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# Terra Preta Sanitation: A Key Component for Sustainability in the Urban Environment

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**Abstract:** Terra Preta Sanitation (TPS) plays a key role in sustainable sanitation (SuSan) and in the sustainable management of resources such as water, energy, soil (agriculture), liquid and solid organic waste streams as well as in the development of sustainable urban environment and infrastructure systems. This paper discusses the advantages of, and requirements for, SuSan systems, focusing on TPS. Case studies showing the stepwise extension and re-development of conventional sanitation systems (CSS) using TPS technologies and system approaches are presented and discussed. Decentralized TPS systems integrated in sustainable urban resource management were implemented in the German cities of Hamburg and Berlin. The compilation of best practice examples and findings using the newest TPS systems illustrates the immense potential of this approach for the transformation from conventional to SuSan systems. For this purpose, the potential savings of drinking water resources and the recycling potential of nutrient components are quantified. The results strongly suggest the need to encourage the development and application of innovative decentralized sanitation technologies, urban infrastructures, and resource management systems that have TP as a key component.

**Keywords:** Terra Preta Sanitation; urban resource management; sustainable development; energy; water; organic waste; infrastructure

## 1. Introduction

The sustainable management and provision of vital resources such as water, energy, and food require integrated solutions that are based on interdisciplinary strategies. This is particularly the case in the urban environment where population densities and the inter-relation of different infrastructure sectors are more complex and challenging than in rural areas. Generally, intensive land use for buildings and infrastructures combined with high population densities in cities result in a physical disconnection between the areas where resources are consumed and those where the resulting waste or metabolites are disposed. In other cases, these resources are improperly managed, despite the fact that, following the principles of integrated urban resource management, waste should be regarded as a resource [1,2].

Buildings and people play a key role in the overall layout and function of urban infrastructure systems for resource management. Most of the urban social activity and resource consumption takes place in buildings as the design, type, and layout of the installed engineering services and infrastructure systems determine the overall performance and resource consumption over the entire lifecycle of a building as well as the required connecting urban infrastructure systems. This is particularly relevant for energy, water, and organic waste management [3–5].

Various new sanitation systems (NSS) have been developed within the last two decades in order to improve sanitary conditions, making them more sustainable in terms of water consumption and resource efficiency and thus providing alternatives to conventional sanitation systems (CSS) [6,7]. CSS are based on centralized drinking water supply and wastewater discharge and treatment systems. Amongst others the disadvantages of CSS include limitations in provision and discharge such as the mixing of sewage streams with different noxious factors (being a barrier for appropriate treatment and reuse) and the supply of drinking water only [5].

Different terminologies for NSS are for instance "resource oriented sanitation" (RoSa) [8], "ecological sanitation" (EcoSan) [9], "sustainable sanitation" (SuSan) [8], and "decentralized sanitation and reuse" [10]. The development of NSS marks a paradigm shift from end of pipe wastewater management systems to resource-oriented sanitation systems [2,11]. Separate collection, treatment and utilization of separated domestic wastewater flows aim to save freshwater, reuse water and to recover valuable nutrients. In many developed countries, NSS are considered more and more an alternative to CSS, but they are difficult to implement due to already existing CSS. In contrast, in developing countries, NSS are much more promising systems for the provision of safe and SuSan due to absence of CSS. New installations of CSS are generally not regarded as appropriate, for instance due to high investment costs, high water demand, electricity requirement and chemical auxiliaries required for their operation. Skilled labor for operation and maintenance is also an important limiting factor [12]. However, both NSS and CSS have possible interfaces to Terra Preta sanitation (TPS) and can contribute to Terra Preta (TP) production [13,14]. TPS systems incorporate the use of so-called effective microorganisms (EMs) for decentralized treatment of human faeces. EMs have been developed in Japan, are produced and distributed worldwide [15], and use a mixture of lactic acid bacteria, yeast and photosynthetic bacteria, actinomycetes, and other beneficial microorganisms [16]. Traditionally, indigenous microorganisms facilitating lactic acid fermentation have been collected in nature and applied in traditional farming methods, for example in Korea and Japan [17]. Quality control of lactic acid bacteria is important for appropriate composting of sewage sludge, food left over, and other organic waste based on microbiological principles and suitable for application in organic agriculture [18]. TPS systems can therefore play a key role in SuSan, resource management, including water, energy, soil fertility (food), liquid and solid organic waste streams, as well as the development of sustainable urban environments and infrastructure systems.

Ancient TPS systems originating from South America and Asia are based on dry toilet and organic waste management systems incorporating charcoal powder, lactic acid fermentation and composting processes. The first approaches to transform ancient TPS to contemporary sanitation systems focused on low-tech sanitation systems with dry toilets and manual mixing of human faeces with EMs, charcoal powder, stone powder and organic substances such as wood-chips. Simple dry toilet TPS systems can be set up easily with a simple bucket for defecation and collection of feces together with EMs, charcoal, and stone powder. After use, the bucket has to be closed with an airtight lid to facilitate odor control by anaerobic fermentation. When the bucket is full, the content has to be emptied for further treatment (composting). Urine has to be collected in a separate container. Such low-tech TPS systems are available for low-cost, are practically proven, easy to manage and maintain, and are accordingly a promising technology for applications in low-income areas without proper sanitation and water infrastructure systems [13,19]. However, dry toilet systems are generally not applicable in areas that are already equipped with water born sanitation systems and flush toilets [2]. Accordingly, TPS sanitation systems have to be generally combined with conventional user interfaces such as flush toilets and/or urinals to meet users' comfort criteria and facilitate potential wide spread applications, including in areas already equipped with CSS.

The main research questions discussed in the framework of this paper are therefore:

- Can case studies of realized and operated water born TPS systems, which are suitable to extend existing CSS, be identified and located?
- What are some feasible and applied technologies and systems approaches for TPS systems in areas with CSS and how do they work?
- What are the benefits and achievable savings of water born TPS in comparison with CSS?

This paper answers the research questions by identification of different system approaches and case studies of water born TPS systems. The specific applied technologies and system layouts are presented for the identified case studies. How the research findings can be implemented in current concepts for sustainable cities and so called "zero emission buildings" capable of producing energy, water, and other resources is also discussed. Such concepts and approaches are known for being new, flexible, and decentralized, thus paving the way towards sustainable resource management, remodeling the urban infrastructure and urban environments in future cities [5]. The specific objectives of sustainable urban resource management systems are to reduce the direct water footprint as much as possible, and to design and operate neighborhoods that process organic waste to nutrient rich soil, produce their own food, and have a net zero energy consumption [20].

TPS sanitation systems are compared with CSS through the examination of case studies, including various approaches for sustainable urban resource management concepts. The only water born decentralized TPS sanitation case studies that could be identified are operated in Hamburg and Berlin (Germany), in the framework of research and development (R&D) projects. The systems in Hamburg and Berlin are therefore serving as best practice examples for new flexible and decentralized approaches towards sustainable resource management and the remodeling of urban infrastructures and urban environments for future cities. The findings quantify and illustrate the savings and recycling potential of resources such as water and nutrients in the framework of TPS use. Furthermore, the "blue diversion" [21] sanitation system which has been developed in Switzerland and is applied in the framework of prototype field testing in Nairobi [22] has been identified as a very promising system approach for the development of water born TPS systems.

The existing R&D projects and sanitation systems in Hamburg, Nairobi and Berlin foster the exchange of the newest developments and compilation of best practice examples. The projects are based on the development of an innovative system configuration of single technologies, where the production and application of TP is a key element in the overall building and urban infrastructure concept. The project experiences and findings are accelerating the development of decentralized and building integrated services, engineering technologies, and infrastructure systems.

In order to discuss the processes and technological approaches for the TPS application, the current paper is divided into the following sections: Section 3.1, "Sustainable Sanitation in Urban Infrastructure Systems", explains the disadvantages of CSS and the requirements for SuSan systems. In Section 3.2, "Approaches for Integrated TPS Systems", two different SuSan system approaches that have TP production as a key component in their design are discussed and two possible extension stages of the conventional sanitation system are further illustrated. The first extension stage is based on the case study in Hamburg. The second extension stage is inspired by the case study in Nairobi. Section 3.3, "TPS System in the Botanical Garden Berlin", discusses a detailed system configuration for a third possible extension stage of CSS by using the example of the TPS system used at the Botanical Garden Berlin. The potential water savings and nutrient recovery of TPS systems are quantified using data from the two case studies in Berlin and Hamburg. Finally, in Section 4, "Conclusion", the advantages and disadvantages of the approaches of the specific systems as well as the challenges and perspectives for further development and integration of TPS systems in urban infrastructures are discussed.

## 2. Method

The application of TPS systems for the management of water, feces, organic wastes, and soil has emerged as an appropriate approach in the transition of CSS towards a more sustainable management of organic resources and soils in cities. To validate this thesis, the transition of existing sanitation systems into more SuSan systems based on the use of TPS systems was examined using case studies and analyzing their applicability and potential towards better sustainable urban resource management.

The selection criteria for case studies in the framework of this research were that the specific water born sanitation system needed to be suitable for the production of TP, that it could be used for the extension of CSS, and that it has been realized and is operating successfully. Accordingly, the following case studies of water born sanitation systems have been identified and selected as excellent examples:

(1) Public toilet facility at the central train station, Hamburg, Germany
(2) Private households, Nairobi, Kenya
(3) Toilet facilities for visitors and employees at the Botanical Garden of Berlin, Germany

This paper is based on the results obtained from the authors' research on TPS Systems and the latest theories for SuSan and urban resource management, considering the identified and selected case studies of water born TPS projects. The case studies provide excellent examples of the successful research, application, and development of water born TPS systems. The study focuses on the effective use and reuse of water, human feces, and organic wastes as well as the use and production of charcoal to produce fertile soil for urban horticulture and agriculture; the insights from case studies demonstrate the applicability and potential of the discussed TPS approaches.

The system approaches of the first two case studies in Hamburg and Nairobi are discussed and analyzed mainly according to qualitative criteria regarding their application potential for stepwise extension of CSS systems. The third case study in Berlin is discussed and analyzed according to qualitative, and as much as possible, quantitative criteria. In order to provide comprehensible information, the TPS system configuration, the specific applied technologies, their working principle and their performance are presented. Recently developed and validated tools are used for the calculation of resource flows and achievable savings of specific TPS technologies and systems in comparison with conventional sanitation technologies and systems. Water use and achievable savings are calculated with the Water Saving Calculator [23]. Nutrient flows and achievable savings are calculated with the Nutrient Calculator [24]. Quantitative and qualitative analysis and the potential for sustainable urban resource management of TPS have been carried out considering recent research findings and the authors' own research.

## 3. Results and Discussion

### *3.1. Sustainable Sanitation in Urban Infrastructure Systems*

CSS in urban areas are generally based on the centralized provision of drinking water and the centralized management of wastewater. Since the introduction of modern water and sanitation systems in the 19th century, the quality of such systems has been optimized to provide sufficient amounts of clean drinking water for a growing number of urban dwellers, and for non-residential uses. The wastewater management systems of cities have been optimized to reduce pollution on surface water bodies. Therefore, the current state-of-the-art wastewater treatment includes the enhanced treatment of wastewater and the elimination of nutrient components such as nitrogen and phosphorous [6].

The enhanced treatment of urban sewage requires more effort and is more energy intensive than conventional wastewater treatment. To reduce the environmental impact of enhanced sewage treatment and to reduce the net energy consumption for wastewater treatment, the anaerobic digestion of sewage sludge for the production of biogas and the combined generation of heat and power are practiced to a growing extent in various cities around the world. However, the liquid effluent of enhanced wastewater treatment systems still contains considerable amounts of nutrients, putting pressure on the ecology of receiving surface waters (depending on the population density and the natural cleaning capacity of the receiving water bodies) [2]. For further optimization of wastewater treatment and the elimination of the remaining nutrients, pharmaceutical and endocrine disruptors, and other micropollutants, additional treatment stages are required such as nano filtration, reverse osmosis, activated carbon absorption, and advanced oxidation processes [25,26].

While CSS are being constantly optimized to enhance their performance and reduce environmental impacts, the inherent disadvantages of CSS are significant barriers for the realization of water and resource efficient sanitation systems [3,4]. Centralized drinking water supply networks are designed for the provision of specific water quantities. Considerable reduction of water consumption and related flow rates (e.g., by population shrinkage and/or significant savings in water consumption) would result in higher stagnation rates and declining water quality in the supply networks. Furthermore, the cost of water supply is generally the largest component of drinking water fees and is determined by the fixed cost of the supply network. Savings in total drinking water consumption would therefore not result in a reduction of total costs, but would accordingly result in rising water prices per $m^3$. Considerable savings in total water consumption are related to the need for enhanced maintenance of the water supply network and restructuring of drinking water fee systems; they are therefore generally not, or only to a limited degree, of interest to drinking water supply companies [5].

Centralized sewerage systems and sewage treatment plants are also designed for the drainage and treatment of specific quantities of wastewater. Considerable reduction of wastewater production and related flow rates (e.g., by population shrinkage and/or significant savings in water consumption), would result in lower flow rates and limit the proper operation of drainage and treatment systems. Furthermore, the construction, operation, and maintenance of sewerage systems, the cost of which locks up investment capital for decades, is responsible for the largest component of wastewater fees. Savings in total wastewater production would therefore not result in a reduction of total costs and would result in the need for enhanced maintenance of the sewerage network and restructuring of the sewage fee systems. A significant reduction in urban water consumption and wastewater production is therefore generally not, or only to a limited degree, in the interest of waste water management companies [5].

In conventional urban sanitation systems, sewage streams with different properties and pollution levels are mixed and treated together. Such systems thus do not facilitate the separation and the appropriate treatment of sewage streams with different properties, which would facilitate the high quality reuse of the contained resources. In contrast to CSS, SuSan systems should be as resource efficient as possible. A high quality reuse of resources such as water, nutrients, energy, and carbon should be the objective. SuSan systems should also contribute to social and economic sustainability, be resilient and be easily adaptable to changing environments, demographic structures, and technical developments [2,5].

Accordingly, SuSan systems should contribute to the flexibility and resilience of urban infrastructure systems. Recent developments in decentralized sanitation systems, with the production of TP as a key component in the sanitation concept, offer many promising possibilities.

Different approaches for water born TPS systems are discussed in the following sections. Three different new and innovative TPS systems have been realized and operated in the framework of R&D pilot projects in Hamburg (Germany), Nairobi (Kenya), and Berlin (Germany). The case studies serve as a starting basis and excellent examples for different TPS sanitation system layout approaches, as well as the integration of TPS systems in urban infrastructure systems and in existing urban sanitation systems.

### *3.2. Approaches for Integrated TPS Systems*

Two different approaches for urban TPS systems are discussed in this section. These approaches involve various system development and expansion stages with different levels of integration of TPS in existing urban sanitation systems. System expansion stage 1 (Section 3.2.1.) considers a TPS system built and operated at a public toilet facility, at the central train station in Hamburg (Germany) [27]. System expansion stage 2 (Section 3.2.2.) is inspired by the "Diversion for Safe Sanitation" project, developed in Switzerland and operated in Nairobi (Kenya) [21] and represents a further extension of stage 1.

#### 3.2.1. TPS System Expansion Stage 1

The main objectives of the TPS System Expansion Stage 1, in operation since 2013 at a public toilet facility at the central train station in Hamburg, are the minimization of the drinking water demand for flush toilets and urinals, as well as the reuse of waste (now resources) from urinals and flush toilets to the greatest possible degree. This decentralized system is connected to both centralized drinking water supply and the urban sewerage system in the city. Similar to CSS, the washbasins are connected to the central drinking water supply network and the resulting greywater is discharged to the urban sewer system.

The installed TPS system consists of the following main components (Figure 1). The blackwater from water saving toilets is separated into a liquid and a solid phase using a wedge wire filter. The solid phase, consisting of feces and toilet paper, is stored in a plastic barrel where it is automatically mixed with small amounts of vegetable charcoal powder (Bio-Char) and liquid EMs. The resulting product undergoes an anaerobic pre-fermentation process that takes place in the barrel, and emits neither odor nor gas. Bio-Char is produced outside the building envelope by means of pyrolysis; EMs are also produced externally.

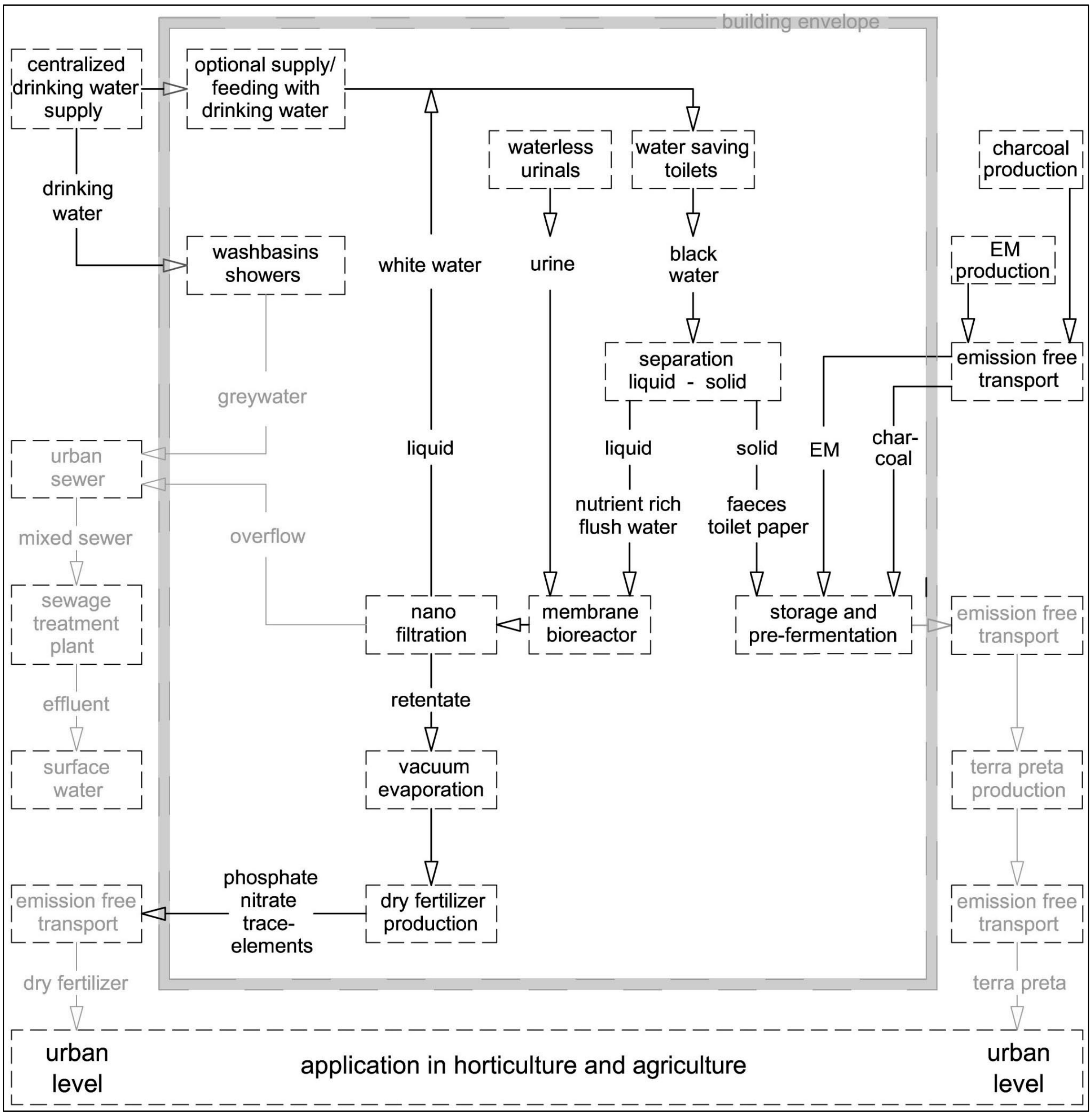
To meet the sustainability criteria, both products should be transported to the toilet facility using emission free transport. Also, the electric energy required for the operation of the pumps, treatment systems, and transport should be emission free and powered by renewable energy [1,2,5,20,28,29].

The pre-fermented mixture of feces, toilet paper, EMs and Bio-Char is transported for the production of TP at a location outside the building. After finalization of the TP production process, the resulting fertile soil is applied at the urban level in urban horticulture and/or agriculture.

The liquid phase from the water saving flush toilets is collected and processed in a membrane bioreactor (MBR) together with the undiluted urine from waterless urinals. The resulting permeate from the MBR treatment process undergoes nano filtration, becoming 'white water' now used as service water for flushing toilets. The overflow of the nano filtration permeate (the amount of 'white water' that exceeds the quantity required for toilet flushing) is discharged into the urban sewer system.

The nutrient rich retentate from the nano filtration process undergoes vacuum evaporation. The resulting product is a dry powder containing phosphate/phosphorous, nitrate and other elements such as potassium which can be used as a fertilizer. The dry fertilizer could be applied at the urban level for horticulture and agriculture.

**Figure 1.** Flowchart of Terra Preta Sanitation (TPS) System Expansion Stage 1, illustrating the connections between processes and/or technologies (in boxes) and resulting products (without boxes). The arrows indicate which processes and products are located inside, and which are located outside the building envelope (symbolized by the light grey square).




The described system facilitates significant savings in water consumption in the operation of the public toilet facility. For waterless urinals and flush toilets, the net water demand is 0. Accordingly, 100% savings in drinking water and related sewage fees for both urinals and flush toilets can result in significant cost savings for the system operator compared with CSS. However, savings in centrally operated infrastructure systems cannot be achieved due to the connection to the urban sewer system, the centralized drinking water supply, and the use of the related services.

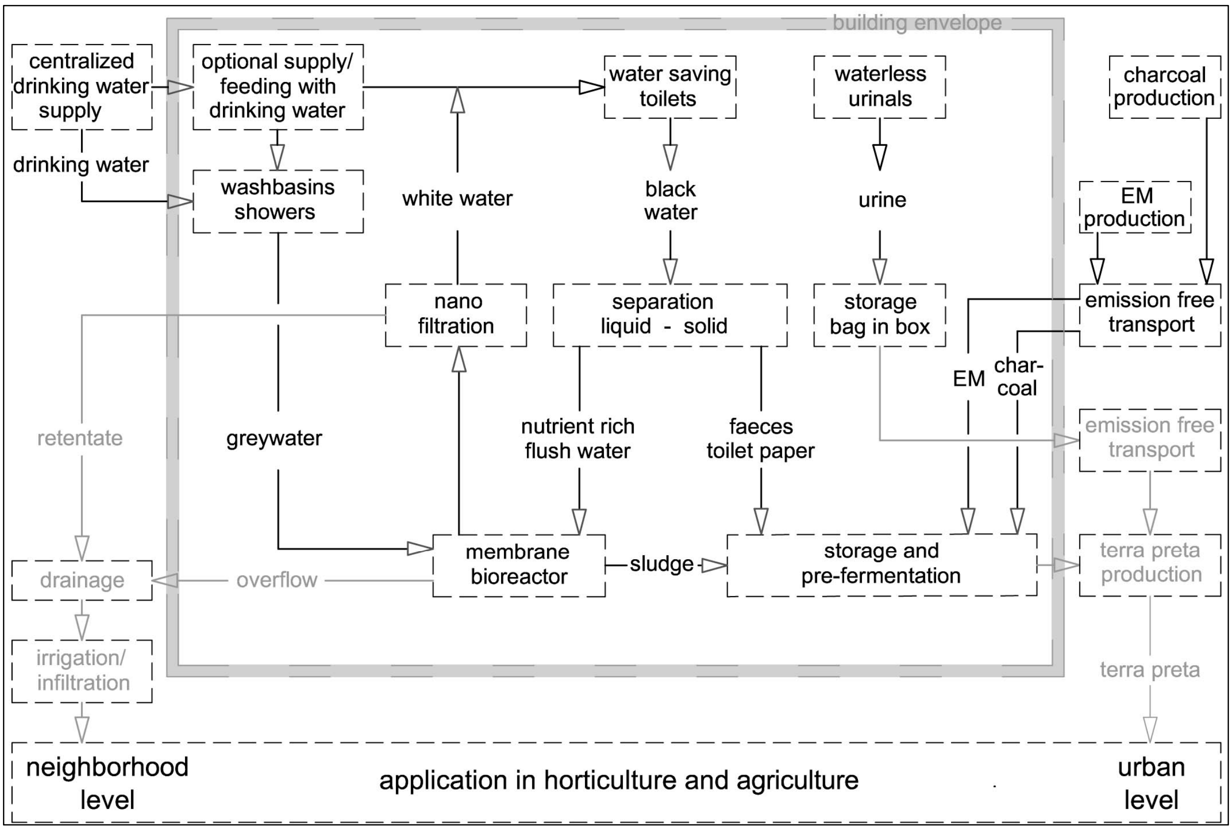
### 3.2.2. TPS System Expansion Stage 2

The main objectives of the TPS System Expansion Stage 2 are the minimization of the drinking water demand for washbasins, showers, flush toilets and urinals, as well as the reuse of resources from these facilities to the greatest possible degree. This decentralized system is connected to the centralized drinking water supply only when it is not connected to an urban sewerage system.

All wastewater is processed and reused within the TPS system as much as possible. The overflow and remaining liquid from wastewater treatment are then used for irrigation at the neighborhood level. The remaining solids from wastewater treatment are used for TP production and application in horticulture and/or agriculture in cities.

This TPS system consists of the following main components and configuration (Figure 2). Blackwater from water saving toilets is separated in a liquid and a solid phase using a wedge wire filter. The solid phase, consisting of feces and toilet paper, is stored together with dewatered sludge from a MBR in a plastic barrel where it is automatically mixed with small amounts of Bio-Char and EMs. The resulting product is pre-fermented in the barrel. The Bio-Char is produced outside the building envelope by means of pyrolysis; EMs are also produced externally. To meet the sustainability criteria, both products should be transported to the toilet facility using emission free transport [1,2,5,20,28,29].

**Figure 2.** Flowchart of TPS System expansion stage 2, inspired by the project "Diversion for Safe Sanitation" [21]. Flowchart illustrating the connections between processes and/or technologies (in boxes) and resulting products (without boxes), indicating also which processes and products are located inside and which are located outside the building envelope.




Urine from waterless urinals is collected in "bag-in-box" containers in the building. The collected urine and pre-fermented organic solids are transported regularly using emission free transport to a location outside the building for the production of TP. After finalization of the TP production process, the resulting fertile soil is applied at an urban level in urban horticulture and/or agriculture.

The liquid nutrient rich phase from the water saving flush toilets is collected and processed in a MBR together with greywater from washbasins and showers. The permeate from the MBR treatment process undergoes nano filtration. The resulting white water from the nano filtration process is used for washbasins, showers, and flushing toilets. The overflow from the MBR and the retentate from the nano filtration process are drained outside the building to be used for irrigation of horticulture or agriculture, and/or infiltration on properties or at the neighborhood level. Therefore, connection to the urban sewer is not required.

The additional freshwater required to supplement this almost closed TPS sanitation system is provided by connection to a centralized drinking water supply. However, this system could also be disconnected from both the urban sewage and the centralized drinking water supply networks. A disconnection is feasible if alternative water resources such as rainwater, groundwater or surface water provide the remaining water demand. If such water resources are used instead of drinking water, they should be connected to a membrane filtration system. After membrane filtration, the filtrate should undergo nano filtration to guarantee a sufficient water quality of the white water to be used for washbasins, showers, and toilet flushing [2,5].

### *3.3. TPS System of the TerraBoGa Project in the Botanic Garden Berlin*

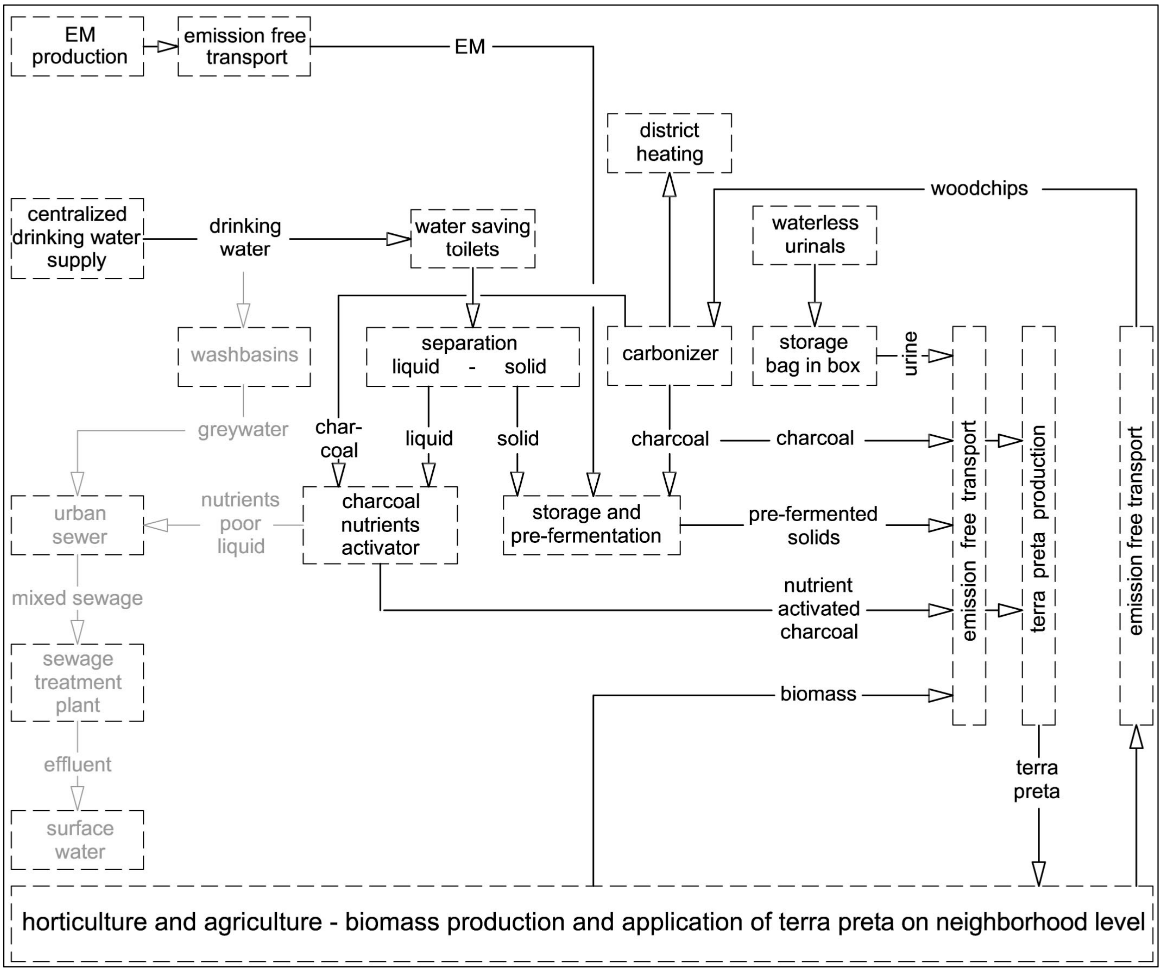
This chapter discusses the integrated TPS system, developed, operated, and evaluated in the framework of the interdisciplinary research project TerraBoGa at the Botanic Gardens in Berlin. The project is funded by the Berlin senate and co-financed by the EU. The initial project funding period of 3 years from September 2010 to August 2013 has been extended to June 2015 [28]. The project could be regarded as a combination and extension of TPS extension stages 1 and 2 (as explained above), which define building envelopes as the borders of the discussed decentralized TPS systems. However, the TPS system of the TerrabBoGa project has no clearly defined system border due to its urban character and because its system components are both inside and outside buildings. In line with the descriptions of the system expansion stages 1 and 2, the TerraBoGa TPS system is presented in the following Subsection 3.3.1. The project background, specific resource flows, and applied technologies are discussed in more detail in Subsections 3.3.2 and 3.3.3.

#### 3.3.1. TPS System at the TerraBoGa Project

The main objectives of the TPS system at the TerraBoGa project [28] are to manage, as effectively and efficiently as possible, the organic resources and nutrients from the garden as well as from a public toilet facility. Organics and nutrients have to be managed according to the principles of closed loop recycling economy, while also addressing energy aspects related to organic waste. The project is connected to both the urban sewer system and the centralized drinking water supply. Only wastewater from toilets is processed with the aim of reusing as much as possible the contained solids and nutrients in the TPS system. The greywater from washbasins and the remaining liquid from wastewater treatment are discharged in the urban sewer system and hence are not reused. In line with this, the urine, organic solids, and nutrients from the blackwater are used for TP production. The TP is applied in horticulture and/or agriculture at the neighborhood level within the botanical gardens.

This alternative TPS system consists of the following main components (Figure 3). Blackwater from water saving toilets is to be separated into a liquid and a solid phase using a wedge wire filter. The solid phase, consisting of feces and toilet paper, is stored in a plastic barrel, the bottom of which contains approximately 10 L of Bio-Char enriched with EMs. After the barrel is filled to its maximum level, the feces and toilet paper are finally covered with another 10 L of Bio-Char enriched with EMs, before the barrel is sealed airtight and replaced with en empty barrel.

**Figure 3.** Flowchart of TPS System of the TerraBoGa project, illustrating the connections between processes and/ or technologies (in boxes) and resulting products (without boxes). All processes except the steps after the discharge of grey water and liquids in the sewer system occur within the botanic garden.




The liquid phase is transported through a so-called "charcoal nutrients activator", a container filled with charcoal that absorbs as much of the dissolved nutrients and micro pollutants as possible. All components are located in an underground chamber next to the public toilet facility to facilitate the discharge of filtered blackwater due to free flow to the public sewer. An opening at the top of the chamber facilitates the removal and exchange of the barrel with pre-fermented solids and the charcoal loaded with nutrients. The Bio-Char is produced using pyrolysis in a "carbonizer" from woodchips, which are waste products from plants growing in the botanic garden. The resulting heat, a byproduct from the pyrolysis process, is used for district heating within the botanic garden. The EMs are produced externally. To meet sustainability criteria, all products should be transported using emission free transport [1,5,20,28].

Urine from waterless urinals is collected in "bag-in-box" containers in the public toilet facility. The collected urine is transported regularly using emission free transport for the production of fertile soil to a location within the botanic garden. The soil production incorporates urine, pre-fermented organic solids, nutrient activated charcoal from the blackwater treatment process, and biomass resulting from the operation of the botanic garden. The resulting TP is applied within the botanical gardens at a neighborhood level in horticulture and/or agriculture.

#### 3.3.2. Background and Resource Flows of the TerraBoGa TPS System

The aims of the TerraBoGa project are the optimal management of material flows to achieve higher resource efficiency through the optimization and redesign of the original organic waste management and sanitation systems. Furthermore, the project aims for the creation of added ecological, economical, and social values for the botanical gardens.

The TPS system of the TerraBoGa project is based on an integrated zero-emission approach. The goal is the realization of a closed loop recycling system for organic materials within the botanic garden. Energy aspects, such as energy efficiency and renewable energy production and utilization, are also addressed. However, both the disposal of organic wastes from the botanic garden as well as the provision of fertilizer and soil for the botanical gardens was originally managed by external service providers. Both disposal and provision were based on a fee system, representing a financial burden on the management of the botanic garden. In order to avoid financial loss and to generate additional values, a closed loop resource management system was designed with the aim of producing organic waste, fertilizer, and soil. The expensive external service provision system was replaced by liquid and solid organic waste processing systems. The function of the system is the local production of fertile black soil and TP, the on-site generation of Bio-Char and district heat, and the operation of the botanic garden itself.

The TerraBoGa project design and setup is fundamentally based on a resource flow analysis. The considered flows include 750 $m^3$ of green garden wastes and approximately 230 $m^3$ of long grass clippings per year. Also included are the organic wastes and nutrients from visitors and staff, which are generally left at the Botanical Garden Berlin in the form of excreta and discharged to the urban sewer system. In addition to the material recycling potential, analysis was also carried out on how the TerraBoGa project could contribute to a $CO_2$ neutral energy supply by using renewable fuels in the form of biomass.

Based on the results from the resource flow analysis, a combined heat and charcoal generator was commissioned and installed at the Botanical Garden Berlin, and started operation in October 2013. The working principle of the facility is that of pyrolysis as it produces fewer emissions than conventional combustion or charcoal burning systems. The Bio-Char is used thereafter for the pre-fermentation and filtration processes as well as for the production of TP. The generated heat is used for district heating at the neighborhood level for the buildings in the botanical gardens.

The TerraBoGa TPS system is also based on an integrated system approach. Addressed are the utilization of nutrients and organics from blackwater and urine for the production of fertile soil, and the sustainable use of other resources, particularly water. Efficient water use is realized by replacing old flush toilets and urinals with waterless urinals and water saving toilets. It is important to highlight that if such urinals and toilets were to be installed in all toilet facilities in the botanical gardens, approximately 2300 $m^3$ of drinking water could be saved per year, while the production of the same quantity of wastewater could be avoided. A financial calculation considering the fees for drinking water and wastewater revealed that, as of June 2014, about 5 Euros per $m^3$ (approximately 11,000 Euro) in drinking water and sewage fees could be saved annually.

Unfortunately, not all of the sanitation facilities in the TerraBoGa project could be remodeled. The conventional toilets and urinals were only replaced in some selected sanitation facilities for employees and visitors to the garden. In the sanitary facility for the gardeners, four toilets were replaced with water saving "GreenGain" [30] flush toilets (see Section 3.3.3 for detailed technology description). In the most frequented public toilet facility for visitors to the botanic garden, three flush urinals were replaced with waterless urinals (see Section 3.3.3, "*Technology Description of the TerraBoGa TPS System*" for detailed technology description). Furthermore, seven of the conventional flush toilets were replaced with seven water saving toilets in the same facility.

However, by installing water saving toilets and urinals it could also be successfully demonstrated that added values can be generated through the saving of resources and related savings in drinking water and sewage fees. Notwithstanding, the installation of water saving toilets and waterless urinals is only the first basic step to facilitate the separated collection of wastewater streams and the recycling of valuable ingredients such as organic material and nutrients.

The urine in the system is collected from waterless urinals by free flow in new and innovative non-ventilated bag-in-box containers [31] (see Section 3.3.3 for detailed technology description) to avoid nitrogen losses due to evaporation [32,33]. For further processing, the urine is discharged by free flow in movable plastic casks. The full casks are then transported to the composting facility of the botanic garden, where Bio-Char gravel is saturated with the urine to absorb and bond the contained nutrients. The urine activated Bio-Char is used at the same location and together with other ingredients for the production of TP.

The separation of solids from the blackwater originating from water saving toilets was first undertaken using a wedge wire filter, which was replaced with a spiral strainer in August 2013 (see Section 3.3.3 for detailed description of technology). The blackwater is transported by free flow through the strainer, which separates the liquid from the solid phase, which consists of feces and toilet paper, and is discharged in plastic barrels with a capacity of 60 L. The empty casks are filled with approximately 10 L of Bio-Char mixed with lactic acid producing EMs before they are connected to the separation system. The mixture of Bio-Char and EMs facilitates a proper pre-fermentation process of solids discharged in the barrel and avoids methane formation. When a cask is filled to 90%, the content is covered with another 10 L of the Bio-Char and EMs mixture before the cask is closed with a lid. Airtight sealing of the filled barrels is crucial to facilitate a proper lactic acid fermentation process.

The liquid phase, originating from the spiral strainer, is almost free of solids, but is rich in nutrients. To facilitate the separation of nutrients from the filtered blackwater, HATI GmbH plans to develop a

Bio-Char filter, a so-called "charcoal nutrient activator". The aim of the filter is to absorb the nutrients from the liquid phase before it is discharged by free flow into the urban sewer system.

According to intermediate project results and calculations, the TPS system can be used to recover the following resources from the installed toilets and urinals in the present design of the TerraBoGa system in the Botanical Garden Berlin:

- Nitrogen: 65 kg/a
- Phosphorous: 8 kg/a
- Urine: 10 $m^3$/a

However, if all toilet facilities for employees and visitors are remodeled and equipped with the TPS system, the amount of total resources that could be recovered from the installed toilets and urinals is largely improved:

- Nitrogen: 1.613 kg/a
- Phosphate 164 kg/a
- Urine: 211 $m^3$/a

After proper lactic acid fermentation, the nutrient rich Bio-Char, EMs, and feces mixture is used together with collected urine, charcoal, green garden wastes and grass clippings for the production of fertile black soil. In order to facilitate proper humification, the mixture has to undergo further fermentation and composting processes. The majority of this TP substrate produced in the Botanical Garden Berlin is used within the gardens for growing shrubs and flowering plants. Part of the TP is also used to grow fast growing timber (e.g., poplar, willow, paulownia tree), which can potentially be used as energy crops and for the production of Bio-Char.

Fast growing timber can be continuously harvested after an initial growing period of 4–5 years. The harvested timber is shredded and dried together with the cut copse and stem wood before it is further processed for the combined generation of charcoal and heat in a carbonization plant (see Section 3.3.3 for a detailed description of technology), which was commissioned and installed in the framework of the TerraBoGa research project. The aim of the TerraBoGa project is the continuous and unlimited operation of the TPS system and the carbonization plant, beyond the limited research project period of approximately 5 years. Therefore, the carbonization plant, the so-called "charcoal producing woodchip boiler" (CPWB) has been designed for the sustainable and efficient processing of biomass in the form of wood materials from the botanical gardens. The CPWB has a production rate capacity of 13 kg/h Bio-Char per 40 kg/h of woodchips with a 60 kW rated heat capacity. The produced heat is distributed via the water born district-heating network and used throughout the year for the heating of water and a neighboring paint shop.

The $CO_2$ emitted during the operation of conventional woodchip boilers is equal to the amount of $CO_2$ absorbed by the biomass during the growth process. Accordingly, the burning of biomass is a $CO_2$-neutral process. In contrast, during the operation of the "charcoal producing woodchips boiler", only the hydrogen contained in the biomass is used for the production of thermal energy where the chemically stable carbon is transformed to charcoal (Bio-Char). One kilogram of pure charcoal binds 3.6 kg of $CO_2$. Taking into account all of the wooden biomass from the botanical gardens that could be processed in the

CPWB, approximately 70 t/a of $CO_2$ could be permanently stored in the TP that is produced and used in the botanical gardens.

The financial funding of the TerraBoGa R&D project by German Federal Ministry of Education and Research (German: BMBF - Bundesministerium für Bildung und Forschung) is limited to June 2015 [28]. However, the aim of the CPWB and the complete applied TPS system, operated and evaluated in the framework of the TerraBoGa research project, is to contribute permanently to the efficient and sustainable use of renewable resources in the Botanical Garden Berlin. Furthermore, the aim of the project is to stimulate further development of TPS systems.

### 3.3.3. Technology Description of the TerraBoGa TPS System

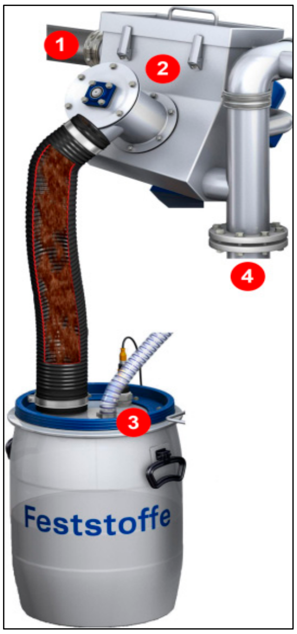
This section presents the specific technologies applied in the TPS systems considered in this paper.

*Water saving toilets*: Commercially available flush toilets or water closets generally use at least 6 liters of water per full flush, or even more. In contrast, the Omnia GreenGain toilet [30] (Figure 4), applied in the TerraBoGa project, only uses 3.5 liters per full flush (feces) and only 2 liters per half flush (urine). Due to the specific working principle with improved hydraulic properties, the toilet has very good flush and cleaning properties, even though the water consumption is comparably small. Due to the small water demand, additional savings can be achieved by using components with smaller dimensions in the systems for water supply and wastewater management.

**Figure 4.** Omnia GreenGain toilet [30].

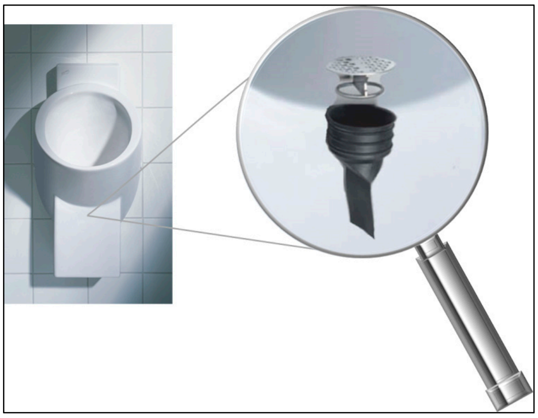
*Blackwater treatment*: Blackwater consists of a mixture of feces, urine, toilet paper, and flush water. For the separation of solids and liquids in blackwater, a separator consisting of a wedge wire filter is connected to the water saving flush toilets. An integrated spiral conveyor connected to the filter transports the separated solids to a storage tank (plastic barrel/cask) where they are mixed with Bio-Char and EMs. Figure 5 illustrates the main components of the blackwater separator.

**Figure 5.** Separator consisting of a wedge wire filter and spiral conveyor for the separation of liquids and solids [34]. The main components are: 1. Black water inflow; 2. Separator; 3. Cask for solid material (Bio-Char, feces, toilet paper); 4. Outlet of the liquid phase.



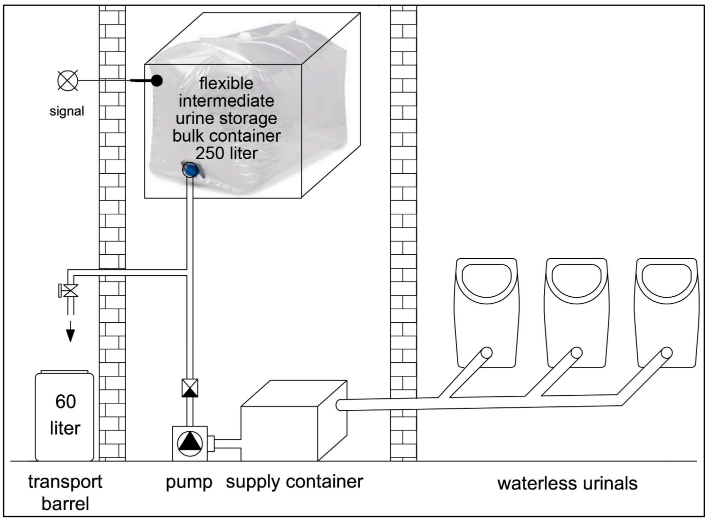

*Waterless urinals*: Many of the waterless urinals available on the market have odor traps, which are filled with liquids, allowing the urine to pass through while closing airtight, and thus trapping odor from the drainage system. In contrast, the waterless Centaurus [35] urinals (Figure 6) installed in the TerraBoGa project have odor traps that are based on a mechanical working principle. A special rubber siphon trap allows the urine to pass through but closes airtight and thus traps odor from the drainage system. No chemicals, no electricity, and no water are required for proper operation.

**Figure 6.** Centaurus waterless urinals and the special rubber siphon trap [35].



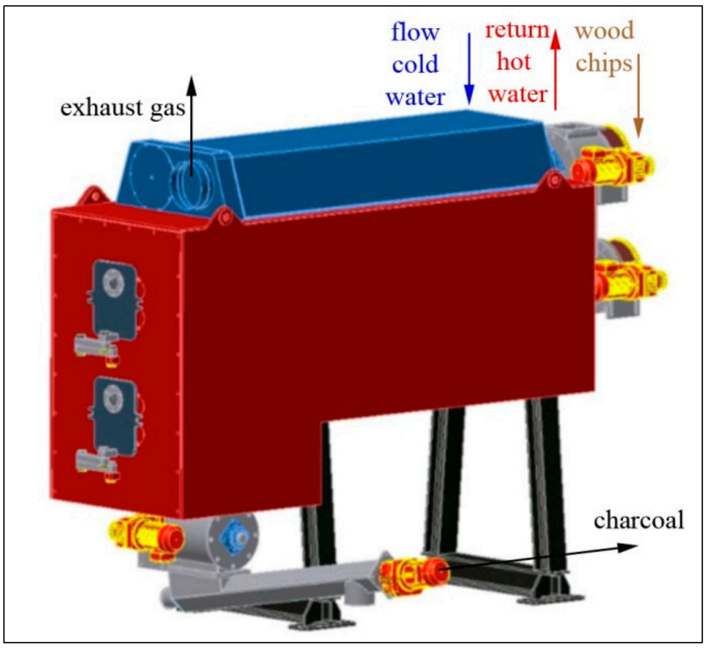
*Urine collection in "bag-in-box" system*: The urine from the waterless urinal is collected by free flow in a small container from where it is pumped into the flexible and non-ventilated bag-in-box container. This container, also known as an 'inliner', unfolds automatically when it is filled and folds in automatically when it is emptied. Accordingly, the contained fluid is independent from the filling level of the container that is always covered by the synthetic tank material and not exposed to air. The advantage of this container type is that nitrogen loss from the urine by evaporation can be effectively avoided. For transport and further processing to TP, the urine is discharged by free gravity flow from the bag-in-box tank with a capacity of 250 L to movable plastic casks with a capacity of 60 L (Figure 7).

**Figure 7.** Urine collection system, including waterless urinals, supply container, bag-in-box container (flexible intermediate bulk container) and barrel for the transport of urine.




*Carbonization of wood chips*: The carbonization of wooden biomass represents a promising technology, as it is effective in carbon dioxide free renewable energy production. Carbonization is safe, energy-effective, environment-friendly, and can contribute significantly to carbon dioxide storage. The 'charcoal producing woodchips boiler' installed in the framework of the TerraBoGa research project is a Biomacon biomass converter [36] (Figure 8). This technology can generate from 40 kg of woodchips, 13 kg of Bio-Char, and with a 60 kW rated heat capacity per hour. Resources required for operation and application of generated products are found within the botanical gardens.

**Figure 8.** Biomacon biomass converter [36] applied in the TerraBoGa research project.



### *3.4. Quantification of Potential Water Savings and Nutrient Recovery Potential of TPS Systems*

The water saving potential of urban and domestic buildings can be calculated using different software programs such as WiseWater [6,37], and could also be estimated for different user groups and domestic environments with agent based models [38]. However, such programs and models cannot be used for the estimation of the water saving and nutrient recovery potential of the non-domestic TPS systems described in the previous chapters. Therefore, the achievable water savings and nutrient recovery potentials of the discussed TPS need to be calculated with another tool such as the "Water Saving Calculator" (WSC) [23] which has been developed for non-domestic environments.

Using the example of the sustainable TPS sanitation facility at the central train station in Hamburg (Section 3.2.1 extension stage 1), the calculation of the water saving and nutrient recovery potential is subsequently described. The applied technologies of toilets and urinals, as well as the collection and storage systems for further processing of collected resources, are similar to the technologies applied in the TerraBoGa TPS system described in Section 3.3.3, "*Technology Description of the TerraBoGa TPS System*".

The water and nutrient flows of the sanitation facility at the central train station in Hamburg have been investigated using the WSC [23]. The accuracy of the WSC, considering different simulated scenarios, has also been validated by measuring the real water use and counting the number of visitors of the public toilet facility. The simulations were executed considering the following preconditions:

- 34,400 visitors or toilet users per year
- 300 working days per year
- Similar numbers of female and male visitors or toilet users
- 80% of the visitors use the toilets only for urination.
- 20% of the visitors use the toilets also for bowel evacuation (fecal)
- In the case of bowel evacuation, the full flush is used on average 1.8 times per toilet use (because the full flush maybe used twice for bowel evacuation).
- Female visitors use the half flush option after urination in 70% of the cases. In the remaining 30%, the full flush option is used (because full flush may be used after urination).
- Male visitors use the half flush option after urination in 50% of the cases. In the other 50%, the full flush option is used (because full flush may be used after urination).
- 20% of male visitors use flush toilets installed in closed cabins for urination instead of waterless urinals.

The regular cleaning of the toilets and urinals has been also considered in the simulation processes. The number of cleaning processes and quantity of water used are listed in Table 1.

In order to facilitate the quantification of water use and potential water savings, which could be achieved with different technology options, simulations were executed with different toilet types. In the case of water closets, two technology options were investigated: (1) conventional water closets (WCs) with 6 and 4 L per full and half flush and (2) water-saving WCs with 3.5 and 2 L per full and half flush. In the case of urinals, two technology options were also considered in the simulations: (1) conventional urinals with 4 liters per flush and (2) waterless urinals. Considering the described basic conditions, the water consumption and the achievable savings with different technology options have been calculated for approximately 34,000 visitors over a period of one year (Tables 2 and 3).

**Table 1.** Quantification of user interfaces, cleaning processes, and number of required flushes for the cleaning of water closets and urinals.

| | |
|---|---|
| **Water Closets** | |
| Number of installed water closets | 9 |
| Number of the cleaning processes per day | 6 |
| Number of full flushes per cleaning process | 1 |
| **Urinals** | |
| Number of urinals | 3 |
| Frequency of the cleaning processes per day | 3 |
| Number of flushes per cleaning process | 1 |

**Table 2.** Quantification of water consumption and achievable monetary savings in drinking water and sewage fees during one year for different WC types in the investigated public toilet facility in Hamburg, Germany (nine WCs).

| Water Consumption and Achievable Savings for Different WC Types and Uses (nine WCs) | Water Saving WC (3,5/2 L) | Standard WC (6/4 L) |
|---|---|---|
| Water consumption for WC flushing | 85,000 L | 151,000 L |
| Water consumption for WC cleaning | 57,000 L | 97,000 L |
| Total water consumption for WC flushing & cleaning | 142,000 L | 248,000 L |
| Achievable savings in water consumption | 106,000 L | 0 L |
| Achievable savings drinking water and sewage fee | 409 Euro | 0 Euro |

**Table 3.** Quantification of water consumption and achievable monetary savings in drinking water and sewage fees during one year for different urinal types in the investigated public toilet facility in Hamburg, Germany (three urinals).

| Water Consumption and Achievable Savings for Different Urinal Types and Uses (three urinals) | Waterless Urinal | Standard Urinal (4 L) |
|---|---|---|
| Water consumption for urinal flushing | 0 L | 44,000 L |
| Water consumption for urinal cleaning | 0 L | 11,000 L |
| Total water consumption for urinal flushing & cleaning | 0 L | 55,000 L |
| Achievable savings in water consumption | 55,000 L | 0 L |
| Achievable savings drinking water and sewage fee | 209 Euro | 0 Euro |

The simulation results show that the water consumption for the cleaning of water closets in the investigated toilet facilities is very high. Approximately 106 $m^3$ water could be saved with the nine water saving WCs compared with the similar amount of standard WCs. Considering the drinking water and sewage fees of 3.86 Euro/$m^3$ (gross including tax) [39], approximately 409 Euro per year could be saved with nine water saving WCs. The additional investment cost for the installation of a water saving WC compared with a standard WC is approximately 300 Euros. Accordingly, the additional investment costs for the installation of nine water saving toilets could be repaid in less than 7 years. In real budgetary terms, this scheme would generate financial savings compared with conventional WCs and urinals after a period of 7 years. However, the scheme would also work as a financial barrier for the installation of new or better designed systems within a period of 7 years.

Compared with standard urinals, 55 $m^3$ of water could be saved with three waterless urinals, and the additional investment costs for the waterless urinals could also be repaid in approximately 6 years. Considering the maintenance and repairs of the urinals, particularly regarding the accident-sensitive flushing valves, it is expected that a saving could be achieved in a much shorter period of approximately 2 years [40]. Achievable savings in drinking water and sewage fees of 409 and 209 Euros can finance the investment costs for water saving WCs and waterless urinals. The achievable savings are relatively small for operators but there are other environmental savings, that are not as easily quantified but are just as important.

According to the urination and bowel evacuation production, considerable amounts of nutrient compounds enter the sanitation system. The estimated number of discharges is listed in Table 4. The nutrient compounds content of human urine and feces in Germany according to the German Association of the water industry (DWA, Deutsche Vereinigung für Wasserwirtschaft) [41] is listed in Table 5.

**Table 4.** Number of urine and bowel discharges of 34,000 visitors per year.

| Title | Title |
|---|---|
| Number of discharges urine female | 12,757 |
| Number of discharges urine male | 12,757 |
| Number of bowel discharges female | 3439 |
| Number of bowel discharges male | 3439 |

**Table 5.** Specific organic dry residue (ODR), biological oxygen demand (BOD), chemical oxygen demand (COD), and nutrient content of human (female and male) urine and feces in one day in Germany.

| Content in Feces (Female & Male) | Gram per Person & Day | Daily Content of Urine (Female & Male) | Gram per Person & Day |
|---|---|---|---|
| ODR | 35 | OTR | 0 |
| BOD5 | 20 | BOD | 5 |
| COD | 60 | COD | 10 |
| Nitrogen | 1,5 | N | 10,4 |
| Phosphorous | 0,5 | P | 1 |
| Potassium | 7,7 | K | 2,5 |
| Sulfur | 0,2 | S | 0,7 |

The calculation of the potential amounts of nutrient compounds that could be collected from the investigated public toilet facility of the central train station in Hamburg has been performed using the "Nutrient Calculator". This calculator is a Microsoft Excel based program developed by Hati GmbH [24] in the framework of the TerraBoGa research project [28].

The Nutrient Calculator takes into account that female toilet visitors use the water closet for urination on average two times more than male visitors. The reason is that male visitors use also urinals for urination while the female visitors do not use urinals at all. Furthermore, the different toilet paper quantity produced by male and female users [42] is also addressed in the potential nutrient calculation. The quantities of specific nutrient components as well as the associated volumes of urine and feces in the toilet facility have been calculated using this software application and are listed in Table 6.

**Table 6.** Amounts of specific nutrients and quantities or urine and feces supplied to the public toilet facility in Hamburg per year using the "Nutrient Calculator".

| **Supply of Nutrients per Year** | **kg** |
|---|---|
| ODR | 333.3 |
| BOD5 | 219.7 |
| COD | 465.8 |
| Nitrogen | 65.6 |
| Phosphorous | 8.8 |
| Potassium | 18.1 |
| Sulfur | 5.1 |
| **Quantity per year** | **$m^3$** |
| Volume urine | 7.3 |
| Volume feces | 1.0 |

In the TerraBoGa project, approximately 5% (volume) of the urine and feces has been considered to enhance the nutrient balance of TP. Accordingly, approximately 170 $m^3$ of high quality TP could be produced with the collected excreta from the public toilet facility per year.

According to the high volume content (95%) of organic waste required to produce TP, all organic residues from the total organic wastes occurring in urban areas (households and other sources including green areas) could be recycled and used for the purpose. Similar to the system approach developed in the TerraBoGa project, specific portions of organic materials with appropriate properties (such as low water content) can be used for charcoal production, facilitating the sustainable local production of all required TP components.

## 4. Conclusions

Applied R&D projects with water born TPS systems in the public toilet facility at the central train station Hamburg (Germany) and the toilet facilities for visitors and employees at the Botanical Garden Berlin (Germany) have shown that CSS optimization can be realized relatively easily. It has been illustrated that specific modules and technologies of CSS can be exchanged. Furthermore, CSS can be extended with decentralized, modular, and small-scale water born TPS systems. Accordingly, the future development of TPS systems should be based on a modular approach that is open to the application of different technologies and adapted to the specific local basic conditions, requirements, and on-going technological developments.

Based on the results of experiences with water born resilient TPS systems in Berlin and Hamburg, it can be concluded that such systems can be successfully implemented in existing CSS and urban infrastructure systems. Such CSS extended with TPS systems facilitate the sustainable management of water, wastewater, energy, organic waste, and urban green waste. The pilot projects also illustrate that investment costs for the extension of CSS can be partly financed with achievable savings in water and sewage fees. This unique and economical recycling concept closes the gap between organic resource management and energy provision and is a very important contribution to the further development and success of sustainable TPS systems.

According to the findings in this paper, TPS systems could contribute significantly to the efficient use and sustainable management of resources such as water and biomass as well as the sustainable management of liquid and solid organic waste. On the other hand, integrated system approaches incorporating energy components in sanitation such as the production of charcoal could contribute to renewable energy production and the effective storage (and use) of $CO_2$.

There are challenges related to the implementation of water born TPS systems in areas, which are already equipped with CSS based on centralized water and sanitation infrastructures. However, low-tech dry TPS systems are a very promising approach to achieving the Millennium Development Goals of providing safe and appropriate sanitation to all dwellers. Due to their nature, TPS systems can also be applied in dry toilet systems operated with a simple dry bucket without the need for any water supply [13,14]. An outstanding example demonstrating that even decentralized water borne SuSan systems are applicable in informal settlements and areas without CSS is the "blue diversion", which has been successfully applied in Nairobi (Kenya) [21,22].

The required charcoal production could be realized with low-tech pyrolysis (biochar) stoves, which are available for a low cost and can also be produced locally, e.g., from recycled cans. Accordingly, the reduction of emissions in the framework of food preparation with timber stoves could be combined with the provision of safe sanitation and the creation of additional values by facilitating fertile black soil production for local agriculture. Due to the nature of lactic acid fermentation processes, such low cost TPS systems are safe as they facilitate the hygienization of feces and disrupt the emission of odors.

The TerraBoGa project at the Botanical Garden Berlin has succeeded in addressing integrated approaches for sanitation, energy provision, and soil quality improvement. It may even be able to contribute to facilitating climate change adaptation and mitigation as well as food security through the TPS system pilot project at the Botanical Garden Berlin.

The success of the TerraBoGa TPS system is in part based on the fact that the system is installed in the botanical gardens where there is a close supply of woodchips to produce biochar and to apply TP in horticulture and agriculture. The system would not work as efficiently if it was installed in a place without a close supply of woodchips and no green areas for the application of TP and would therefore require transportation of both woodchips and TP. Accordingly, and consistent with sustainable development principles, the future development of TPS systems should incorporate the nearby production of woodchips and application of TP, and concepts for emission free transport. Based on the research project's findings, it can be concluded that the TPS system is very promising as a possible solution to the problems related to the provision of safe and affordable sanitation while also solving issues related to CSS.

In light of the above, applied research projects that consider TPS systems, such as the TerraBoGa, are critical in promoting public awareness in aspects related to sustainable development, as they may also lead to discussions on energy efficiency and the economy of recycling. This could in turn improve the exposure of resource efficiency, which is unfortunately generally neglected in public discussions. However, Bio-Char and TP have been discussed extensively in both scientific fields and the media with positive results.

It is important to highlight that the execution of applied research projects that identify and investigate the possibilities for the stepwise implementation of TPS systems, remodeling and/or rebuilding conventional urban sanitation systems will be very important for the further development of sustainable urban sanitation. Nevertheless, due to the high fixed costs for operation and maintenance, the remodeling of existing centralized infrastructures for water management and sanitation is still a challenging task.

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## Author Contributions

This paper was primarily produced by the main author Thorsten Schuetze based on his own research and investigations in the identified locations in Germany as cited. Moreover, his expertise and large experience in the use of novel approaches for sustainable sanitation was incorporated and became crucial for the development and integration of the manuscript contents and relevance. The co-author, Vicente Santiago-Fandiño, also with experience on sustainable sanitation participated by revising, refining and providing comments to the draft manuscript as well as incorporating information when deemed necessary. The interaction with the main author was close and interactive at all times ensuring a successful collaboration until the final production of the paper.

## Conflicts of Interest

The authors declare no conflict of interest.

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