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Application Potential of Wastewater Fertigated Short Rotation Coppice Systems in a Selected Region (Aligarh, UP, India)

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Abstract: In many Indian regions, increased wastewater is both a threat to public health and the environment, but it also presents an opportunity as a source of water and nutrients. With less than one-third of India's wastewater treated and an alarming water scarcity situation, efficient wastewater treatment and reuse schemes are needed to face impending water and fertiliser shortages. This study explores the application potential of wastewater fertigated Short Rotation Coppice systems (wfSRC) as a cost-efficient and promising solution for treating and reusing wastewater in a specific region (400 km^2, 184 settlements) of Aligarh (UP), India. Based on real data from a local wfSRC pilot site using bamboo, willow, and poplar, we analysed the system's treatment performance, nutrient recovery, carbon sequestration potential, land requirements, biomass production potential, and cost–benefit, under various scenarios. The results show that the pilot wfSRC system is efficiently treating 250 m^3/day of domestic wastewater on 6864 m^2 of land, and serving 2500 people. The land requirements for wfSRC systems vary depending on local conditions (e.g., climate, soil type, wastewater composition) and user demands (e.g., water reuse efficiency, type, and amount of biomass). The calculated areas ranged from 2.75 to 25.7 m^2/PE, which equates to a required land area in the whole study region of between 108 and 1006 ha in 2036. This would produce up to 100 DM t/ha/year of valuable biomass. Early local stakeholder involvement and the monitoring of pollutants are recommended as priorities during the planning process for the large-scale implementation of wfSRC systems in India.

Keywords: potential of wastewater fertigated/irrigated Short Rotation Coppice/Plantation (SRC, SRP) in India; nature-based wastewater treatment and reuse systems; phytofiltration; sustainable biomass (willow, poplar, bamboo) production systems

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1. Introduction

India, like many low- and middle-income countries, lacks widely available, sustainable, and functioning facilities for wastewater treatment and reuse, particularly in rural areas. Even in densely populated urban areas, less than 30% of households are connected to wastewater treatment plants [1] and only 28% of the 26.4 km^3 of wastewater generated annually in India is treated [2]. State governments are responsible for the collection, treatment, and potential reuse of wastewater. The main focus of current wastewater treatment efforts is to support centralised systems for the larger cities along major rivers, while the needs and potential in rural areas are neglected [3]. Specific actions such as the Clean Ganga Programme are attempting to improve the situation by planning and financing wastewater infrastructure (e.g., sewer collection systems and STPs) in states with low treatment capacity, as is the case in Uttar Pradesh (37.2%) [2]. Much of the untreated wastewater in India is discharged to water bodies or used, directly or indirectly, to irrigate crops. Using a GIS-based modelling approach, Thebo et al. have calculated that in India, an area of 8.9 million hectares is being irrigated with untreated wastewater [4].

As a result of this unregulated application of wastewater, most open water bodies and groundwater sources are becoming increasingly polluted, resulting in serious environmental and health challenges such as diarrhoeal diseases and other enteric disorders [5,6]. The situation is worsened by the large proportion of rural inhabitants in India who rely on untreated groundwater for their daily drinking and other water use needs. In parallel, as the world's most populous country, sustainable and highly productive agriculture is critical to India's domestic food security, strengthening a bio-based economy, and eradicating poverty. The high levels of water consumption associated with current agricultural practices have led to falling ground water tables and an increasing shortage of irrigation water in many regions of India [7]. More than 50% of the agricultural land in India is located in areas with high to extremely high water stress, which is alarming in light of future projections [8].

Therefore, a key challenge for the sector is to develop an integrated approach which combines wastewater treatment, reclamation, and reuse with efficient biomass production. The current situation in India makes it imperative to develop the concept of the circular economy in the wastewater sector, using affordable, nature-based solutions which are managed by the community to recover valuable resources and guarantee proper wastewater treatment and high-quality sanitation. Numerous treatment approaches, such as constructed wetlands, have been implemented and studied in India [9]. Nevertheless, the high investment costs and lack of additional income sources for operators seem to be important barriers to the sustainability of these technologies. A promising, cost-efficient alternative could be wastewater fertigated Short Rotation Coppice systems (wfSRC).

WfSRC are wastewater fertigated agro-forestry systems in which treatment takes place in a vegetated soil surface (root zone). These systems are characterised by high biomass production, using fast growing tree or grass species (e.g., willow, poplar, bamboo) which are managed in short rotation cycles [10]. WfSRC systems remove various components from wastewater through microbial degradation, natural oxidation, adsorption, and plant uptake. The main advantages of wfSRC systems include low investment and operational costs, minimal energy requirements, eco-friendly features (e.g., support of high biodiversity), no sludge production, self-regeneration capacity, and efficiency in removing diverse types of pollutants. In addition, these systems are designed to replenish groundwater sources and reduce GHG emissions [11]. There is extensive experience and ample data about these systems from developed countries, particularly in Europe and the US [12–17], but there is little available about their performance in low- and middle-income countries [18].

A full-scale wfSRC pilot plant has been established at Aligarh Muslim University in Aligarh (Uttar Pradesh) under the EU-INDIA PAVITR project (2019–2024). Its operation and performance indicators are being monitored and the data are being collected. The initial results underline its potential as a beacon demonstrator of a regional nature-based approach. However, many successful demonstrators for sustainable wastewater treatment and reuse have been built in India without having any measurable impact on the general situation due to the absence of workable strategies for their replication [19]. We contend that well-planned, large-scale sustainable wastewater treatment and reuse solutions need to be implemented at a regional scale in India, involving innovative and comprehensive spatial planning analysis, the use of scenario tools, and local stakeholder feedback. The data generated, based on local conditions and needs, should be the basis for future decision making and investments regarding the implementation of wastewater infrastructure. Therefore, the study focuses on the application potential of wfSRC systems in the targeted region of Aligarh by analysing (i) the level of wastewater treatment and water and nutrient reuse performance that can be expected, (ii) the footprint needed to establish such a system,

(iii) the type and amount of biomass that can be produced, and (iv) the estimated relevant costs and benefits of the approach.

2. Results

2.1. Results of wfSRC Pilot System

2.1.1. Climate

During the study period (29 March 2022–28 March 2023), 958 mm rainfall was measured, resulting in an average of 2.62 mm/day. Average ET rates were 3.04 ± 1.42 mm/day, adding up to 1108 mm over 365 days. The mean air temperature was 24.5 °C with a daily average minimum temperature in January of 4.5 °C and a maximum daily average of 38 °C temperature in May, reflecting the hot subtropical climate. Equally, relative humidity levels were generally high with a mean value of 74% on the pilot site over the monitored period.

2.1.2. Wastewater Application

A total of 83,949 m^3 of wastewater was applied over 6864 m^2 during the study period (33.5 ± 9 mm/d). Irrigation was interrupted for 19 days due to power cuts, pump failures and monsoon flooding. The hydraulic load met the water requirements of bamboo, willow, and poplar plants. Average values from the analysis of wastewater samples taken from the homogenisation tank are shown in Table 1.

Table 1. Characterisation of applied wastewater.

Parameters	Units	Average Values	*n*
COD	mg/L	199 ± 48	6
BOD_5	mgO_2/L	102 ± 17	5
TDS	mg/L	673 ± 108	6
TKN	mg/L	39 ± 10	6
Nitrate	mg/L	26.8 ± 9.5	6
PO_4–P	mg/L	8.8 ± 1	3
pH	-	7.8 ± 0.3	6

2.1.3. Plant Development and Biomass Yield

An extreme heat wave (up to 48 °C) and an irregular irrigation scheme (well water) during the first 4 months after planting led to mortality rates of 90% for poplar, 50% for willow, and 28% for bamboo (99% of *Dendrocalamus strictus* died). Replanting took place in August 2022 (*Bambusa bambos* and *Salix alba*) and in January 2023 (*Populus tremula*). In total, 10 bamboo, 10 willow, and 10 poplar plants were marked for monitoring, and three randomly selected areas of 1 m^2 of each species were harvested manually on 17 January 2023. The five monitored plants of *Bamboo vulgaris* presented an average stem diameter (1 m above ground) of 3.8 cm and an average height of 7.4 m. The potential biomass harvest of *Bamboo vulgaris* corresponds to 270 ± 40 t/ha fresh biomass with a water content of 66% (stem) and 47% (leaves). This is in the top range of documented bamboo biomass harvest data from India [20]. *Bambusa bambos* reached a stem diameter of 1.8 cm and a height of 4.8 m. *Bambusa bambos* presented 242 ± 56 t/ha of fresh biomass with a water content of 54% (stem) and 56% (leaves). *Salix alba* presented average stem diameters (5 cm above ground) of 3.2 cm and a height of 1.4 m. The harvested biomass corresponds to 61 ± 12 t/ha/year fresh biomass with a water content of 43% (stem) and of 65% (leaves). *Salix purpurea* showed an average stem diameter of 1.3 cm, an average height of 1.4 m, and a biomass production of 3.5 ± 3.9 t/ha/year fresh biomass with a water content of 58% (stem) and 50% (leaves). *Populus tremula* developed an average stem diameter (1 m above ground) of 4.2 cm and an average height of 4.4 m. The potential biomass without leaves corresponds to 77 ± 31 t/ha/year fresh biomass and 45 ± 15 DM t/ha/year with a water content of 46% (Table 2).

Table 2. Amount and characterisation of harvested biomass.

Species	Harvested Biomass (Fresh) in t/ha/year	K in mg/g [1]	P in mg/g [1]	N in % [1]	C in % [1]
Bamboo vulgaris	270 ± 40	8.7 ± 4.5	1.6 ± 0.3	1.8 ± 0.8	43.4 ± 2.0
Bambusa bambos	242 ± 56	12.9 ± 4.5	1.6 ± 0.3	1.8 ± 1.0	43.7 ± 2.2
Salix alba	61 ± 12	5.2 ± 1.6	2.0 ± 1.3	1.4 ± 0.7	43.0 ± 3.7
Salix purpurea	3.5 ± 3.9	6.9 ± 2.8	1.8 ± 1.1	1.7 ± 1.3	45.7 ± 0.8
Populus tremula	77 ± 31	2.4 ± 0.3	0.8 ± 0.1	0.6 ± 0.1	46.9 ± 0.2

[1] based on dry material.

Most of these figures are in the upper range of biomass harvests from wfSRC systems that have been reported in the literature: 4 to 24 t DM/ha/year for willow, 5 to 37 t DM/ha/year for poplar, and 10–105 t DM/ha/year for bamboo [18,20–22]. Enhanced biomass growth in this wfSRC system can very likely be linked to the additional supply of nutrients, irrigation water, and favourable soil and climatic conditions. The reported low biomass production of *Salix purpurea* was probably due to the heat wave and irregular irrigation during the first year of cultivation. By replanting and continuously applying wastewater, higher biomass harvests are expected in the future. Nevertheless, for the calculation in our scenarios, the following extrapolated data on potential biomass harvest have been used: 100 DM t/ha/year for bamboo, 25 DM t/ha/year for willow, and 30 DM t/ha/year for poplar.

2.1.4. Removal Capacity of the wfSRC System

To evaluate the wfSRC system's capacity to remove wastewater contaminants, the chemical composition of the homogenisation tank effluent was compared with that of the percolated water, intercepted in all sectors by the water collectors. This comparison was conducted in terms of concentrations.

COD and BOD_5 removal efficiencies increased with time and soil penetration depth. The reduction in COD and BOD_5 in all sectors of the system occurred mainly in the first 30 cm of the soil profile, reaching 95 ± 2% and 97 ± 0.4%, respectively, in the poplar sector, 94 ± 2.3% and 99 ± 0.8%, respectively, in the willow sector, and 93 ± 2.5% and 98 ± 1.1%, respectively, in the bamboo sector, after one year of wastewater application. Similar BOD_5/COD removal rates have been reported in numerous wfSRC systems [18]. In the soil filtration sector (not planted), COD and BOD_5 removal efficiencies of 78 ± 3% and 93 ± 0.2% were observed. These results suggest a high level of oxidation of the organic matter content of incoming wastewater, in all sectors.

After one year of wastewater application, PO_4–P removal rates in the bamboo sector were 86 ± 11%. In the poplar sector, the average PO_4–P removal rates were 73 ± 13%. In the willow sector, PO_4–P removal efficiency reached 89 ± 16%. In the soil filtration sector, PO_4–P measurements showed removal efficiencies of 58 ± 13%. It seems that wfSRC systems can reliably remove PO_4–P if they are well-designed and managed in terms of the size of the wfSRC area relative to the loading rate, tree species, soil properties, and resulting retention time given the incoming PO_4–P load at the relevant site.

TN also showed high removal rates. The results of combined NH_4–N and NO_3–N measurements at 100 cm depth in the bamboo sector were 77 ± 0.5%, in the poplar sector 78 ± 1.5%, and in the willow sector 85 ± 1.3%. In the soil filtration sector, combined NH_4–N and NO_3–N measurements showed removal efficiencies of 75 ± 13%. TN removal rates of over 90% have been reported in other wfSRC systems [18], which is consistent with the findings of this study. Nevertheless, some NO_3–N values were above the actual discharge limit and did not show a significant reduction with increasing soil depth, probably because negative charges inhibit absorption into clay particles in the soil. Additionally, the very low organic content in the soil is probably limiting the denitrification process. Previous studies on nitrate leaching from wfSRC systems show that the leaching of NO_3–N occurs in the establishment year but reduces over subsequent periods to near-zero [23].

The average pH value of the percolation water analysed decreased slightly from 7.8 ± 0.3 to 7.6 ± 0.1. In natural soil-based systems such as wfSRC, populations of pathogens such as coliforms (FC and TC) are minimised due to oxidation, desiccation, antagonistic interactions with soil microbes, and exposure to sunlight [24]. In this study, the total coliform bacteria (MPN/100 mL) detected in all samples varied between 50 and 1500. No *E. coli* was detected in any sample at 100 cm depth. The application rate used on the treatment area (2.75 m^2/PE) proved highly efficient, and already in the establishment year fulfilled most of India's new discharge limits for pH, TSS, BOD_5, COD, TP, and faecal coliforms. Only some NO_3–N values remained above the discharge limit. No significant differences were found between the plant species (willow, poplar, bamboo) in relation to wastewater treatment efficiency. In the municipal wastewater used, no concentrations of heavy metals above the legal limits were detected. Analyses of biomass and soil samples also showed no significant accumulation of heavy metals (Pb, Cd, Cr) during the testing period.

2.2. Regional Potential Analysis

The first year's results indicate that the pilot wfSRC system installed is achieving sufficient treatment efficiency, and, as plants and their root systems grow, performance should improve over time. The 6864 m^2 plot has treated approximately 250 m^3/d of domestic wastewater and served some 2500 people. The surface requirement and potential biomass yield of bamboo, willow, and poplar wfSRC systems were calculated for all known settlements in the study area (see Supplementary Table S1). The results for an example settlement of 2500 people and for the whole study region are presented in Table 3.

Table 3. Overview of application scenarios.

Scenarios		Bamboo [1] wfSRC		Willow [2] wfSRC		Poplar [3] wfSRC	
		Min.	Max.	Min.	Max.	Min.	Max.
land area (ha) required in 2036	village 2500 PE region 100%	0.69 108	2.33 364	0.69 108	4.28 669	0.69 108	6.43 1006
pot. biomass yield in DM in t/year	village 2500 PE region 100%	69 10,800	233 36,400	17 2700	107 16,725	21 3240	193 30,180
pot. resource recovery (TN) in kg/year	village 2500 PE region 100%	1256 196,560	4240 * 662,480	240 37,530	1487 232,478	40 6241	373 58,336
pot. resource recovery (TP) in kg/year	village 2500 PE region 100%	30 4737	103 16,020	12 1819	72 11,266	6 853	51 7976
pot. resource recovery (TK) in kg/year	village 2500 PE region 100%	897 140,400	3029 473,200	90 14,067	558 87,137	50 7808	465 72,734
carbon content (biomass) in t/year	village 2500 PE region 100%	30 4720	102 15,907	7 1162	46 7198	10 1520	91 14,160

[1] *Bamboo bambusa* (stem + leaves), [2] *Salix alba* (stem + leaves), [3] *Populus tremula* (stem only), * theoretical value only (higher than TN input) based on measured TN in harvested material and extrapolated biomass production.

While the recommended minimum land requirement for a 2500 PE village was 0.69 ha for all tree species, the maximum land requirements were 2.3 ha for bamboo, 4.3 ha for willow, and 6.4 ha for poplar. Data for a selected example village (Ksimpur Nagla) are shown in Figure 1.

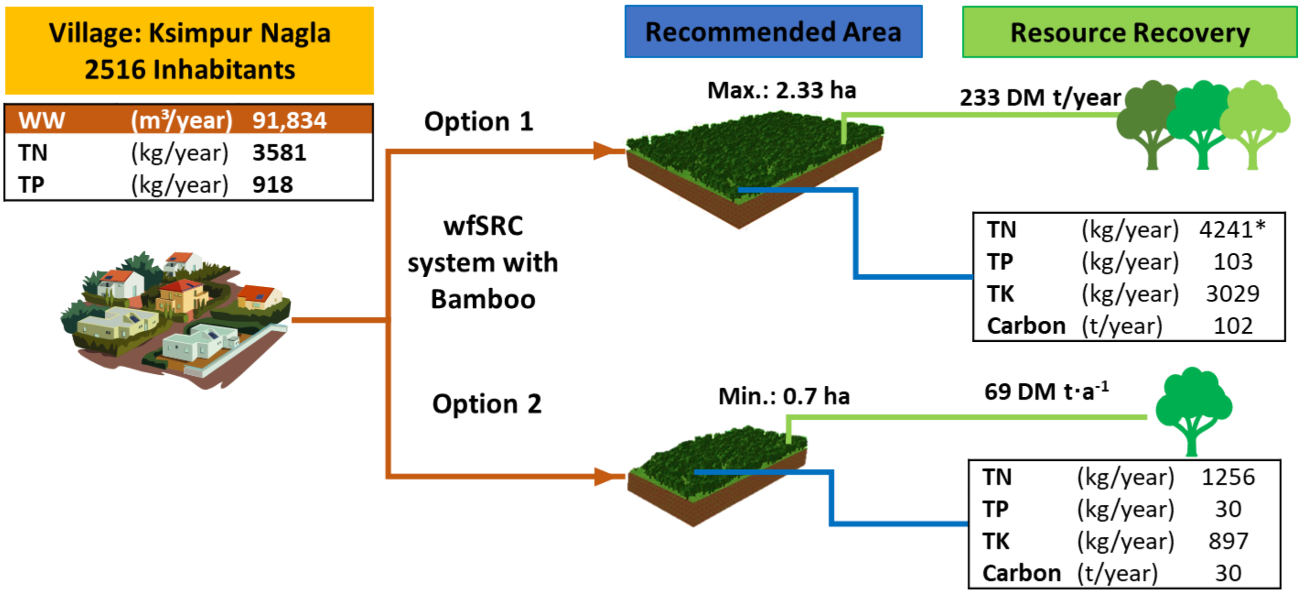

Figure 1. Potential scenarios for Ksimpur Nagla applying a bamboo wfSRC system, * theoretical value only (higher than TN input) based on measured TN in harvested material and extrapolated biomass production.

Based on estimated population growth, and assuming that all 184 settlements implement wfSRC systems to collect and treat 100% of their wastewater, the selected region would need a minimum of 63 hectares at present (Figure 2). This requirement would increase to 108 hectares by 2036. However, if maximum land area is considered, the land requirement would increase to 364 hectares for bamboo, 669 hectares for willow, and 1006 hectares for poplar wfSRC systems by 2036. This represents between 0.27% and 2.5% of the total area of the study region being required for wfSRC systems. It is important to note that this land, whilst acting as a wastewater treatment unit, is still highly productive and has the potential to generate revenues, enabling economic self-sufficiency.

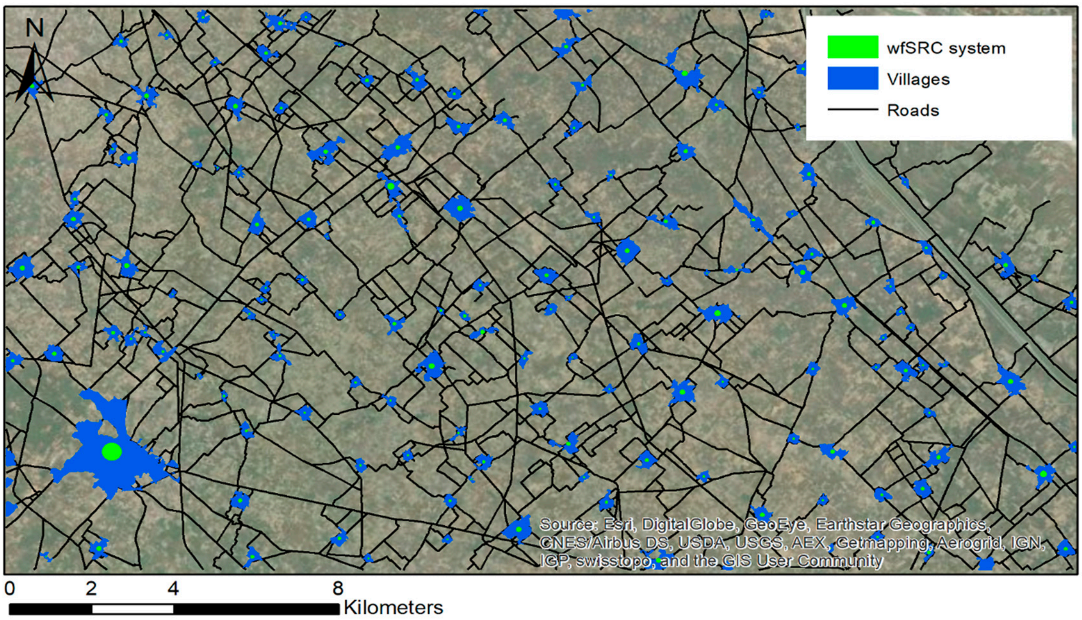

Figure 2. Potential map of wfSRC systems for the study region (minimum land area in 2021).

2.3. Economics of Treatment and Biomass Production in wfSRC Systems

The economics of wfSRC systems have been studied before and depend mainly on local cost factors [25,26]. A cost–benefit estimation for a standard wfSRC system (1 ha) using bamboo over a period of 25 years in the region of Aligarh (UP) was carried out, based on documented local data from the pilot plant. The calculation makes no claim to completeness and does not consider factors such as the cost of land, inflation, depreciation, or rising labour costs (see Supplementary Table S2). The total estimated costs (CAPEX and OPEX) are 4,657,500 INR (55,890 USD) over a period of 25 years, resulting in average annual costs of 318,740 INR (3825 USD), or 88 INR (1.05 USD) per person. This cost should be considered in light of potential income from sales of biomass. There are multiple market opportunities for the biomass that wfSRC systems produce, both in the material and bioenergy value chains. In addition to local uses such as fuel wood, charcoal, construction and furniture material, and paper pulp, there is a growing global interest in converting biomass material into other biofuel commodities (e.g., bioethanol, bio-CNG, char production).

At the pilot site in Aligarh, poplar, willow, and bamboo biomass has been successfully grown and harvested. Estimating the economic value of the biomass produced depends on the quality, type of use, and area of sale. In India, poplar biomass prices are around 5000 INR/t [27] and for willow between 3000 and 8000 INR/t [28,29]. Conditions for bamboo production seem to be very promising, as it is strongly supported by the Indian government (National Bamboo Mission) and some literature suggests biomass prices of more than 10,000 INR (124 USD) per ton of harvested bamboo [20]. Figure 3 shows a cost–benefit estimate for a bamboo-based wfSRC system under the given conditions in Aligarh over a 25-year period. At a conservative estimate of an average price of INR 8000/t DM bamboo biomass and 100 DM t/ha/year harvested, after the initial investment, an income of INR 800,000 (USD 9700) per hectare per year could be generated from the third year of cultivation. The total annual benefit is estimated at INR 465,199 (USD 5656) per hectare. This figure does not include other high-potential-income opportunities associated with various carbon trading schemes, although these should be included in future cost–benefit studies.

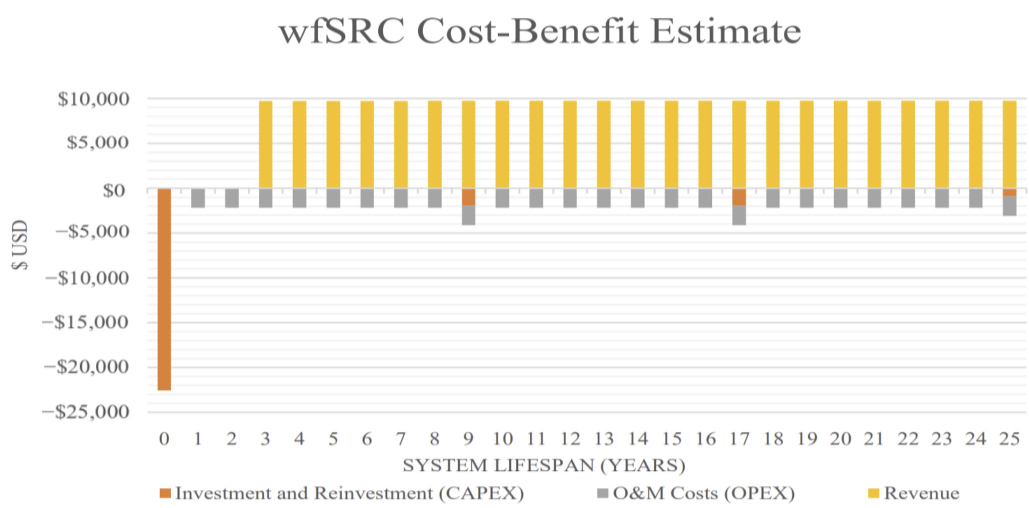

Figure 3. Cost–benefit estimate for a bamboo wfSRC system (1-ha) over 25 years.

It can be concluded that the pilot wfSRC system shows effective treatment and biomass production results for all species applied, and represents a suitable and very cost-effective option for improving the wastewater management, health care, and nutrient reuse in the selected region, as well as producing valuable biomass. To make the best possible use of the water and nutrient potential of existing wastewater, and fulfil the very ambitious current discharge limits, we recommend a wfSRC area of between 2.8 and 9.3 m^2/person in the

Aligarh region. Considering the data presented here, a direct application of wfSRC in the region of Aligarh seems to be possible and even recommended.

3. Discussion

All three species applied in the wfSRC system performed well. The HLR of 36.4 mm/day of wastewater observed exceeded the ETc rates and water demand of all three species, resulting in percolation water for groundwater recharge. This finding is in line with other studies which show that mature bamboo plantations in tropical climates do not exceed average ETc rates of 13 mm/day [30]. This suggests that the land requirements for local wfSRC systems vary depending on factors such as the local soil infiltration capacity, water requirements of the plants used, and the operational focus of users. If land availability is limited and/or groundwater recharge is the focus, maximizing wastewater loading rates to up to 70 mm/d may be possible under favourable conditions (soil characteristics), therefore reducing land requirements from 2.75 m^2/PE to 1.43 m^2/PE. On the other hand, to maximise water and nutrient reclamation, treatment efficiency, and ETc, and to minimise discharge into groundwater, an area of up to 26 m^2/PE in the case of poplar wfSRC systems is recommended.

The values of biomass produced are conservative estimates and are likely to increase in the coming years as the plants develop further. The bamboo wfSRC system presented the highest biomass production rate in the first year and promising forecasts for the second and third years [22]. Higher biomass yields will result in better income opportunities for operators, but also improve carbon sequestration and resource recovery. In addition, the already satisfactory treatment performance of the system will further improve over time as the root system develops. This will be particularly important for wfSRC systems taking in a close-to-maximum wastewater load, especially for NO_3–N and PO_4–P values. Our calculated TN removal values of more than 100% in the bamboo wfSRC scenario with maximum land requirements are theoretical values based on the measured TN in harvested material and extrapolated with the biomass production. As these values are higher than the total TN input from wastewater, in practice values below 100% are to be expected.

Plant selection for the pilot plant in Aligarh was based on the literature and the availability of local saplings; other tree and plant species or varieties may have better characteristics for use in regional wfSRC systems and may also be more attractive from an economic point of view, making such systems more sustainable. Plant selection is an important point to be considered for the establishment of new systems, and for further studies.

The data collected suggest that wfSRC systems offer similar treatment efficiency and scalability compared to other technical and natural wastewater treatment systems. However, they exhibit much higher potential for resource recovery and cost-effectiveness. By minimizing energy consumption, reducing chemical use, promoting carbon sequestration through plant growth, enhancing groundwater recharge, and supporting biodiversity, wfSRC systems have a significantly smaller environmental footprint compared to other systems. While they do require larger land areas than technical systems, their land requirements are similar to other natural systems. Moreover, through the production and marketing of selected valuable biomass streams, wfSRC systems cannot only cover investment and operating costs but also generate profits, and, consequently, income for local operators. In summary, wfSRC systems offer a nature-based, decentralized, and sustainable approach to wastewater treatment with several advantages, especially in regions with limited infrastructure.

The large scale implementation of wfSRC systems may obtain, treat, and valorise large amounts of wastewater from settlements in a region, which would have numerous positive environmental and economic effects but would at the same time reduce the availability of "free" sources of nutrients and irrigation water for local farmers. Moreover, the promising economic framework data for wfSRC systems may create a risk of distributional struggles and reduce the production of local food. To avoid such social conflicts, it is highly recommended that local stakeholders, including farmers, are involved from an early stage in the development and operation of community-based wfSRC systems. Additionally, the long-term application of wastewater for fertigation purposes should consider strategies for monitoring heavy metals and other pollutants in the wastewater and soil. Specific policies to treat, for example, industrial wastewater separately are recommended to reduce the build-up of potentially harmful substances.

Given the very similar climatic and socio-economic baseline conditions in many regions of the developing world, there appears to be an enormous global application potential for wfSRC systems.

4. Material and Methods

To assess the application potential of wfSRC systems for the selected region we (a) evaluated the performance of an operational local research plant; (b) assessed the situation in the selected region; (c) developed different application scenarios for wastewater management in the region; (d) performed a cost assessment considering investment as well as re-investment, operation and maintenance (O&M) costs, and potential income from biomass commercialisation over the lifetime of the system; and (e) estimated the application potential.

We collected real field data and analysed the data using IBM SPSS Statistics (version 19, IBM, Armonk, NY, USA). We calculated mean values and standard deviations to understand data characteristics. Further, a one-way analysis of variance (ANOVA) was performed to assess group differences when test assumptions were met (normal distribution and homogeneity of data).

4.1. Study Region

The selected study region has an area of about 400 km^2 and is located in Aligarh, in the north-western part of Uttar Pradesh in India (Figure 4). The region has an elevation of approximately 178 masl and is bound by the rivers Ganges and Yamuna. It is considered to be a notably fertile plain, sloping from the north to the south-east. The soil composition of the area varies from sands, loams, and silts to heavy clays that are all ill-drained and sometimes charged with salts. Aligarh's climate is classified as Cwa by the Köppen–Geiger system, being a monsoon-influenced, humid, subtropical climate. In summer, average temperatures lie between 28 and 38 °C, peaking in June. In winter, temperatures vary between 7 and 11 °C on average, with January having the lowest average temperature of the year (7.9 °C). The winter rainfall is considerably less than in summer. Between 900 and 1100 mm of precipitation falls annually in Aligarh, mostly during the monsoon season which starts in June and continues until early October [31].

Like many other Indian regions, the area is characterised by a rapidly growing population which has increased by more than 30% in the last decade [32]. It is a rural region but contains diverse settlements, towns, and villages. There are very limited available data about wastewater and other infrastructure in the area, so the data required for this study were collected through satellite imagery and site visits.

Based on Khurelbaatar et al. [33], the population of the study area was estimated to be 218,241 in 2021 and is projected to reach 391,324 by 2036. One small city (Atrauli), with about 65,000 inhabitants, and 184 villages were identified in the study area. More than 80% of the villages identified are classified as small settlements with less than 2500 inhabitants [33]. Wastewater production in the study region is reported to be between 80 and 125 Lcpd [34]. For this study, an average value of 100 Lcpd was assumed. Based on the calculated population size and the assumed wastewater production, total regional wastewater volumes of 7,965,797 m^3/year in 2021 and 14,283,326 m^3/year by 2036 were used as the basis for the scenarios. Taking into account the results of local wastewater analyses [35], which show an average BOD_5 of 102 mg/L, a TKN of 39 mg/L, and a TP of 10 mg/L, approximately 80 t/year of TP and 311 t/year of TKN are potentially available in the selected region as a local source of fertiliser, in addition to the irrigation water potential.

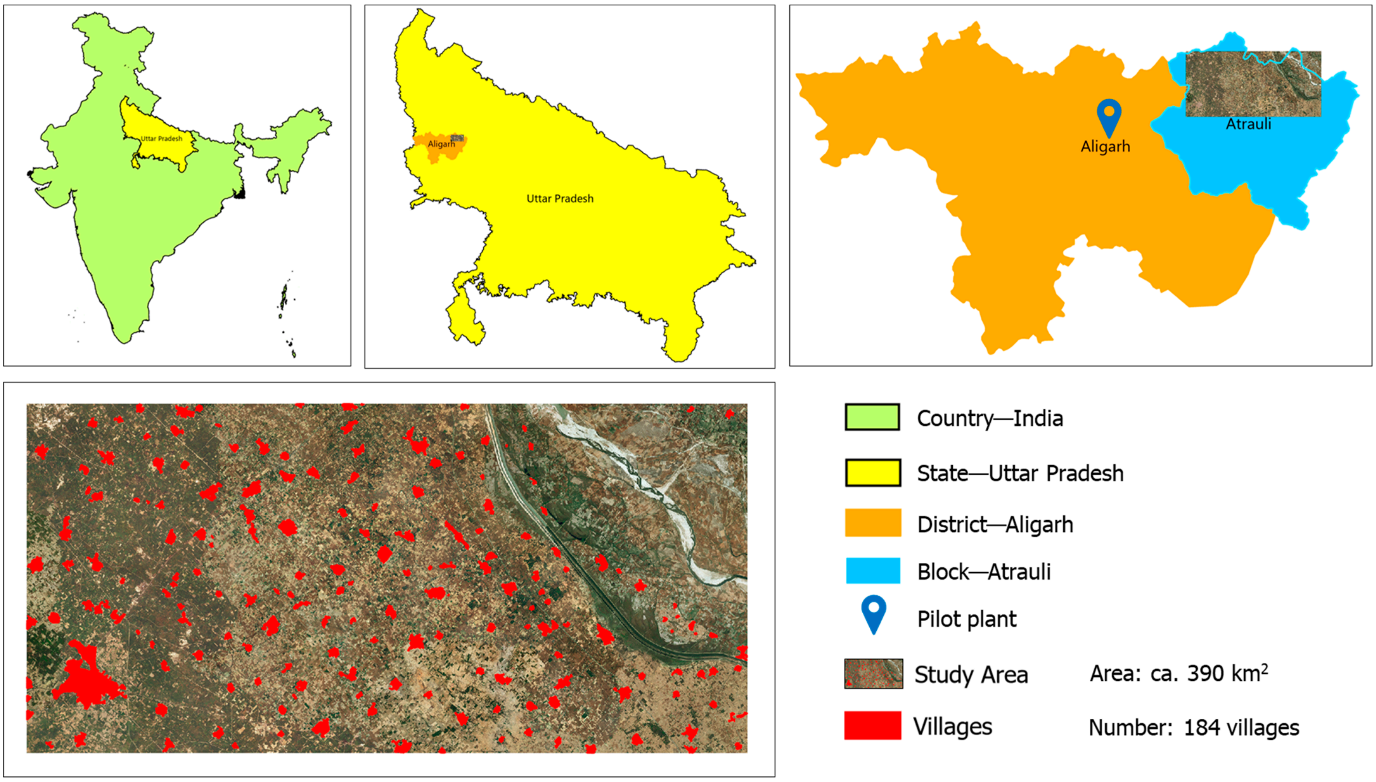

Figure 4. Location of the pilot plant and study region.

In the study region, wastewater is currently handled locally. Wastewater is transported via open drainage ditches from the houses in the settlements into nearby ponds, from where it evaporates, infiltrates the ground, or is used for agricultural irrigation. During the monsoon period, excess water and nutrients are discharged to open water bodies nearby. However, it is difficult to obtain reliable information on local wastewater treatment and reuse due to the lack of data and records. Existing regulations on wastewater management, water treatment, discharge, and reuse are described in the Environmental Protection Rules of the Ministry of Environment, Forest and Climate Change (MoE-FCC), which, in 2018, have been challenged in the National Green Tribunal (NGT). In 2019, the following sewage discharge standards were set for the whole country [36]: (pH 5.5–9; TSS 20 mg/L; BOD_5 10 mg/L; COD 50 mg/L; TKN 10 mg/L; Total phosphorus 1 mg/L; Faecal coliform (FC) 100 MPN (desirable), 230 MPN (permissible).

4.2. WfSRC Pilot Plant at AMU in Aligarh

4.2.1. Location and Conditions

The wfSRC pilot is located on the AMU premises in Aligarh at the research wastewater treatment complex (27°55′15″ N 78°03′39″ E). The trial is taking place on a 0.75-hectare plantation. Prior to establishing the plantation, the land had been used to cultivate crops (rape seed, wheat). Soil at the test site is characterised as very fine sandy loam (54.24% sand, 29.86% silt and 15.9% clay) according to the USDA classification. The very fine sand fraction comprises 48.8% of the total sand fraction. By applying the falling head method, a saturated hydraulic conductivity of 1.36×10^{-1} cm/s was measured. Groundwater table depth varies from 10 to 12 m. Rainfall and the evapotranspiration rate were measured and calculated over the first year of wastewater application (29 March 2022–28 March 2023).

4.2.2. System Design

The wfSRC system is divided into three sectors of 2.288 m^2 each (52 m × 27 m), in which species of willows, poplars, and bamboos are planted. Plant selection was based on a literature review and the local availability of saplings. In the poplar sector, one-year-old poplar (*Populus tremula*) trees were planted in January 2022 at a density of 10,000 plants/ha. In the willow sector, two one-year-old willow species (*Salix alba*, *Salix purpurae*) were planted in August 2021 at a density of 10,000 plants/ha. The bamboo sector was also planted in August 2021 with equal numbers of three different bamboo species (*Dendrocalamus strictus*, *Bambusa vulgaris*, *Bambusa bambos*) at a density of 20,000 plants/ha. An area of 25 m^2 in the bamboo sector was not planted and acted as a soil filtration unit for comparison. In addition, a reference area of 30 m^2, containing 15 plants of each species, receives water from a local drinking well to enable the comparison of plant parameters such as growth rate, accumulation of nutrients, and pollutants in the infiltrated water, biomass, and soil. Wastewater irrigation started on 29 March 2022 and will continue at least until 31 January 2024. The system has been designed to receive and treat mechanically pre-treated (screened) municipal wastewater from the AMU University facilities, with a capacity of 250 m^3/day, equivalent to 2500 PE. Crop evapotranspiration (ETc) was calculated as a product of Reference Evapotranspiration (ETo) and the Crop Coefficient (kc) in accordance with the FAO crop coefficient approach [37].

Water is fed to each sector in turn from a homogenisation tank via a PVC pipe manifold, using a submerged wastewater pump (5–7 kW). PVC water pipes, elbows, and valves form a standard irrigation system which is replicated in each sector. On each plot, 1 cm diameter holes are drilled into alternating sides of the distribution pipes at 50 cm intervals, allowing water to discharge into furrows, and the pipe is laid at a slope of 1% to ensure that water reaches the entire plot.

By manually opening and closing valves, each sector can be irrigated separately. Irrigation volumes are measured using an online flow meter, and once the planned flow in one sector is reached, the next sector is irrigated (approx. 250 m^3/d/sector).

4.2.3. Monitoring and Control Instrumentation

Wastewater irrigation is monitored using eight dielectric volumetric soil moisture, soil temperature, and salinity sensors (Sentek, Stepney, Australia, TriSCAN®) installed at depths of 10–130 cm, with 10 cm measuring the capacity intervals. By measuring Volumetric Water Content (resolution of 0.1 mm and variation of 0.1%) and salinity (EC at ±8.1%) at different depths, the type of irrigation water (rainwater or wastewater) and depth of penetration can be determined. The manufacturer's recommended calibration equation for loamy sand and sandy loam textures is being used, as local soil was classified as very fine sandy loam [38]. The distribution of the sensors is as follows: bamboo sector (2), willow sector (2), poplar sector (2), reference garden (1), and soil filtration area (1). Sensors in each sector are placed centrally and midway between water outlets and the sector border. Percolation water quality is monitored using 24 passive water traps, installed in January 2022 at 30, 90, and 200 cm depths, through which water is intercepted by a funnel as it trickles down and stored in a 300 mL container from which samples can be retrieved for analysis by means of a syringe. These traps are installed in sets of 3 on each of the planted sectors, at the depths specified. As an additional control, in August 2022, 8 vacuum-based water samplers were installed at 100 cm depth in each sector. These samplers consist of a 2-litre container, connected to a ceramic cell where a differential vacuum is induced to capture adjacent water and collect it every two weeks. The samplers are cleaned and checked for leaks (pressure test) on a monthly basis. An online camera (iMetos Crop View, Pessl Instruments, Weiz, Austria) and online weather station (iMetos 3.3s, Pessl Instruments) to monitor temperature, wind speed, radiation, rainfall, and vegetation development complete the system (Figure 5). The test site is protected by a wall to avoid any external interference, and all systems at the pilot plant are checked in a 14-day rhythm. The soil sensors, camera, and weather station are connected with a data logger, which has a built-in UMTS/CDMA modem for direct communication with the FieldClimate web platform. The system has a non-volatile internal memory and can store up to 8 MB of logged data (ca. 1 month). FieldClimate is used to gather, calculate, analyse, and graphically present the agro-meteorological data from measurements performed by the sensor in the test site.

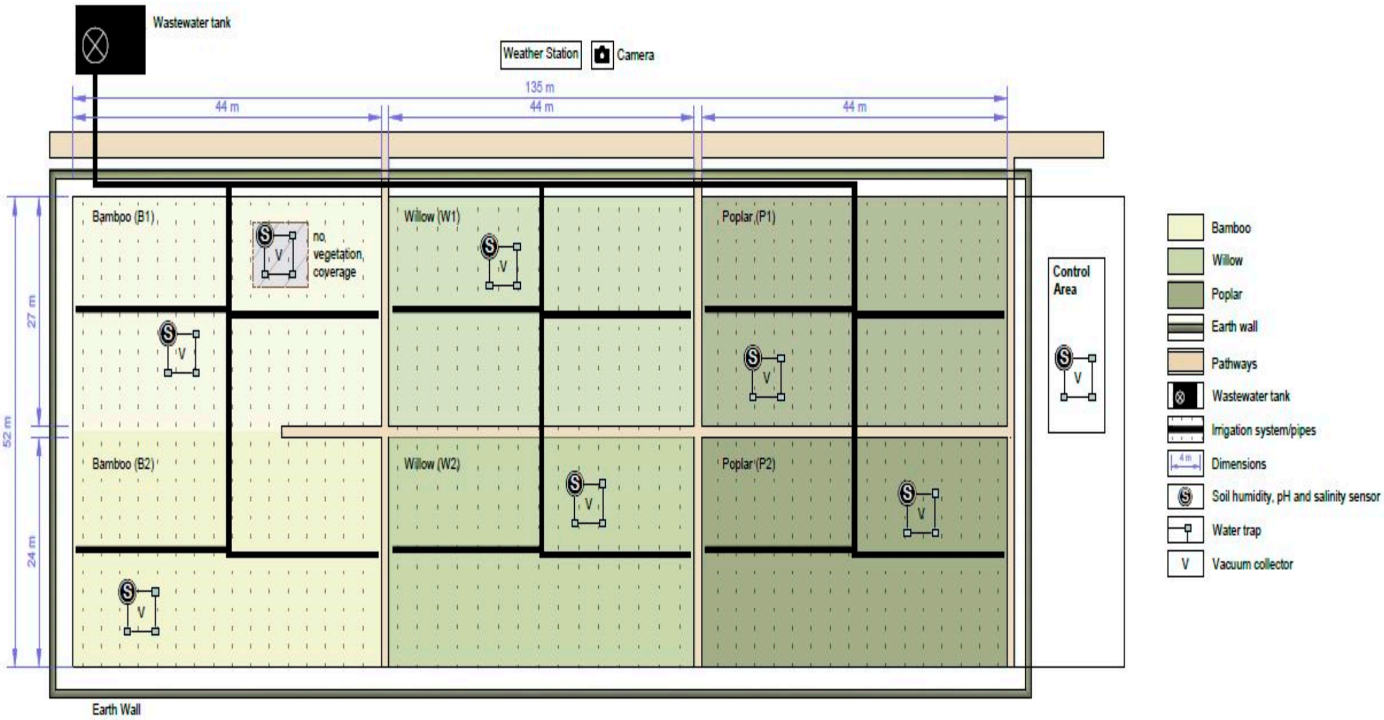

Figure 5. Design of the pilot wfSRC system at the AMU facilities in Aligarh.

4.2.4. Water Quality Analysis

The chemical and microbiological quality of the influent wastewater and of the deep percolation water which has exited the wfSRC system is analysed to assess treatment performance. Samples from the homogenisation tank (wastewater), percolation water (treated water), and a nearby well were collected and analysed in a 2-week rhythm for pH, electric conductivity, redox potential, and oxygen saturation using calibrated electrodes. Chemical oxygen demand (COD), biological oxygen demand (BOD_5), total nitrogen (TN), ammonium (NH_4–N), nitrate (NO_3–N), and orthophosphate (PO_4–P) were analysed following standard methods [39]. In addition, indicator bacteria of faecal contamination (FC), Total Coliforms (TC), and *E. coli* were analysed using the most probable number (MPN) method [40].

4.2.5. Plant Development, Biomass Yield, and Elemental Composition of Soil and Biomass

Plant physiology parameters including height, thickness, and number of shoots are measured in situ every 6 months, for 10 preselected and marked plants per sector, and in the reference garden to gain a general impression of plant development. The aboveground biomass of three randomly selected 1 m^2 plots of each sector was harvested manually and analysed 1.5 years after planting in January 2023 during the plant dormancy period. From each of these plant samples, leaves and mid-stem segments were collected to estimate dry biomass yield, excluding root biomass. The samples were weighed both on-site and in the lab to determine the fresh and dry mass of the biomass yield. Furthermore, biomass samples underwent analysis to determine their carbon to nitrogen (C/N) ratio using an Elementar Vario Macro Cube (Langenselbold, Germany) elemental analyser. The proximate analysis was conducted using thermogravimetry (TG) with a Mettler Toledo Thermogravimetric Analyser (TGA3—Gießen, Germany) coupled with a Differential Scanning Calorimeter (DSC+) for the determination of moisture, volatile matter, fixed carbon, and ash content. Additionally, the concentrations of various metals—including Na, Ca, Fe, Zn, Cd, Ni, Cr and Cu—and the nutrients P and K were measured using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES). Prior to measuring, plant aliquots of 0.1000–0.5000 g were dried, milled, and weighed, and placed into Teflon vessels. A solution of 4 mL of conc. HNO_3 and 2.00 mL H_2O_2 was added to the loaded vessels. The vessels were tightly closed, and the samples were digested in a microwave (Anton Paar Multiwave 3000, Graz, Austria) at 180 °C. After cooling down, the samples were transferred to 50 mL tubes, filled up to the 50 mL mark with Milli-Q water, and analysed using a Thermo Scientific ICAP 7000 series (Thermo Fisher Scientific, Waltham, MA, USA). Caloric values of harvested biomass samples were measured according to DIN EN 14774-2 for solid biofuels. The potential biomass yield of each species was extrapolated to 1 ha based on the measured data. The biomass yields were validated through values found in previous studies [18] and locally available data from plant nurseries.

The differences in the chemical composition of the harvested biomass and of collected soil samples from the different sectors were evaluated. A correlation analysis (Spearson correlation) was carried out to determine the relationship between TN and TP content in the harvested biomass and nutrient use efficiency.

4.2.6. Carbon Sequestration Potential

The intertwined processes of photosynthesis and respiration in willows, poplars, and bamboo plants found within the wfSRC environment facilitate rapid growth, while concurrently sequestering significant quantities of carbon dioxide (CO_2). This results in the development of a chemically diverse ligno-cellulosic resource that offers a broad range of applications. Bamboo has been documented to have annual carbon accumulation rates as high as 2–14 t/ha/year, which suggests it has significant potential for successful carbon farming [41].

4.3. GIS-Based Regional Upscaling and Scenario Development

To explore the potential impact of implementing wfSRC in India on a regional scale, the characteristics of the pilot plant were applied to the selected study region.

4.3.1. Considered Scenarios

In contrast to many projects that prioritise cities and urban areas for the implementation of water and wastewater infrastructure [3], this study focuses on the potential of the wfSRC system as a promising wastewater management solution for rural areas in India. While Khurelbaatar et al. [33] deals with the development of centralised and optimised wastewater management options in the same region, in this study, we suggested that each village would be equipped with its own wfSRC system. The region would have a 100% connection rate, meaning that the whole population would be connected to a wastewater collection system and thus to the wfSRC systems at a local level. For each village, the three different tree species for the wfSRC system were considered and the land requirements calculated based on the data collected from the demonstration plant at the AMU. A further set of scenarios was developed to take into account the potential to increase the area of the wfSRC for each tree species. In this option, while the hydraulic load remained the same, the area of the wfSRC was increased and adjusted to the potential evapotranspiration rate of the plant species (ETc) to minimise deep percolation from the system. This option therefore offers the advantage of maximizing the reuse efficiency of the wastewater, hence increasing the biomass yield while minimizing the risk of groundwater contamination.

4.3.2. Regional Upscaling and Potential Analysis

Two options for the land required for the wfSRC were estimated for each village. One option considered the recommended minimum footprint of the system, while the second option considered the maximum land requirement, which relies on ETc and irrigation load. Then, the biomass yield was estimated using the measured values for the three different species at the pilot plant and the estimated land requirements. The recovery rates of nitrogen, potassium, and phosphorus, and the potential for carbon sequestration were also calculated for each settlement and for the entire region, using the available wastewater volume and the average concentration measured at the pilot plant during the monitoring campaign.

4.3.3. Land Requirements

The pilot plant was designed for a hydraulic loading of 250 m^3/d, estimated to serve 2500 PE, taking into account the reported water consumption rate of 125 LPCD in Aligarh [42] and an estimated wastewater return co-efficiency of 0.8 [43]. As a result, the specific land requirement for the pilot plant was calculated as 6864 m^2/2500 PE = 2.75 m^2/PE. This specific land requirement is within the range of comparable natural-based solution systems. The assumed HLR of 33.3 mm/d of wastewater plus average precipitation at the site of 2.62 mm/d are less than the maximum loading rate of 73 mm/d, typically recommended for soils with hydraulic conductivity similar to that at the pilot plant [44]. Despite this relatively low HLR, the specific land requirement of the demonstrated pilot was used in the scenarios related to the recommended minimum land requirement. For the scenarios related to the recommended maximum land requirement, the ETc values for each plant were used. The ETc values reported for bamboo, willow, and poplar depend on factors such as climate, soil type, plant density, and, most importantly, water availability and fertilisation, but estimated average rates for the region are 11 mm/d, 6 mm/d, and 4 mm/d, respectively [45–47]. By matching the water demand of plants and the HLR, the deep percolation of water out of the wfSRC system would be minimised.

The recommended maximum land requirements are calculated as 9.3 m^2/PE for bamboo, 17.1 m^2/PE for willow, and 25.7 m^2/PE for poplar wfSRC systems. The minimum and maximum specific land requirements for each plant were then used to calculate the potential size of the wfSRC for each village in the study region. Then, the biomass yield was estimated using the measured values at the pilot plant and the estimated land requirements. The recovery rate of nitrogen, potassium, and phosphorus, and the potential for carbon sequestration were also estimated for each settlement and for the entire region based on average concentrations measured in the biomass samples at the pilot plant.

4.4. Economics of Treatment and Biomass Production in wfSRC Systems

Documented investment, reinvestment, and O&M costs of the pilot system in Aligarh were calculated as a reference cost for the region and are based on documented local data from that site. Only the basic parts of the system, which are needed to install and run a wfSRC system, were included; thus, sensors, weather stations, and monitoring equipment were left out of the CAPEX equation. The expected lifespan of wfSRC systems in the region was estimated at 25 years to calculate OPEX and the economic revenues they would provide. In addition, the economic value of the biomass yield was estimated. While the investment and O&M costs were estimated using real local data, the estimate of the economic return of the biomass harvest was carried out based on assumptions which drew on both local and international data. Additional income opportunities from carbon trading schemes like the clean development mechanism (CDM) were considered but not included in the estimations.

5. Conclusions and Recommendations

Balancing the needs of a growing population in India, which is producing more municipal wastewater, and limited finances, land, and water resources, requires that wastewater is managed efficiently and safely. This research project aims to contribute to the sustainable management of wastewater and resources in rural India through the innovative application of wfSRC systems, and it investigated and analysed the application potential of wfSRC systems for a specific region in India. The study demonstrated that implementing wfSRC systems using bamboo, willow, or poplar combined effective wastewater treatment performance with high biomass production, resulting in an excellent cost–benefit ratio under conditions in the Aligarh region (UP). Using this potential, not just in Uttar Pradesh but in many rural areas in India and worldwide could make a significant contribution to the urgently needed shift towards sustainable wastewater treatment, a bio-based circular economy, productive water and land management, health care, and regional development, addressing socio-economic and ecological concerns and complying with the UN's Sustainable Development Goals.

In addition to the strategy of focusing on large cities, the large-scale implementation of natural-based wastewater treatment systems such as wfSRC in rural areas could significantly reduce the diffuse pollution of river tributaries, and would make a valuable contribution to poverty reduction, regional value chain development, and water-related health problem reduction. In addition, other benefits for local biodiversity, soil fertility, carbon emission reduction, and carbon sequestration could be realised. Ultimately, the findings will inform strategies for addressing water and nutrient management issues, not only in India but also in regions facing comparable resource management challenges.

Implementing wfSRC systems requires the careful planning and consideration of various factors. The following recommendations and practical tips should be considered in future studies and in strategies for implementing wfSRC systems to manage wastewater irrigation related hazards:

- Site selection: select sites with suitable soil conditions (soil tests for filtration capacity, hydraulic conductivity, and drainage behaviour are recommended) and suitable climate (no sub-zero temperatures, sufficient sunlight).
- Species selection: select plant species that are well adapted to the local climate, can withstand the conditions created by the effluent, and have a high economic value.
- Planting density: determine this based on the selected species, soil quality, and available space. For bamboo, poplar, and willow, a density of 10,000/ha and an establishment period of 12 months without wastewater irrigation are recommended.
- Wastewater: ensure reliable supply of wastewater from a nearby source and assess BOD_5/COD and nutrient content and the presence of hazardous substances (e.g., heavy metals).
- A risk management plan and user manuals for wfSRC systems should be considered for each practical application including pest control, regular analysis of soil, biomass, and percolation water samples by an independent local institution to evaluate long-term effectiveness (data collection and monitoring programme).
- A regional platform including important local stakeholders should be established before large scale implementation to address issues regarding conflicting uses of land and wastewater and biomass commercialisation strategies.
- Training, capacity building, and awareness campaigns for users and stakeholders about both the potential and the environmental and health risks of utilizing wastewater in wfSRC systems are needed, and should be supported by demonstration projects in suitable regions to demonstrate their potential and feasibility.
- The long-term impacts of emerging and toxic compounds in wastewater on the environment and human health should be assessed through future research.
- Research on local short-rotation species for biomass production (e.g., breeding programmes) and research on alternative biomass use for high value applications should be intensified to further increase the income potential for operators of wfSRC systems.

One limitation of this study is that the data come from just one pilot site in India and therefore do not cover all climatic, geographic, and social conditions. Therefore, it is recommended that the treatment and biomass production estimates presented here are validated before use in other geographic locations.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/recycling8050075/s1, Table S1: Surface requirement and the potential biomass yield per settlement. Table S2: Cost overview bamboo WfSRC system in Aligarh (India).

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Data Availability Statement: The raw and processed data supporting the conclusion of this study will be made available by the authors, without undue reservation. Further enquiries should be directed to the corresponding author M.H., mhaenel@ttz-bremerhaven.de.

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