widespread in developing countries and take advantage of the feedstocks that are locally available. The technology for small-scale, low-technology anaerobic digesters is well established and widely applied in developing countries. As of 2011, there were over 31 million biogas units in India and China alone [20] and 45 million worldwide [21].

CW used to treat wastewater could provide a renewable and sustainable bioenergy source without placing burdens on water resources or displacing other food or energy crops. Integrating wetland biofuel production with other sustainability strategies can provide compounded benefits and assist developing countries toward food and energy security [17]. Liu et al. [9] projected that if CW treated all of the wastewater in China, a land area equal to less than 20% of China's fallow land would be required and could produce 8.2×10^7 GJ/year in bioenergy, enough to meet the energy demands of about two million households in China [18]. There are clearly practical constraints at this scale. However, the use of CW to treat wastewater instead of traditional activated sludge systems saves in energy costs to treat the wastewater

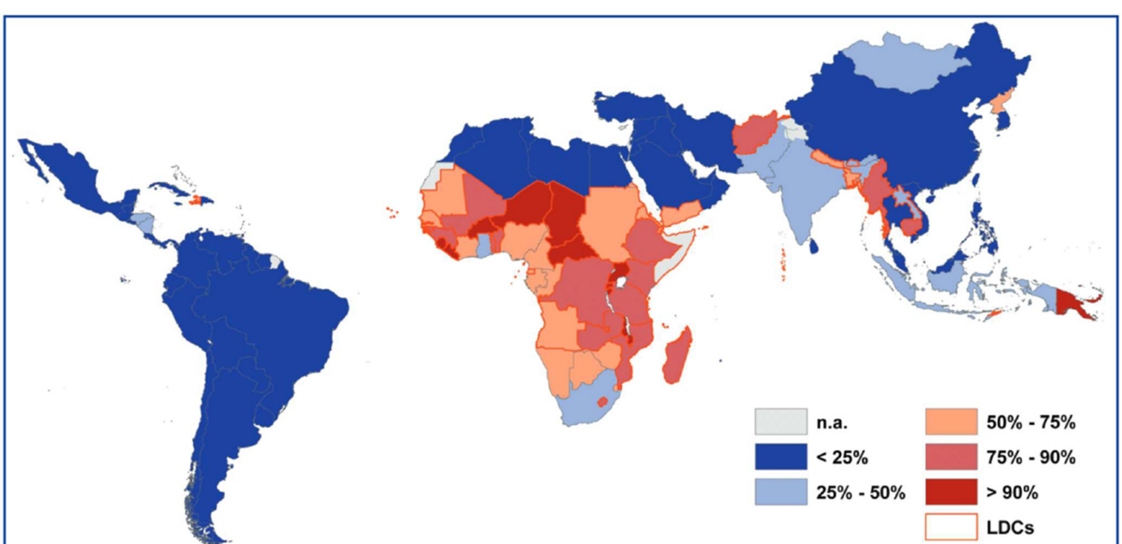

Fig. 1. Share of population without access to modern fuels for developing countries, 2007. (LDCs = Least developed Countries) (Reproduced from UNDP [15]).