

The role of constructed wetlands for biomass production within the water-soil-waste nexus

C. T. Avellan, R. Ardakanian and P. Gremillion

ABSTRACT

The use of constructed wetlands for water pollution control has a long standing tradition in urban, peri-urban, rural, agricultural and mining environments. The capacity of wetland plants to take up nutrients and to filter organic matter has been widely discussed and presented in diverse fora and published in hundreds of articles. In an ever increasingly complex global world, constructed wetlands not only play a role in providing safe sanitation in decentralized settings, shelter for biodiversity, and cleansing of polluted sites, in addition, they produce biomass that can be harvested and used for the production of fodder and fuel. The United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES) was established in December 2012 in Dresden, Germany, to assess the trade-offs between and among resources when making sustainable decisions. Against the backdrop of the Water-Energy-Food Nexus, which was introduced as a critical element for the discussions on sustainability at Rio +20, the UNU was mandated to pay critical attention to the interconnections of the underlying resources, namely, water, soil and waste. Biomass for human consumption comes in the form of food for direct use, as fodder for livestock, and as semi-woody biomass for fuelling purposes, be it directly for heating and cooking or for the production of biogas and/or biofuel. Given the universal applicability of constructed wetlands in virtually all settings, from arid to tropical, from relatively high to low nutrient loads, and from a vast variety of pollutants, we postulate that the biomass produced in constructed wetlands can be used more extensively in order to enhance the multi-purpose use of these sites.

Key words | bioenergy, biogas, constructed wetlands, resources-oriented sanitation, wastewater treatment

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INTRODUCTION

Water supply, pollution control, agricultural resource management, and energy production have been treated traditionally as independent problems to be solved separately. It is becoming more apparent that interconnections among cycles of water, nutrients, and energy can now be exploited in systems that perform multiple functions optimized to provide services for human communities, while improving ecosystem health. Properly designed and operated, constructed wetlands for the treatment of wastewater can provide functions that include safe sanitation in decentralized settings, shelter for biodiversity, and cleansing of polluted sites. In addition, constructed wetlands produce biomass that can be harvested for the production of fodder and fuel.

The concept of considering interconnected systems is exemplified by the Water-Energy-Food Nexus, which was

introduced as a critical element for the discussions on sustainability at Rio +20. UNU was mandated to pay critical attention to the interconnections of the underlying resources, namely, water, soil and waste. The United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES 2017) was established in December 2012 in Dresden, Germany, to assess the trade-offs between and among resources when making sustainable decisions.

Using wetlands to treat wastewater addresses at least three major elements in sustainability: water and sanitation, energy, and greenhouse gas (GHG) emissions. Sustainable use of resources is a key element in achieving goals on ending poverty established initially by the Millennium Development Goals. Established by the United Nations

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Conference on Sustainable Development, Rio + 20, in 2012, the further evolved Sustainable Development Goals, SDGs (UNDP 2017), articulated the three pillars of sustainable development: environmental, social, and economic. Of the 17 SDGs, at least two are relevant to the integrated use of constructed wetlands: *SDG Goal 6: Ensure access to water and sanitation for all* and *SDG Goal 7: Affordable and clean energy*. Climate change is addressed in SDG Goal 13 and has been more fully considered in the 2015 Paris Agreement (Climate Action 2015) of the Conference of Parties of the UN Framework for Climate Change. Here, nations committed to sufficiently reduce their GHG emissions to limit global warming to less than two degrees Celsius by the end of this century.

Wastewater treatment

Wastewater treatment embodies aspects that include human health, ecosystem stability, energy, and GHG emissions. Worldwide, nearly 60 million kg/year of biochemical oxygen demand (BOD) are removed by wastewater treatment plants, along with over 4 million kg of nitrogen and nearly a million kg of phosphorus (Corcoran 2010). In municipal-scale wastewater treatment plants, the carbon associated with BOD is typically converted to microbial biomass, which in turn is removed as a dense organic sludge, which, when stabilized, dried or composted, can be used as an energy or nutrient source. These types of treatment systems are highly efficient in terms of the physical space they occupy and the amount of BOD that can be removed per unit cost. But they are also expensive, complex, centralized, and require vast amounts of energy (three percent of all electricity use in the United States, for example) and trained personnel to operate and maintain them (McCarty *et al.* 2011).

Wastewater treatment technology is unevenly distributed worldwide. In North America and Western Europe, for example, more than three quarters of wastewater produced is treated, compared with West and Central Africa, Southern Asia, and East Asia, where more than three quarters of wastewater discharged is not treated (Corcoran 2010). Not surprisingly, investments in sanitation infrastructure reflect economic prosperity. Ashley & Chapman (2006) estimated that investments in infrastructure necessary to meet minimum health and environmental standards by the year 2030 range up to 1.2 percent of gross domestic product (GDP) for high-income countries, while low-income countries need to invest up to 6.3 percent of their GDP to bring treatment facilities up to standard.

Constructed wetlands provide a low-cost, low-maintenance alternative to traditional wastewater treatment and have been widely used in both centralized and decentralized systems (Zhang *et al.* 2014). The physical space necessary for constructed wetlands is larger than that for municipal technologies (Kivaissi 2001), but comparable to other more traditional low-technology alternatives. For example, to treat domestic-strength wastewater using constructed wetlands in a temperate climate would require an area on the order of 7 m²/person (Rousseau *et al.* 2004), while a non-aerated facultative lagoon would require 2 to 5 m²/person and 0.2 to 0.5 m²/person for an aerated lagoon (Kivaissi 2001). 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 (Yang *et al.* 2008). However, perhaps the most significant benefits of constructed wetlands for wastewater treatment may be their capability to offset GHG emissions and to produce energy (e.g., Liu *et al.* 2012).

Greenhouse gas emissions

Constructed wetlands affect GHG cycles both in the treatment of wastewater and in the production and use of their biomass. With regard to infrastructure and treatment, CO₂ emissions occur during construction, harvesting, and in the decomposition of organic matter. During their operation, constructed wetlands are net emitters of methane, but sinks of CO₂ through their accumulation of organic matter and are net GHG sinks (Liu *et al.* 2012; Mander *et al.* 2014). In addition, traditional wastewater treatment systems emit 591 kg CO₂ for every kilogram of nitrogen removed, while wetland systems emit 0.9 kg CO₂ per kg nitrogen (Liu *et al.* 2012).

Use of the biomass produced by wetlands impacts GHG cycles as well. Factors that need to be considered include bioenergy production and transportation and the offsetting effects of biomass as a fuel source relative to the fuel it replaces. A hypothetical example is a wetland system which produces solid fuel that replaces a wood fuel source. This can result in a decrease in deforestation, with positive impacts related to the continued sequestration of carbon in the above-ground biomass of the forest itself and preservation of organic carbon contained in soils that would not be eroded (Fargione *et al.* 2008).

Energy

Considering the water-energy nexus, traditional wastewater treatment is a significant consumer of energy. In the

United States, wastewater treatment accounts for about 3% of the national electricity load (USEPA 2006). Municipal wastewater treatment plants consume up to 2.2 megajoules (MJ = 10^6 joules = 10^{-3} GJ or gigajoules) per cubic metre of water treated (McCarty *et al.* 2011). Many facilities in industrialized regions produce methane through sludge digestion that is either used as a heat source within the treatment plant, used for some other renewable energy purpose, or simply flared and wasted (McCarty *et al.* 2011). Constructed wetlands as wastewater treatment systems require far less energy to treat wastewater (6.8% of the energy demand of a traditional activated sludge plant, according to Shao *et al.* (2013) and have the potential to be net suppliers of energy and contribute to the bioenergy portfolios of countries.

The production of bioenergy to reduce reliance on fossil fuels has been controversial. Biomass energy has the potential to contribute up to 50 EJ (Exajoules = 10^{18} joules), or about ten percent, to the global energy supply by 2035. However the primary source of biomass for this energy would be terrestrial energy crops (Slade *et al.* 2014). Debate is usually centred around the use of arable land to meet energy security needs at the expense of food security (Müller *et al.* 2008). Additionally, the water demands to grow energy crops are significant and may be prohibitive and threaten water security in water-scarce regions (Strzepek & Boehlert 2010). Other competing uses for bioenergy resources include wood for forest products and protection of biodiversity (Smeets *et al.* 2007).

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. Liu *et al.* (2012) projected that if constructed wetlands 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 (Zheng *et al.* 2014). There are clearly practical constraints at this scale, however the use of constructed wetlands to treat wastewater instead of traditional activated sludge systems saves in energy costs to treat the wastewater (Shao *et al.* 2013) and produces a bioenergy resource.

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 (Figure 1). Wood is the fuel source for 42% of this population and results in deforestation, soil erosion, and other ecosystem disturbances (Legros *et al.* 2009). Biofuel from constructed wetlands can at least partially ease the reliance on unsustainable solid fuel sources in developing countries. Integrating wetland biofuel production with other sustainability strategies can provide compounded benefits and assist developing countries toward stable food and energy security.

Here, we consider the potential for constructed wetlands to purify wastewater while contributing to renewable water and energy cycles. We address the following questions: Which wetland plant species can be used and why? How can wetland biomass be converted to usable energy at a scale appropriate for developing countries? And, how can constructed wetlands be integrated into resource management programs in developing countries?

METHODS

Our work is a synthesis of recent research and practice related to constructed wetlands for wastewater treatment

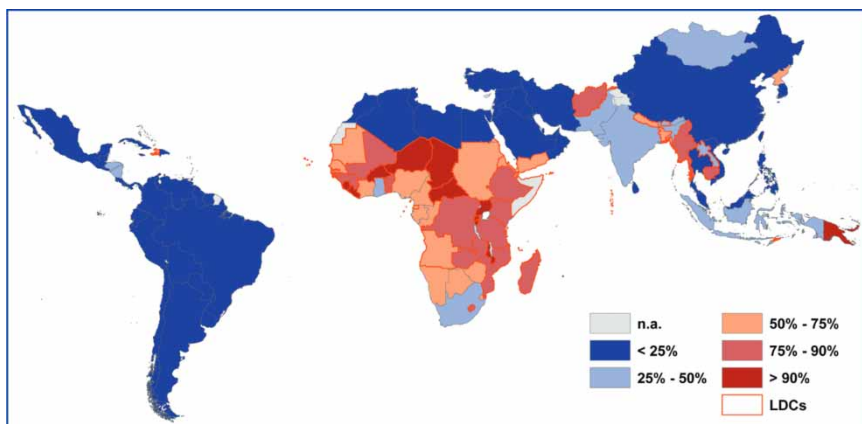


Figure 1 | Share of population without access to modern fuels for developing countries, 2007. LDCs, Least Developed Countries. (Reproduced from UNDP: Legros *et al.* (2009).)

and biomass as a green energy source. We consulted peer-reviewed literature from the research community, international governmental and non-governmental organizations, and such grey-literature sources as technical guidance documents and white papers. Online searches were conducted using Google Scholar (Google 2017) and Thompson Reuters Web of Science (Clarivate Analytics 2017). Our searches included the following topics: Constructed wetlands for wastewater treatment, wetland biomass for biofuel production, bio-energy crops and process, process design for bio-energy, energy and green energy portfolios for developing countries, global wastewater treatment, GHG emissions related to wastewater treatment and biofuel production, and life cycle assessment for wastewater treatment and energy production. References were organized using the open-source reference database system, Zotero (Zotero 2017). References assembled for this research will be available through the United Nations University FLORES institute website (UNU-FLORES 2017).

RESULTS AND DISCUSSION

Our analysis of constructed wetlands as wastewater treatment systems considers selection of the plants themselves, the potential for harvested biomass as an energy source, and some of the challenges in implementing these systems in the integrated management of water, nutrient, and energy cycles.

Wetland plants for wastewater treatment

Plant types

In a literature survey of 643 constructed wetlands from 43 countries, Vymazal (2013) found that of the 150 plant species used, the five most common genera were *Typha*, *Scirpus* (*Schoenoplectus*), *Phragmites*, *Juncus*, and *Eleocharis*. Most of the wetlands surveyed were in North America (56%) and Europe (22%). In a survey of 36 constructed wetlands in developing countries, Zhang *et al.* (2014) found that *Phragmites* and *Typha* (35% and 10%, respectively) were the most commonly used plants. In a review of constructed wetlands in African countries, Mekonnen *et al.* (2015) listed 12 wetlands, which used primarily *Phragmites*, *Typha*, and *Cyperus papyrus*.

Plants can be selected based on energy yield, measured as the production of dry biomass per unit area and time, for example tonnes per hectare per year. On this basis, Laurent

et al. (2015) ranked *Arundo donax* (giant reed) and *Spartina cynosuroides* with the highest energy yields for wetland plants, with averages of about 30 and 12 tonnes ha⁻¹ year⁻¹, respectively. Liu *et al.* (2012) measured energy yield as GJ/ha/year using plant growth rates (kg ha⁻¹ year⁻¹) and used an energy conversion factor of 18.5 MJ/kg. They ranked *A. donax*, *Phragmites australis*, and *Typha angustifolia* as the highest energy producers (Figure 2), which corresponds with the findings of Laurent *et al.* (2015) for *A. donax* and *Typha*, but not *P. australis*. Actually Laurent *et al.* (2015) rank *P. australis* as having a relatively low energy yield.)

With regard to suitability for energy production, two of the five most commonly used wetland plants worldwide, *Typha* and *Phragmites* (according to Liu *et al.* 2012), are also superior biomass producers. The remaining three most commonly used wetland plants, *Scirpus*, *Juncus*, and *Eleocharis*, are all notably slower growing, and less well suited as energy crops (Figure 2). The highest energy producer, *A. donax*, has been relatively under-used in constructed wetlands.

The selection of plant types for constructed wetlands has not necessarily been based on the potential of the plants to produce biomass energy, or even based on their efficiency at pollutant removal, although both of these parameters vary widely from plant to plant. Plant selection has likely been based more on local availability, suitability to local climate conditions, and tolerance to influent water quality (Wu *et al.* 2015). Vymazal (2011) noted that mixes of species may be more effective than single species in withstanding seasonal and other ambient variations. Protecting regions from introduction or spread of invasive, non-native species has also been an important consideration (Zedler & Kercher 2004; Piwpuan *et al.* 2014).

Effects of harvesting

A harvesting program for treatment wetlands needs to optimize both pollutant removal and biomass growth. With regard to pollutant removal, uptake of nitrogen and phosphorus is mediated by microbial systems in the soil and root zones of emergent wetland plants (Vymazal 2007). For aerobic processes in the root zones, adequate resupply of oxygen from the wetland plants themselves is necessary (Wang *et al.* 2014). An ongoing maintenance program can prevent accumulation of detritus, which can impair performance and cause re-release of nutrients (Thullen *et al.* 2005). Harvesting to collect biomass as a renewable energy source provides this benefit, and with proper timing of

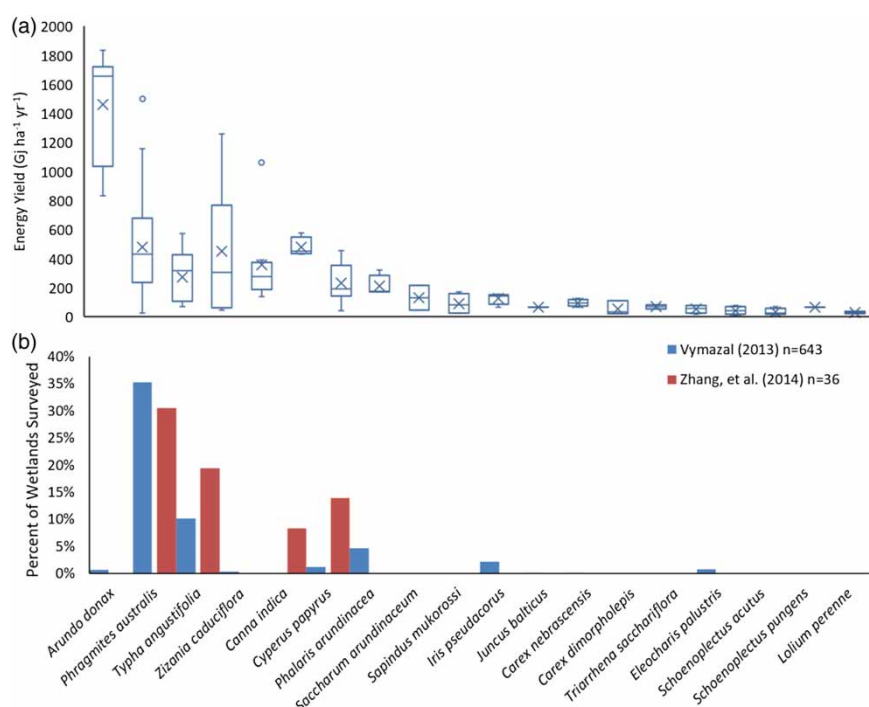


Figure 2 | Energy yield and occurrence of wetland plants in constructed wetlands for wastewater treatment. (a) Energy yield for wetland plants used in treatment wetlands. The line and X within each box are the median and mean values, the top and bottom edges of the boxes represent 25% and 75% of all data. Open circles outside the boxes represent extreme values. (b) Types of wetland plants identified in two reviews of constructed wetlands for wastewater treatment. Sources: Liu *et al.* (2012); Vymazal (2013); Zhang *et al.* (2014).

harvests, can optimize biomass growth for enhanced performance in carbon and nutrient removal (Thullen *et al.* 2005).

With regard to regrowth after harvesting, Jinadasa *et al.* (2008) studied growth and uptake rates in a tropical setting. Regrowth of *Scirpus* and *Typha* was rapid after first harvesting, but progressively slower after subsequent harvests. Frequent harvesting can slow biomass production, but frequent thinning, rather than complete removal of a plant, results in the highest biomass production (Sale & Wetzel 1983; Jinadasa *et al.* 2008). Sustainable long-term production of biomass requires maintaining plants in a rapid-growth phase through this thinning process (Thullen *et al.* 2002). This approach is consistent with strategies to mimic natural wetland systems in early successional stages (Thullen *et al.* 2005).

Potential for energy production

Biomass generated by constructed wetlands can be converted to energy in three broadly defined processes: direct combustion, biogas production, and bioethanol production. The relative advantages and disadvantages of these processes vary with the scale of system employed.

Constructed wetlands for wastewater treatment can be applied in settings that range from small villages to megacities, but for the purpose of this analysis, we will focus on the range of wetland sizes already in operation in developing countries. Zhang *et al.* (2014) surveyed treatment wetlands ranging in size from 0.25 m² to over 30 ha. Excluding the two largest wetlands (17.4 and 35.2 ha), the remaining 56 wetlands had a mean area of 412 m², but a median area of only 22 m². Considering that treatment wetlands serve roughly 7 m²/person (Rousseau *et al.* 2004), most constructed wetlands support communities of less than about 60 people. At this scale, direct combustion and biogas production are likely the most economical bioenergy alternatives.

Direct combustion involves minimal processing, whereby harvested biomass is either dried and used as a fuel source, or formed into briquettes by shredding the biomass, mixing it with an additive, and compressing it into briquettes (Li & Zhang 2011). Wichmann (2016) assessed the transfer of agricultural biomass technology to the processing of *Phragmites* for biogas production, direct combustion, and thatching. Direct combustion has several advantages for small-scale applications. The fuel is easily transported and can be adapted to traditional solid-fuel cooking stoves or

for heating (Tucho & Nonhebel 2015). Direct combustion also has low infrastructure costs and a low level of expertise necessary to operate and maintain systems.

A hypothetical community of 60 people would require a wetland area of about 420 m². If the wetland produces 15 tonnes dry mass ha⁻¹ year⁻¹, a moderate level of productivity according to Laurent *et al.* (2015), the wetland can supply the community with 630 kg year⁻¹ of dry biomass. The dry biomass has an energy content of about 16 MJ Kg⁻¹ (Kitzler *et al.* 2012), so the wetland can produce about 10 GJ year⁻¹. An average household in Ethiopia requires about 7 GJ year⁻¹ for cooking (Tucho & Nonhebel 2015) and there are about 5 persons per home (USAID 2001), so the annual energy requirement for cooking in this community of 12 homes is about 84 GJ. The biofuel produced by the treatment wetland can therefore supply about 12 percent of the cooking fuel needs of the village.

The other likely alternative for a community of 60 residents is to convert the harvested wetland biomass to methane in an anaerobic reactor. Biogas production requires more coordination and complexity, but allows mixtures of other available organic matter to increase biogas yield (Marchetti *et al.* 2016) and has the potential to employ proven, small-scale biogas technologies. For example, the Gobar gas plant was designed to be a simple, family-scale anaerobic digester designed to process livestock waste, but which can be modified to treat a combination of organic materials (Pullen 2015). Small-scale anaerobic digesters are already common in many parts of the world, with more than 45 million units in Asia and 4 million in India. With more than 200,000 biogas units in operation, Nepal has the highest number of small-scale biogas digesters per capita in the world (Gebreegziabher *et al.* 2014).

For our hypothetical community of 12 households, a constructed wetland could collect and treat the wastewater and a biogas unit could convert the wetland biomass to biogas at a conversion rate of about 18.5 GJ Kg⁻¹, which is slightly higher than that for direct combustion (Liu *et al.* 2012), for an energy supply of about 14 percent of the community's energy needs for cooking. A biogas system requires the community to make a greater commitment to infrastructure, training, operation, and maintenance than for a direct combustion system. Distribution of the biogas can also be a challenge. But because biogas reactors can also use livestock, agricultural residue, and nearly any other form of organic waste as a fuel source, these systems have the potential to provide a community with almost complete energy independence.

Opportunities and challenges

Constructed wetlands to treat wastewater have the potential to provide a bioenergy resource at a wide range of scales, particularly if other sources of organic matter are included in the bioenergy process. This bioenergy source can be an effective component in a community that takes advantage of multiple, integrated uses of their water, nutrient, and carbon resources (Figure 3). The resources to be economized are water, organic carbon as a fuel source, and nutrients as a fertilizer source. In an integrated village waste system, wastewater can be treated using constructed wetlands and the effluent water can be used for irrigation. Biomass from fallow crops, municipal solid waste, and food waste can be used as biomass augmentation in reactors that process treatment wetland biomass. Digestate from biogas and bioethanol reactors can be used as compost on agricultural fields. Moreover, wetland biofuels can mitigate the use of scarce resources and ecologically disruptive practices. Constructed wetlands for wastewater treatment provide a range of ecosystem services and can create GHG sinks.

Clearly these systems are sustainable in the environmental sense, but to apply them in developing countries, they also need to be sustainable financially and in terms of community ownership. The single most common failure in the long-term success of development projects has been the lack of commitment of local populations to operate and maintain facilities, due at least in part to the delivery of technology inappropriate to, or unacceptable by, local communities (Kumar & Corbridge 2002). Constructed wetlands for wastewater treatment and biofuel production have the potential for sustainability in all its definitions, if care is given to community acceptance from project inception. A vision for successful implementation may include a community's consideration of the system as a resource that both protects their health and provides energy security, self-determination, and independence.

CONCLUSIONS

Constructed wetlands for wastewater treatment can be the cornerstone in integrated management of water, nutrient, and energy cycles. To return to our original questions:

Which wetland plant species can be used and why? The selection of plants will be affected by local climate, availability of plants, and the need to prevent or control invasive species. The fastest-growing plants that can also

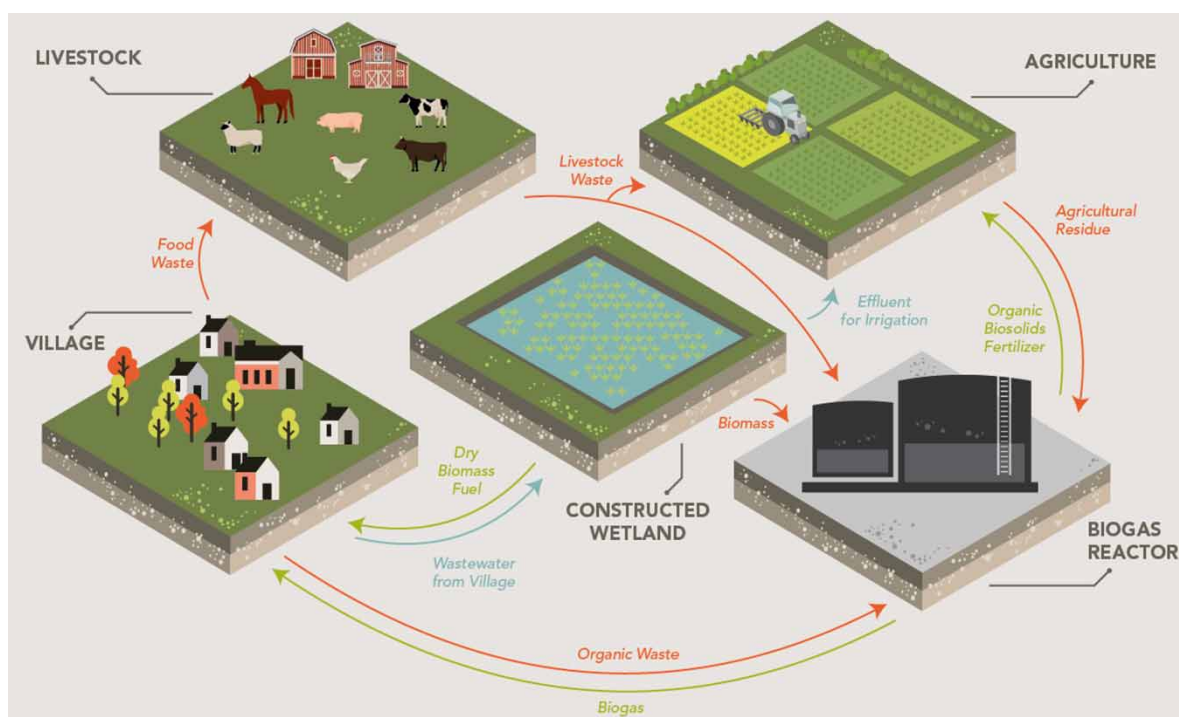


Figure 3 | The potential for constructed wetlands to influence interactions among water, waste, nutrient, and energy at village and municipal scales.

thrive under conditions of frequent pruning will be best suited for this application. The plants most commonly used in constructed wetlands, which also have fast growth rates, are *Phragmites* and *Typha*. Less commonly used, but desirable due to its fast growth, is *A. donax*.

How can wetland biomass be converted to usable energy at a scale appropriate for developing countries? In order of increasing complexity, three appropriate technologies are direct combustion, biogas production, and bioethanol production. At the smaller scales now in operation for treatment wetlands in developing countries, direct combustion and biogas production are the most promising technologies. The direct combustion of dry biomass harvested from treatment wetlands can provide more than 10 percent of the cooking energy needs of a small village. If a community can make sustained investment in the more complex technology of biogas production, other sources of organic matter can be added to harvested wetland material and potentially provide complete energy independence for the community.

How can constructed wetlands be integrated into resource management programs in developing countries? Treatment wetlands can be the common thread that creates the soil-water-waste nexus in a community. The wetlands themselves can improve the health and sanitation conditions in a village. Energy provided by wetland biomass

can offset scarce and environmentally damaging sources, such as collection of firewood. At the smallest and least complex level, dried or briquetted biomass can be combusted as a cooking or heating fuel source. More complex biogas and bioethanol reactors, made economically feasible with wetland biomass feedstocks, can improve a community's energy security when additional organic sources are used. These can include livestock, household, and agricultural wastes. This conversion of a waste product into an energy resource can be an effective strategy in 'closing the loop' in water and energy cycles and results in improved environmental conditions as well as increased food and energy security.

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