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# Wet coffee processing wastewater treatment by using an integrated constructed wetland

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## ABSTRACT

A wet coffee processing plant is an agro-industry that generates huge volumes of medium to high-strength wastewater that needs proper treatment before being released into the environment. Low-income countries must adopt an integrated, easily adaptable, and eco-friendly system to treat such effluent. The objective of this study was to treat wet coffee processing wastewater (WCPWW) using pretreatment units (aeration and sedimentation) and a macrosom scale HSSFCW cells, each 1.80 m × 0.60 m × 0.50 m (length × width × depth; area = 1.08 m$^2$) planted with emergent wetland plants. Three HSSFCW cells whose bottom and sides get lined with plastic membranes were filled with gravel and planted with the wetland plants (*Cyperus alternifolius*, *Vetiveria zizanioides*, and *Pennisetum purpureum*), while the fourth cell was left unplanted (control). The HSSFCW cells were fed with different tap water and WCPWW mix ratios at the 7 d interval until the plants adapted to the new environment. After pretreated and pH adjusted to 6.10, the WCPWW was allowed to enter the HSSFCW cells from an equalization tank via plastic pipes equipped with control valves. Triplicate samples were collected from the inlets and outlets of each treatment unit and analyzed in the laboratory according to standard methods. The results revealed that sedimentation and aeration units achieved 51.80 and 19.80 for BOD$_5$, 61.60 and 22.10 for COD, –46.70 and 26.50 for NO$_3^-$–N, 17.0 and 38.50 for NH$_3$–N, 19.10 and 8.10 for PO$_4^{3-}$–P, 76.10 and 19.60 for TSS, 50.90 and 27.50 for TDS and –23.30 and 27.70 for EC % removals, respectively. HSSFCW$_2$, (planted with *V. zizanioides*) and HSSFCW$_3$ (control) cells achieved 78.50 and 61.70 for BOD$_5$, 80.10 and 69.10 for COD, 70.20 and 43.20 for NO$_3^-$–N, 50.10 and 29.0 for NH$_3$–N, 79.60 and 57.40 for PO$_4^{3-}$–P, 72.40 and 65.80 for TSS and 51.20 and 42.80 for TDS, and 31.10 and 22.30 for EC % removal respectively. The wetland cell, HSSFCW$_2$ achieved a better % removal for organic matter, solids, and nutrients. In conclusion, the integrated system is a good option for treating WCPWW. The treatment system must integrate more units to achieve effluent compliance with discharge limits.

*Keywords:* Constructed wetland; Integrated system; Pretreatment unit; Treatment efficiency; Wetland plants; Wet coffee processing wastewater

## 1. Introduction

Water pollution due to improper wastewater management is becoming a challenge for developing countries. Studies revealed that discharging untreated wastewater into water bodies severely threatens the diversity and survival of aquatic organisms [1]. Pollution also changes the physical, chemical, and biological water qualities, making it unsuitable

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for an intended purpose [2]. Though composition depends on the type of industry and its water usage, the wastewater may contain solids, biodegradable and non-biodegradable organics, oils and greases, heavy metals, dissolved organics, acidic, and coloring compounds [3]. Wastewater impacts on the receiving environment depend on its composition and flow characteristics [4].

In recent times, Ethiopia has faced industrial and chemical pollution due to the government's policy and rapid agro-industry expansion to ensure economic development [5]. Studies revealed that about 90% of industries in Ethiopia discharge their effluents directly into nearby rivers, lakes, and streams without any form of treatment might be due to the high construction, operation, and maintenance costs of the conventional treatment technologies [6,7]. The organic and inorganic pollutants are much higher than the discharge limits and harmful to humans and aquatic organisms [8]. Thus, pollution of water bodies due to discharging enormous quantities of untreated wastewater is very pervasive in the major cities, rivers, and lakes. Industrial effluents and domestic sewage contribute large amounts of nutrients and toxic substances that adversely affect on aquatic biota [9].

Coffee originated in Ethiopia and spread worldwide across Egypt, Yemen, and Italy by travellers [10]. The coffee plant was first discovered and cultivated in the Southwest Province of Ethiopia around 1000 AD [11]. Many nations have shown tremendous interest in growing and producing coffee on a commercial scale as it is the most traded commodity after petroleum [12,13]. Ethiopia is the largest producer of the unique and renowned Coffee Arabica in Africa and the world [11]. The country contributes 6.4% of global coffee production annually by devoting 600,000 hectares of its agricultural land to coffee farms [12,14]. Coffee is one of the export commodities for Ethiopia to earn significant amounts of foreign currencies.

Once harvested, coffee berries must take to the coffee processing plants. The quality of coffee beans begins to deteriorate a few hours after being picked, necessitating immediate processing in a plant often established very close to the coffee farms. Fundamentally two coffee processing methods exist namely, the wet and dry methods [15]. Each wet coffee processing step generates a huge volume of wastewater, thereby contributing a significant pollution load [14]. Many coffee processing firms dispose of effluent from de-pulping, fermentation, and washing steps to nearby water bodies [15]. A wet coffee processing plant is a small-scale agro-industry that produces a huge volume of wastewater. Developing countries like Ethiopia cannot afford conventional wastewater treatment technologies due to high construction, operation, and maintenance costs. Moreover, effluents from conventional treatments fail to meet discharge standards. Thus, it is imperative to look for a cost-effective, eco-friendly, and easily adaptable treatment system to comply with the discharge regulations and to maintain public health.

Over the past five decades, constructed wetlands (CWs) have significantly expanded from domestic sewage treatment to various industrial effluents [4]. The wet processing method is preferably used for rip coffee fruits to produce good quality coffee beans [16]. This method yields coffee pulp, mucilage, wastewater, and coffee beans with hulls. Two variations exist for wet coffee processing, conventional and advanced methods [17]. After de-pulping, coffee beans are transported to fermentation tanks to break down and remove mucilage. The wastewater originates from the de-pulping, fermentation, and washing steps [13]. Anaerobic fermentation may take place from 12 to 36 h depending on the temperature and altitude of the surrounding environment, the thickness of the mucilage layer, and the concentration of enzymes [18]. Coffee mucilage's fermenting sugars form organic and acetic acids, which make the resulting wastewater very acidic (pH as low as 3.8) [15]. Ether, crude fiber, ash, nitrogen fiber, tannin, sugars, and caffeine are the major components of coffee pulps [14]. The wastewater from mucilage washing is mainly composed of protein, sugars, pectin acid, and ash [19]. Wet coffee processing wastewater (WCPWW) contains a complex mixture of chemicals whose composition varies with time, type of processing method, and coffee variety [15]. The WCPWW is highly colored, acidic, and contains significant organic matter (BOD and COD) and non-biodegradable organics [20]. The WCPWW often classified as physical (color, odor, temperature, electrical conductivity, turbidity, suspended and dissolved solids), chemical (COD, $BOD_5$, nutrients, acidity, basicity, and TOC), and biological characteristics. Wet coffee processing requires a huge volume of water, approximately 8–10 L/kg of coffee bean produced if the water is not recycled [13,16]. The biological treatment of such effluent necessitates adjustment of nutrients and pH to enhance pollutant removal efficiencies [15]. The advanced wet coffee processing method follows the same procedure as the wet processing method for de-pulping, except the mucilage is removed by friction as the coffee beans pass between a revolving perforated drum and an inner perforated tube having a counter flow of water [15].

Wet coffee processing plants generate a huge volume of wastewater rich in suspended and dissolved organic and inorganic pollutants [21]. The WCPWW causes pollution at the local level due to its strength and volume [13]. Organic and acetic acids from fermenting sugars threaten the survival of higher plants and animals [3]. Moreover, it's total suspended solid is high in digested mucilage which may clog up waterways and contribute to the anaerobic conditions by forming surface crust [21]. Discharging such wastewater directly to water bodies may cause severe health effects, including sensitization of the eye and ear, skin irritation, stomach pain, nausea, and breathing difficulties among residents [14,22]. Also, the indiscriminate use of fresh coffee pulp affects crops through acid formation and fire hazards from fermentation [21].

Several treatment methods have been developed to alleviate the impacts of WCPWW on receiving environment [13,15,23]. The most appropriate and promising treatment method must consider the issues of effectiveness, availability, affordability, and eco-friendly concerns. Biological treatments (e.g., aerobic lakes, lagoons, constructed wetlands, expanded granular sludge bed bioreactor) and physicochemical treatments (e.g., zero-valent iron treatment, membrane filtration, ionizing radiation, adsorption, electrochemical oxidation, chemical coagulation and flocculation, and advanced oxidation process) have been used to treat WCPWW [13,24]. Aerobic lakes (aerobic lagoons) have been used to treat WCPWW in Brazil [3], while a meaningful treatment option has yet to be devised in Ethiopia to treat the WCPWW.

A constructed wetland (CW) is an engineered system that utilizes the same processes as the natural wetland in a more controlled environment to treat wastewater from various sources [25]. Due to its low energy consumption, and low construction, operation, and maintenance costs, CWs become the most widely used wastewater treatment options in many parts of the world [26–29]. As a sustainable and reliable wastewater treatment method, CWs treat wastewater with various types and levels of pollutants [25,27,30]. They can treat municipal wastewater, industrial and agro-industrial effluents, urban runoff, landfill leachates, acid mine drainage, and domestic sewages [31]. CWs can tolerate high hydraulic loads and toxic pollutants, which makes them the most effective bioreactors, even in a hostile environment [32,33]. However, studies on issues that improve pollutant removal efficiency, operation, suitable plants, and substrate for treating WCPWW are not fully studied. A CW imitates the ecological system of natural wetlands and combines the physical, chemical, and biological treatment mechanisms to remove pollutants [34]. It is an emerging eco-friendly treatment technology designed to overcome the limitations of natural wetlands [35]. CWs ensure more reliable control over the hydraulic regime and perform consistently compared to the natural wetlands [36]. Thus, CWs are eco-friendly treatment technology for small industries, such as wet coffee processing firms, which cannot afford the costly conventional treatment systems [9].

The design and construction of CWs must consider the natural processes to treat wastewater in a controlled environment [37]. A CW may consist of treatment steps built according to the expected flow and hydraulic loading rates [38]. The heavier the loading rate, the larger the CW system to effectively remove the pollutants [32]. CWs can be built with much greater control to establish experimental treatment facilities with a well-defined composition of substrate, plants, and flow patterns and have several benefits, such as site selection, flexibility in sizing, and control over hydraulic loadings and retention times [34]. In CWs, wastewater goes through a series of purification processes, including biodegradation, filtration, sedimentation, and adsorption resulting in a significant reduction in organic, suspended solids, nutrients, and pathogens [24].

CWs can be classified based on different criteria, including the dominate macrophytes (free-floating, submerged, rooted emergent), size/surface area (microcosms ≤ 0.50 $m^2$; macrocosms 0.51–5.0 $m^2$, pilot and full scale >5 $m^2$), hydrology (free water surface and subsurface) and flow types (vertical or horizontal flow) [39]. A wetland is defined as a complex assemblage of water, substrate, plants (vascular and algae), litter (fallen plant materials), invertebrates (insect larvae and worms), and microorganisms (mostly bacteria) [24]. Its function and performance depend on water depth, temperature, pH, and DO concentration [40]. A free water surface flow constructed wetland (FSFCW) is densely vegetated by a variety of plant species with water depth <0.40 m and hydraulic loading rates of 0.70–5.0 $\mu m^3$/d [25]. Its top surface layer is aerobic, while the deeper water and substrate are anaerobic. The design, construction, maintenance and operational costs of FSFCW are relatively low. The FSFCW provides habitat for native and migratory birds and accessible to the public but requires a larger area than other types of CWs [41]. Subsurface flow-constructed wetlands (SSFCWs) use a bed of gravel as a substrate to support the growth of rooted plants. Bed depth typically ranges between 0.30 and 1.0 m and water flows under the surface [25]. SSFCW has a typical hydraulic loading ranging from 2.0 to 20.0 $\mu m^3$/d and demonstrates a higher pollutant removal efficiency than an FSFCW [42]. The earth provides insulation to cold climates without providing habitat for birds and access to humans and animals [43]. SSFCW can be either a horizontal flow (HSSFCW) with a typical bed depth <0.60 m (substrate is water saturated), and the bottom bed is sloped to minimize flow above the surface or a vertical flow CW (VSSFCW) [26]. Due to the hydraulic constraints imposed by the substrate, SSFCWs are reasonably suitable for wastewaters having low solids and uniform flow patterns [44]. It has been suggested that the SSFCW provides greater surface area and rapid treatment and is smaller than FSFCW [45]. SSFCWs have several advantages over the FSFCWs, including a greater ability to treat wastewater with high organic loads, tolerate colder climates, greater treatment per unit area (due to a greater surface rendered by substrate), reduced odors and insects breeding (e.g., mosquitoes), low exposure risk to hazardous substances and microbial pathogens [32]. SSFCW is lower in operating costs, requires a low level of training for operators, and is aesthetically pleasing [30]. To maximize performance and minimize costs, a combination of different wetland systems (hybrid CWs) has been introduced [26].

CWs separate and transform pollutants via several mechanisms as the water flows through them. The predominant mechanisms and sequence of reactions depend on the external input parameters (wastewater quality and quantity and hydrologic cycle) and the internal interactions and characteristics of the wetland [46]. Pollutant removal mechanisms in CWs are numerous and often interrelated [24] (Tables 1 and 2).

Substrates (soil, sand, gravel, rock, organic matter such as compost), sediments, and litter may support organisms responsible for wastewater treatment in CWs [25]. They provide permeability to water through the wetland, a site for chemical and biological (microbial) transformations of pollutants and storage for contaminants. Due to low flow velocities and high productivity, substrates and litters may accumulate, increasing the amount of organic matter, which provides sites for material exchange, microbial attachment, and energy for driving important biological reactions [44]. The substrate's physical and chemical attributes may change upon flooding with wastewater, which is important in the construction and operation of CWs [32]. In a saturated substrate, water replaces the atmospheric gases in the pore spaces that limit oxygen availability for microbial metabolism (anaerobic condition dominates) [47]. Since oxygen is consumed more rapidly than it can be replaced, the substrates become anoxic (a precondition for removal of pollutants such as nitrogenous compounds and heavy metals) [48].

Wetland plants play key roles in CWs to enhance treatment processes by filtering the wastewater, regulating flow, controlling algal growth, contributing oxygen, up taking and storing heavy metals and nutrients and providing large surface area for microbial treatment. They offer a large

Table 1
Treatment processes in the CWs

| Mechanism | Process |
|---|---|
| Physical | - Sedimentation of denser particles |
| | - Filtration of lighter particles by macrophytes and biofilms |
| | - Aggregation of particles either for sedimentation or filtration |
| | - UV degradation |
| Chemical | - Precipitation |
| | - Adsorption onto substratum and detritus |
| | - Volatilization |
| Biological | - Microbial decomposition and mineralization of organic matter |
| | - Microbial transformation of nutrients (nitrification/denitrification) |
| | - Direct biological uptake by algal and microbial biofilms |
| | - Indirect uptake from within the root zone by biofilms and macrophytes |
| | - Pathogens die-off as a result of microbial competition |
| | - Direct grazing of organic matter by animals |

Table 2
Pollutant removal processes in HSSFCWs

| Pollutants | | Removal processes |
|---|---|---|
| Organic matter (BOD or COD) | | - Biological degradation, sedimentation, microbial uptake |
| Suspended solids | | - Sedimentation and filtration |
| Nutrients | Nitrogen | - Sedimentation, volatilization, filtration, nitrification/denitrification, microbial and plant uptake |
| | Phosphorus | - Sedimentation, filtration, adsorption, microbial and plant uptakes |
| Pathogens | | - Natural die off, sedimentation, filtration, adsorption |
| Heavy metals | | - Sedimentation, adsorption, plant, and microbial uptakes |
| Organic pollutants | | - Adsorption by biofilms and soil particles |
| | | - Decomposition due to long retention times |

surface area for attaching microbial populations and transporting gases to and from the roots and rhizomes within the substrate [30]. The oxygen transferred to the root zone plays a major role in creating a thin-film of the aerobic region to support aerobic microbial populations that transform trace organics, nutrients, and metallic ions. In saturated soil, by-products of aerobic microbes can easily be utilized by anaerobic ones [34]. Leaves and stalks of wetland plants provide a canopy of shade to control algal growth by limiting sunlight penetration. The growth of algae may deter oxygen transfer to the water column at the water-atmosphere interface, besides decreasing wastewater temperature during summer [15]. Wetland plants also vent gaseous by-products of anaerobic decomposition in the substrate [34]. The rooted emergent wetland plants may reduce the water volume due to high transpiration rates. Wetland plants may also reduce the suspended solid contents of the wastewater by impeding flows [34].

The most commonly used wetland plants in SSFCWs are cattails (*Typha* species), bulrush (*Scirpus* species), and giant reed (*Phragmites* species) [15,34]. These plants tend to create a single species by inhibiting the growth of other plants. The selection of wetland plants depends on the ability for climatic adaption, easy availability, and the goal of the CWs [49]. The plant species selected must survive in the climatic conditions where the CW is used [47]. Also, wetland plants must survive the variability and toxic effects of wastewater. If the goal of the CW is to remove nutrients, the ability of the plant to uptake and store nutrients must be the priority [31]. The storage ability of the plants is related to the amount of nutrients accumulated during the growth period that can be removed once harvested [31]. If frequent harvesting is to be made, the uptake capacity may give the rate at which plants uptake nutrients and the frequency of harvesting [47]. Wetland plants enhance wastewater treatment processes via filtration, adsorptions, and sedimentation of pollutants [50]. Metabolically, wetland plants uptake pollutants to produce organic carbon and oxygen, improving water quality [34]. Nutrient uptake depends on the growth and biomass production of wetland plants. Rooted emergent wetland plants utilize their roots to obtain sufficient nutrients from wastewater. At the same time free-floating species use their numerous root hairs to get nutrients from the water column and substrates. These plants often grow in CW beds to stimulate uptake and create suitable conditions for the oxidation of pollutants, thereby improving the treatment system’s performance [51]. Thus, plant selection and management must consider bed surface area per volume, bed design, optimal depth, HRT, and favorable substrates [52]. If the wetland plant is intended as an oxygen source for nitrification, the bed depth should not exceed its root penetration capacity to ensure oxygen availability throughout the bed profiles [51].

The other component of CWs contributing to the degradation of pollutants comes from microbial groups such as bacteria, fungi, algae, and protozoa. The function of CWs depends on microbial metabolisms (aerobic, anaerobic, and/or facultative anaerobes). Microorganisms transform pollutants while obtaining nutrients or energy for their normal metabolic processes [34]. Microbial biomass is the major sink for organic carbon and many nutrients [9]. Microbial activity transforms many organic and inorganic pollutants into insoluble substances. It alters the substrate's redox conditions, which affects the processing and/or nutrient recycling capacity of the CWs [46]. Pesticides and heavy metals may affect microbial community, thus care must be taken to prevent the introduction of such chemicals at harmful concentrations [47]. This study used an integrated treatment system composed of sedimentation, aeration, and HSSFCW cells to treat WCPWW. The wastewater samples collected from local wet coffee processing plants were characterized before and after sedimentation and aeration. The HSSFCW cells planted with different wetland plants were evaluated for their BOD$_5$, COD, $NO_3^-$–N, $NH_3$–N, $PO_4^{3-}$–P, TDS, TSS, pH, DO and EC changes as the WCPWW flow from inlets to outlets.

## 2. Materials and methods

### 2.1. Description of the study area

The study was conducted in the Jimma zone, Southwest Ethiopia. Jimma zone is Ethiopia's largest coffee producer, covering ~55% of national annual coffee production. The raw wet coffee processing wastewater samples were collected from wet coffee processing plants found in the Jimma zone. Four pilot HSSFCW cells, each with the dimension of 1.80 m × 0.60 m × 0.50 m (length × width × depth) and bottom and sides lined with 0.50 mm thick impermeable PVC membrane were constructed in Jimma Institute of Technology (JiT) campus. The cells were made operational for one month in treating WCPWW collected from the different districts of coffee processing plants.

Materials, equipment, chemicals, and reagents were used to conduct the study and analyze the WCPWW before and after treatment in the constructed wetland. Three types of rooted emergent plants: Umbrella plant (*Cyperus alternifolius*), Vetiver grass (*Vetiveria zizanioides*), and Napier grass (*Pennisetum purpureum*) (Fig. 1) were collected from the local area and used in the constructed wetland cells to treat WCPWW.

A 0.30 m$^3$ volume sedimentation tank was used to remove suspended and settleable solids from the WCPWW. The addition of calcium hydroxide ($Ca(OH)_2$) converts the acetic acid in the WCPWW to calcium acetate with a simultaneous change in pH from 4.40 to 6.10. The $Ca(OH)_2$ was used to neutralize the pH of the raw WCPWW. A 0.150 m$^3$ flow equalization tank with a control valve was used to regulate wastewater flow rate into the wetland cells. Four 0.025 m$^3$ volume outlet storage tanks were used to store effluents collected from each HFSSCW cell. Gravels of diameter size between 20–30 mm were used at the middle zone of the CW cells, while gravels 40–80 mm were used at the inlet and outlet zones of the CW cells as substrate. Polyvinyl chloride (PVC) plastic pipes of 1/2-inch (0.0127 m) of diameter were used to supply, distribute and collect the wastewater from the CWs. Metal valves of 1/2-inch diameter were used to manage wastewater flow into the wetland cells. A 0.50 mm thick PVC plastic membrane was used to line the bottom and sides of each CW cell to prevent percolation and infiltration of pollutants into the groundwater. Stopwatch and measuring cylinders were used to measure the inflow and outflow rate of the wastewater. Plastic bottles were used to collect wastewater samples from the different sampling points of the treatment system for laboratory analysis. The following equipment and apparatus were used during sample collection and analysis: BOD incubator, digital thermometer, pH meter (pH 3310), electro-conductivity (Cond 3110), Oven, DO meter, BOD bottle, Erlenmeyer flasks (500 mL), aluminum weighing dishes, glass fiber filter disks, suction flasks, membrane filter funnel, Gooch crucibles, Whatman filter paper (0.47 μm), measuring cylinders (50 and 100 mL), digital weighing balance, evaporating dishes, desiccator, and beakers (1,000 mL) were also used during the study.

### 2.2. Sample collection and sampling procedures

Triplicate wastewater samples were collected from the different sampling points of the treatment system for one month during the study period. The effluents from the

Fig. 1. Wetland plants used during the study: *Cyperus alternifolius* (a), *Vetiveria zizanioides* (b), and *Pennisetum purpureum* (c).

HSSFCW cells were collected once per week (Table 3). Totally 24 wastewater samples were collected during the study period to analyze wastewater quality parameters. The triplicate samples were analyzed for wastewater quality parameters. Assuming the WCPWW fed into the HSSFCW cells leaves the system after 7 d of HRT, three round grab wastewater samples were collected using polypropylene plastic bottles and stored in a cool box at 4°C and transported to Environmental Science and Technology Laboratory, according to sample preservation and handling principles to analyze different wastewater quality parameters. The samples were collected for one month at the interval of 7 d after the wetland plants established themselves and were fully grown.

### *2.3. Laboratory analysis and measurements*

All the studied wastewater quality parameters (pH, DO, COD, $BOD_5$ TSS, TDS, $NH_3$–N, $NO_3$–N, $PO_4^{3-}$–P, EC, turbidity, and temperature) of the raw WCPWW were analysed at Environmental Science and Technology laboratory, according to the standard methods for water and wastewater [53] (Table 4). Samples were stored in the refrigerator at 4°C before analysed. Effluents of sedimentation, aeration, and HSSFCW cells were also analyzed for the same parameters. Non-conservable parameters (DO, EC, pH, and temperature) were measured onsite at the time of sampling at the inlets and outlets of the treatment system using a portable multi-parameter test apparatus. All chemicals and reagents used for the analysis of WCPWW were analytical laboratory grade purchased from Neway PLC, a local supplier.

### *2.4. Experimental setup and design of HFSSCW*

An HSSFCW system was constructed at the Jimma Institute of Technology (JiT) campus using bricks, gravel, and cement to investigate its WCPWW treatment potential. The system consisted of four similar-sized HSSFCW cells, each with a dimension of 1.80 m long × 0.60 m wide × 0.50 m deep (surface area = 1.08 $m^2$). The bottom floor of the system was made to have a 1% slope from the inlet to the outlet to avoid a hydraulic head loss. The WCPWW was fed into the HSSFCW cells at an average flow rate of 0.027 $m^3/d$. The inflow and outflow rates of the WCPWW were measured using the fill and empty method using a stopwatch and measuring. The HRT of the WCPWW through HSSFCW cells was found to be 20 d (0.54 $m^3$/0.027 $m^3/d$) with inflow and outflow rates of 0.029 and 0.025 $m^3/d$, respectively. The maximum flow rate through each HSSFCW cell was found to be 0.029 $m^3/d$, while the minimum flow rate was 0.025 $m^3/d$ with an average flow rate of 0.027 $m^3/d$. Literature review survey revealed that the HRT of HSSFCW ranges from 6 to 8 d to ensure adequate nitrification rates [54]. The study considered approximately 6.825 ≈ 7 d HRT, and Darcy's formula was used to calculate the theoretical flow rate [54]. The porosity of the wetland substrate was estimated by dividing void volume by total volume, which was found to be 0.35 or 35%. After raising the pH of WCPWW from 4.40 to 6.10, the wastewater was allowed to enter the HSSFCW cells planted with macrophytes and unplanted cell for secondary/biological treatment. Stoichiometrically, 1 g of $Ca(OH)_2$ was used to neutralize 1 L of acidic raw WCPWW. In the presence of $Ca(OH)_2$, the acetic acid converts to calcium acetate with a radical change in the solution's pH from 4.40 to 6.10, favoring the treatment potential of wetlands. The WCPWW was neutralized in a sedimentation tank and remained there for 1 d to receive primary treatment (pH adjustment and solids sedimentation) and then passed over a corrugated plastic sheet for the aeration process. An equalization tank was used to regulate the flow rate of the wastewater into the HSSFCW cells (Fig. 2). The polypropylene (PP) pipes of l/2-inch (0.0127 m) in diameter were used to supply, distribute and collect wastewater that received primary treatment. A sedimentation tank was connected through a single pipe with control valve and

Table 4
Wastewater quality parameters test and measurement methods

| Parameter | Method | Remarks |
|---|---|---|
| Biological oxygen demand (BOD) | 5-Day BOD Test | |
| Chemical oxygen demand (COD) | Hach-Lange LCK 114 | |
| Total dissolved solids (TDS) | Gravimetric method | |
| Total suspended solids (TSS) | Gravimetric method | |
| Ortho phosphate ($PO_4^{3-}$–P) | Hach-Lange LCK 350 | |
| Nitrate nitrogen ($NO_3$–N) | Hach-Lange LCK 339 | |
| Ammonia nitrogen ($NH_3$–N) | Hach-Lange LCK 304 | |
| Electrical conductivity (EC) | Electrode method | |

Table 3
Sampling points and their description

| Sample point code | Description |
|---|---|
| $S_0$ | Raw WCPWW after screening and influent of sedimentation tank |
| $S_1$ | Effluent of sedimentation tank and influent of aeration tank |
| $S_2$ | Effluent of aeration tank and influent of equalization tank |
| $S_3$ | Effluent of equalization tank and influent of $HSSFCW_1$, $HSSFCW_2$, $HSSFCW_3$, and $HSSFCW_4$ |
| $S_4$ | Effluent of $HSSFCW_1$ |
| $S_5$ | Effluent of $HSSFCW_2$ |
| $S_6$ | Effluent of $HSSFCW_3$ (control) |
| $S_7$ | Effluent of $HSSFCW_4$ |

the wastewater fell over a plastic sheet for aeration process (Fig. 3b). The equalization tank was connected through PVC pipes with a control valve to HSSFCW cells (Fig. 3a). The two major components of the piping system in the HSSFCW cells were the inlet and outlet pipes (Fig. 3c).

A plastic membrane liner was used to prevent percolation and infiltration of pollutants into the groundwater (Fig. 4a). Once lined with plastic membrane the wetland cells were filled with gravels and planted with wetland plant species (Fig. 4b). The substrate for the growth of wetland plants in the current HSSFCW system was 20–30 mm gravel. The gravel was carefully washed before being used in the HSSFCW cells to minimize their impacts on the treatment of WCPWW. The substrate was filled up to a height of 0.40 m of the wetlands based on the recommended gravel size range of 20–40 mm for HSSFCW cells [53].

Fig. 2. Sedimentation (a), aeration (b), and equalization (c) processes.

Fig. 3. Inlet piping to HSSFCW from equalization tank (a), aeration piping within HSSFCW cells (b), and outlet piping of HSSFCW cells (c).

Fig. 4. HSSFCW cells before (a) and after planting with emergent wetland plants (b).

Three plant species viz., Umbrella plant (*C. alternifolia*), Vetiver grass (*V. zizanioides*), and Napier grass (*P. purpureum*) were selected based on prior information on their usage in CW, aesthetic landscaping applications, ease of accessibility, and wastewater treating potential. Using these plants in HSSFCWs can combine wastewater treatment and landscape beautification material. After the wetland cells were filled with gravel, the plants were established. The first HSSFCW cell was planted with *C. alternifolia*, the second cell was planted with *V. zizanioides*, the third cell was filled with gravels only (unplanted) to be used as a control and the froth cell was planted with *P. purpureum*. The plants were collected from Jimma Awetu and Kito natural wetlands and transplanted into the HSSFCW cells. Before transplantation, soil, and litter were removed from the roots by washing with tap water to prevent debris from exerting organic matter and minimize their impacts on the treatment of WCPWW. Once transplanted, the wetland plants were allowed to grow in the CW cells. Until the wetland plants were fully established, HSSFCW cells were fed only with tap water for two months and once the plants reached their acclimatization stage and fully grown, the WCPWW was diluted with tap water at different ratios (75:25, 50:50, 25:75 and 0:100) (Table 5) and fed to the HSSFCW cells for one month. The gradual rather than sudden increase in the concentration of WCPWW reduces shock and provides an adaptation period for the wetland plants.

### *2.5. Data processing and analysis*

Statistical data analyses were performed using Microsoft Excel® (MS Office 2010) and Origin Pro 9 (Origin Lab Corporation®) software. Data were analyzed using the mean and standard deviation to compare the treatment efficiency of the sedimentation, aeration and HSSFCW cells regarding the change in the wastewater quality parameters ($BOD_5$, COD, $NO_3^-$-N, $NH_3$–N, $PO_4^{3-}$-P, and DO, EC, pH, turbidity and temperature) as the WCPWW treated by the integrated system. The removal efficiency for each wastewater quality parameter was calculated using Eq. (1).

$$\text{Removal efficiency}(\%) = \frac{C_i - C_e}{C_i} \times 100 \tag{1}$$

where $C_i$ is the influent concentration of the wastewater parameter; $C_e$ is the effluent concentration of the wastewater parameter.

## 3. Results and discussion

The study investigated raw WCPWW characterization and pollutants removal efficiency of the sedimentation tank, aeration, and the HSSFCW cells planted with different emergent wetland plants. The results obtained from the laboratory analysis of raw WCPWW were characterized and the mean values of the influent and effluent of HSSFCW cells for some physicochemical parameters are shown in Table 6. The removal efficiency of sedimentation, aeration, and the four HSSFCW cells are summarized in Table 7. The visual appearances of raw WCPWW and after treatment with the integrated system are shown in Fig. 5a and b, respectively.

### *3.1. Characteristics of raw WCPWW*

The $BOD_5$ concentration of WCPWW ranged from 1,943 to 3,464 mg/L with a mean of 2,693 ± 760 mg/L, while COD concentration ranged from 4,978 to 5,822 mg/L with a mean of 5,496 ± 453 mg/L (Table 6). These $BOD_5$ and

Table 5
Percentage dilution ratio of tap water and wastewater

| Schedule | Dilution % | | Total |
|---|---|---|---|
| | Tap water | WCPWW | |
| First week | 75 | 25 | 100 |
| Second week | 50 | 50 | 100 |
| Third week | 25 | 75 | 100 |
| Fourth week | 0 | 100 | 100 |

Table 6
Influent and effluent characteristics of raw WCPWW and HSSFCW cells (all units in mg/L except EC, temperature. and pH)

| Parameter | Raw WCPWW | Mean ± SD pretreatment influent | | Mean ± SD HSSFCW cell effluent | | | |
|---|---|---|---|---|---|---|---|
| | | Sedimentation | Aeration | $HSSFCW_1$ | $HSSFCW_2$ | $HSSFCW_3$ | $HSFFCW_4$ |
| $BOD_5$ | 2,693 ± 760 | 1,297 ± 97 | 1,039 ± 87.0 | 235 ± 28.0 | 223 ± 32.0 | 397 ± 101 | 247 ± 55 |
| COD | 5,496 ± 453 | 2,109 ± 627 | 1,642 ± 430 | 346 ± 60.0 | 328 ± 135.0 | 508 ± 136 | 371 ± 71 |
| $NO_3^-$–N | 20.3 ± 3.80 | 29.8 ± 2.3 | 37.7 ± 10.5 | 13.9 ± 2.9 | 11.2 ± 1.90 | 21.4 ± 5.4 | 15.7 ± 2.8 |
| $NH_3$–N | 4.7 ± 0.45 | 3.9 ± 0.44 | 2.4 ± 1.0 | 1.4 ± 0.25 | 1.2 ± 0.42 | 1.7 ± 0.53 | 1.3 ± 0.41 |
| $PO_4^{3-}$–P | 7.3 ± 2.10 | 5.9 ± 1.50 | 5.4 ± 1.20 | 1.7 ± 0.43 | 1.1 ± 0.01 | 2.3 ± 0.51 | 1.6 ± 0.5 |
| TSS | 1,857 ± 228 | 433 ± 113 | 348 ± 128 | 113 ± 23.0 | 96 ± 13.0 | 119 ± 13 | 115 ± 22 |
| TDS | 1,826 ± 250 | 897 ± 107 | 703 ± 89.0 | 367 ± 122 | 343 ± 124 | 402 ± 60 | 372 ± 64 |
| pH | 4.4 ± 0.30 | 6.1 ± 0.37 | 6.4 ± 0.30 | 6.6 ± 0.15 | 6.7 ± 0.32 | 6.8 ± 0.1 | 6.5 ± 0.25 |
| DO | 0.92 ± 0.34 | 1.2 ± 0.36 | 1.4 ± 0.35 | 3.2 ± 0.45 | 4.1 ± 0.72 | 1.6 ± 0.1 | 2.9 ± 0.24 |
| $T$ (°C) | 24.3 ± 0.45 | 23.9 ± 0.95 | 23.5 ± 0.6 | 20.8 ± 1.0 | 19.5 ± 0.9 | 23.1 ± 0.5 | 21.4 ± 0.72 |
| Turbidity (NTU) | 292 ± 73.0 | 137 ± 58.0 | 98 ± 26.0 | 34 ± 18.0 | 27 ± 17.0 | 39 ± 19.0 | 32 ± 9.0 |
| EC (µS/cm) | 1,016 ± 23 | 1,253 ± 128 | 981 ± 192 | 682 ± 130 | 689 ± 112 | 762 ± 192 | 676 ± 117 |

Table 7
Percentage removal efficiency of sedimentation, aeration, and HSSFCW cells

| Parameter | Removal efficiency (%) | | | | | |
|---|---|---|---|---|---|---|
| | Sedimentation | Aeration | $HSSFCW_1$ | $HSSFCW_2$ | $HSSFCW_3$ | $HSFFCW_4$ |
| $BOD_5$ | 51.80 | 19.80 | 77.30 | 78.50 | 61.70 | 76.20 |
| COD | 61.60 | 22.10 | 78.90 | 80.10 | 69.10 | 77.40 |
| $NO_3$–N | –46.70 | –26.50 | 63.10 | 70.20 | 43.20 | 58.30 |
| $NH_3$–N | 17.0 | 38.50 | 41.60 | 50.10 | 29.00 | 45.80 |
| $PO_4^{3-}$–P | 19.10 | 8.10 | 68.50 | 79.60 | 57.40 | 70.30 |
| TSS | 76.10 | 19.60 | 67.50 | 72.40 | 65.80 | 66.90 |
| TDS | 50.90 | 27.50 | 47.80 | 51.20 | 42.80 | 46.90 |
| EC (μS/cm) | –23.30 | 21.70 | 30.40 | 29.70 | 22.30 | 31.10 |

Fig. 5. Visual appearance of WCPWW before (a) and after treatment (b).

COD concentrations were much lower than the previously reported concentrations of 10,800 and 15,780 mg/L, respectively for the Jimma zone [22]. The concentrations of $BOD_5$ and COD failed to meet the Ethiopian standard discharge limits of 80 mg/L for $BOD_5$ and 250 mg/L for COD [55]. The $BOD_5$ concentration of 3,800–4,780 mg/L and COD concentration of 6,420–8,480 mg/L were reported for wastewater from conventional wet coffee processing plants [21]. The raw WCPWW is also characterized for its nutrient (N and P) contents. The result showed that the WCPWW had $NO_3^-$–N, $NH_3$–N and $PO_4^{3-}$–P concentrations that ranged from 16.30 to 24.20, 4.40 to 5.20 and 5.10 to 9.20 mg/L, with mean values of 20.30 ± 3.80 mg/L, 4.70 ± 0.45 mg/L and 7.30 ± 2.10 mg/L, respectively. These $NO_3^-$–N, $NH_3$–N, and $PO_4^{3-}$–P contents of WCPWW were found to be higher than the previously reported concentration of 4.51 ± 1.62 mg/L for $NO_3^-$–N, 39 ± 0.65 mg/L for $NH_3$–N and 3.32 ± 0.50 mg/L for $PO_4^{3-}$–P, respectively for WCPWW from the same area [17]. The concentrations of $NO_3^-$–N and $PO_4^{3-}$–P were higher than national discharge limits, while the concentration of $NH_3$–N was lower than discharge limits [55]. Similar studies revealed the mean concentration of $NH_3$–N of 90.0 mg/L in WCPWW [17]. The study also revealed a mean concentration of 17.80 mg/L for $NO_3^-$–N. Almost the same mean concentrations of 23.0 mg/L of $NO_3^-$–N and 7.30 mg/L of $PO_4^{3-}$–P were reported from the conventional wet coffee processing plants [20].

The TSS and TDS concentrations of the raw wet coffee wastewater were found to be ranged from 1,636 to 2,093 mg/L and 1,606 to 2,099 mg/L, respectively with an average value of 1,857 ± 228 mg/L for TSS and 1,826 ± 250 mg/L for TDS. These TDS and TSS contents of wet coffee processing wastewater were much lower than the previously reported values of 5,434 and 8,638 mg/L for TSS and TDS in the same study area [1]. These concentrations of TSS and TDS failed to meet the national standard limits of 100 mg/L for TSS and 3,000 mg/L for TDS [55].

The raw WCPWW also showed a pH value ranging from 4.10 to 4.70 with a mean value of 4.40 ± 0.30. This study found the same pH value of raw WCPWW almost similar to the previously reported pH value of 4.13. This value failed to meet the national discharge limits of 6–9. It might be due to the fermentation of sugars in the mucilage in the presence of yeasts to alcohol and $CO_2$ [17]. In this study, the mean concentrations of 1,016 ± 23 μS/cm for conductivity, 292 ± 73 NTU for turbidity, and 0.92 ± 0.34 mg/L for DO were found for raw WCPWW. These results are nearly similar to the values reported in the previous study of up to 747 μS/cm for conductivity, 271 NTU for turbidity, and 2.40 mg/L for DO. Turbidity indicates the quantity of suspended and colloidal materials in the wastewater, while conductivity measures the ability of an aqueous solution to carry an electrical current. In other words, conductivity indicates the quantity of dissolved inorganic matter in the wastewater.

Onsite measurement of the WCPWW temperature was found to be ranged from 23.8°C to 24.7°C, which is below the national standard of 40°C [55].

### *3.2. Performance of pretreatment units (sedimentation and aeration)*

The pretreatment operation was carried out with sedimentation and aeration processes before the WCPWW entered into the HSSFCW cells mainly to remove solids and avoid clogging of wetland beds [32]. Once the pH was adjusted to near neutral using $Ca(OH)_2$, no significant pH change was observed as the WCPWW flowed across the integrated treatment system. Then after the raw WCPWW solids were settled in the sedimentation tank and aeration was carried for 8 h before collection in equalization tank as a pretreatment to reduce acidic pH, suspended solids, and BOD of WCPWW before it entered the constructed wetland cells. With 1 d retention time and 8 h aeration, the sedimentation tank achieved the average removal efficiency of 51.80% for $BOD_5$, 61.60% for COD, 76.10% for TSS and 50.90% for TDS while the aeration process achieved an average removal efficiency of 19.80% for $BOD_5$, 22.10% for COD, 19.60% for TSS and 27.50% for TDS (Fig. 6). These results fall within the ranges of values reported in the previous works in which the sedimentation tank reduced at least 60% to 70% of the incoming $BOD_5$ and TSS, respectively, to reduce the wetland length [43]. The volume of the accumulated sludge and retention time are design criteria to size the sedimentation tank that feeds into the subsequent process. Based on empirical evidence, the retention time of at least 1 d for the sedimentation tank is recommended to remove 60%–70% of the incoming $BOD_5$. The sludge accumulated at the bottom of the tank reduces the volume of the tank with time. Thus, the recommended volume of the tank must be at least two times the daily average flow of wastewater. In this study, a volume of 300 L sedimentation tank was used, which is greater than three times the daily flow volume of WCPWW [43].

In this study, the mean concentration of $BOD_5$ decreased after pretreatment in sedimentation tank from 2,693 ± 760 mg/L to 1,297 ± 97 mg/L white aeration process reduced $BOD_5$ of WCPWW from 1,297 ± 97 mg/L to 1,039 ± 87 mg/L. It indicates that sedimentation and aeration units achieved average $BOD_5$ removal efficiency of 51.80% and 19.80%, respectively. It shows that the sedimentation tank achieved a good performance in removing $BOD_5$ though the value failed to comply with the national discharge limit of 80 mg/L. The reduction in the organic matter concentration might be associated with settling solids in the WCPWW. Another reason for decrease in the $BOD_5$ concentration of WCPWW might be related to the degradation of organic matter by aerobic bacteria due to the availability of sufficient DO, hence, lowering the $BOD_5$ concentration [41]. The mean COD concentration of raw WCPWW was reduced from 5,496 ± 453 mg/L to 2,109 ± 627 mg/L as the result of the sedimentation process, while the aeration process reduced the influent COD concentration from 2,109 ± 627 mg/L to 1,642 ± 430 mg/L. The result showed that the sedimentation reduced the COD concentration of the influent WCPWW by about 61.80% while the aeration process removed 22.10% of the influent COD. Since the concentration of COD after sedimentation and aeration processes failed to comply with the national discharge limits of 250 mg/L, the WCPWW was further treated in HSSFCW cells planted with different rooted emergent plants.

The total solids concentration in influent wastewater represents the colloidal and dissolved species. In this study, the mean TSS concentration was reduced from 1,857 ± 228 mg/L to 433 ± 113 mg/L, while the mean concentration of TDS was reduced from 1,826 ± 250 mg/L to 897 ± 107 mg/L after sedimentation while the aeration process reduced TSS and TDS concentrations from 433 ± 113 mg/L to 348 ± 128 mg/L and 897 ± 107 mg/L to 703 ± 89 mg/L, respectively. The result revealed that the sedimentation achieved removal efficiency of 76.10% and 50.90% for TSS and TDS, respectively, while the aeration process achieved 19.60% and 27.50% removal efficiency for TSS and TDS, respectively. The mean TSS concentration of 348 ± 128 mg/L after pretreatment revealed that the effluent failed to comply with the national discharge limit of 100 mg/L, but the mean TDS concentration of 703 ± 89 mg/L after pretreatment revealed that the wastewater complies with the national discharge limit of 3,000 mg/L. Most suspended solids in WCPWW are settleable, but smaller ones need more settling time to be

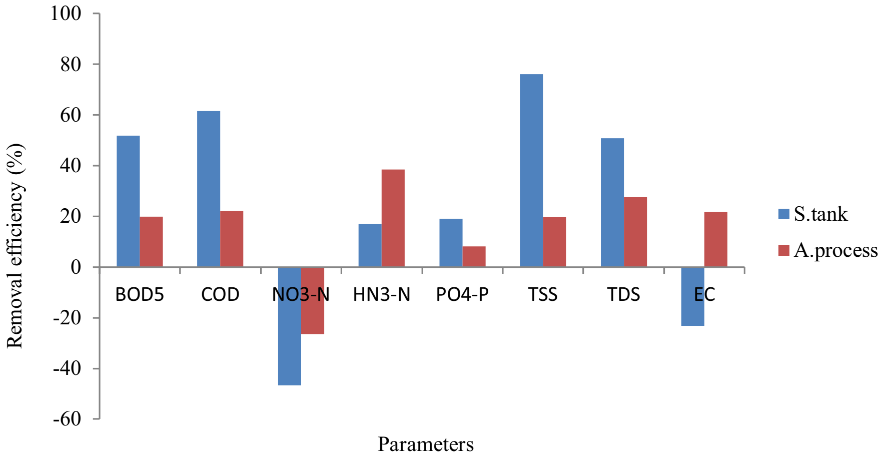

Fig. 6. Removal efficiency of some parameters by sedimentation and aeration units.

removed effectively. Thus, the effluent was further treated with the constructed wetlands (Fig. 7) to meet the discharge limit [41].

Among the studied parameters, the concentration of $NO_3^-$–N increased from 20.30 ± 3.80 mg/L to 29.80 ± 2.30 mg/L after sedimentation, while it increased from 29.80 ± 2.30 mg/L to 37.70 ± 10.50 mg/L following aeration. It might be due to the oxidation of ammonia and nitrite to $NO_3^-$–N by nitrifying bacteria that significantly increased the concentration of $NO_3^-$–N after pretreatment. Although the discharge limit for $NO_3^-$–N is 20 mg/L, the mean concentration after pretreatment, 37.70 ± 10.50 mg/L, is much higher than the national discharge limit. Thus, the aeration effluent was further treated in the constructed wetland cells so that the concentration of $NO_3^-$–N meets the national discharge limit. The mean concentration of $NH_3$–N decreased from 4.70 ± 0.45 mg/L to 3.90 ± 0.44 mg/L after the sedimentation, while it increased from 3.90 ± 0.44 mg/L to 2.40 ± 1.0 mg/L after aeration. The result revealed that the sedimentation and aeration units achieved the removal efficiency of 17.0% and 38.50% for $NH_3$–N, respectively. The decrease in the concentration of $NH_3$–N might be due to the presence of most of the nitrogen as ammonia that escaped the system by volatilization. Furthermore, some $NH_3$–N might have been converted to nitrate–nitrogen hence increasing the nitrate–nitrogen concentration, but reduced the amount of ammonia–nitrogen after the pretreatment. Nitrogen is limited in effluents to prevent Eutrophication in surface waters. Nitrogen can be removed in wetlands by plant or algal uptake, nitrification and denitrification and loss as ammonia gas to the atmosphere by volatilization [40]. The immediate decrease in the concentration of $NH_3$–N before the wastewater entered to vegetated wetlands might have helped the wetland plants to tolerate the very toxic ammonia gas. The mean concentration of $NH_3$–N after pretreatment (2.40 mg/L) indicated that the effluent complies with the national discharge limit of 5 mg/L. The pretreatment units generally showed the lowest removal efficiency for phosphorus (as $PO_4^{3-}$–P) mainly due to the limited physicochemical and biological processes responsible for the $PO_4^{3-}$–P removal from the WCPWW. The slight decrease in $PO_4^{3-}$–P concentration after pretreatment might be associated with precipitation and adsorption by dissolved species.

### 3.3. Removal efficiency of HSSFCW cells

Laboratory results revealed that the influent mean $BOD_5$ and COD concentrations were found to be 1,039 ± 87 mg/L and 1,642 ± 430 mg/L, respectively. The mean effluent $BOD_5$ and COD concentrations of the HSSFCW cells were found to be ranged from 223 ± 32 mg/L to 397 ± 101 mg/L and 328 ± 135 mg/L to 508 ± 136 mg/L, respectively. The $NO_3^-$–N, $NH_3$–N and $PO_4^{3-}$–P influent mean concentrations were found to be 37.70 ± 10.50 mg/L, 2.40 ± 1.0 mg/L and 5.40 ± 1.20 mg/L, respectively. The mean effluent concentrations were respectively ranged from 11.20 ± 1.90 mg/L to 21.40 ± 5.40 mg/L, 1.20 ± 0.42 mg/L to 1.70 ± 0.53 mg/L and 1.10 ± 0.01 mg/L to 2.30 ± 0.510 mg/L for the same parameters. The mean influent concentrations for TSS and TDS were respectively 348 ± 128 mg/L and 703 ± 89 mg/L. The effluent mean TSS and TDS concentrations of HSSFCW cells were respectively ranged from 96 ± 13 mg/L to 119 ± 13 mg/L and 343 ± 124 mg/L to 402 ± 60 mg/L. The removal efficiency of vegetated HSSFCW cells performed better than unplanted for most of the parameters studied. The national discharge limit signifies 250 mg/L for COD, 80 mg/L for $BOD_5$, 20 mg/L for $NH_3$–N, 20 mg/L for $NO_3^-$–N, 5 mg/L for $PO_4^{3-}$, 1,000 mg/L for TSS, 3,000 mg/L for TDS, 40°C for temperature and 6–9 for pH [55]. The effluent discharge limit of a wet coffee processing wastewater has to comply with standard discharge limits depending on local environmental legislation. The effluent concentrations for some parameters of HSSFCW cells failed to comply with the discharge limits. However, the values of $NO_3^-$–N, $NH_3$–N, $PO_4^{3-}$, TDS, temperature and pH comply with discharge limits. It is obvious that in case of discharging to a municipal sewer discharge limits are less stringent than when the effluent is discharged to a sensitive receiving water bodies (rivers, Lakes, estuaries, Sea, etc.). For this reason, the removal of organic compounds is important to avoid anaerobic conditions in the receiving waters. The presence of oxygen depleting substances leads to very low concentration of DO in the receiving water bodies. This in-turn affects aerobically respiring aquatic organisms [9].

Fig. 7. Planted HSSFCW cells before (a) and after (b) feeding with pretreated WCPWW.

Effluent from the HSSFCW cell planted with *V. zizanioides* showed DO concentration ranging from 0.92 ± 0.34 mg/L to 4.10 ± 0.72 mg/L. There were only slight differences in temperature and pH between influent and effluents of HSSFCW cells.

### *3.3.1. Removal of $BOD_5$ and COD*

Fig. 8 shows the mean $BOD_5$ and COD removal efficiency of the HSSFCW cells. The removal efficiency of the HSSFCW cells planted with rooted vegetation ranged from 76.20% to 78.50% for $BOD_5$ while it ranged from 69.10% to 80.10% for COD. The maximum $BOD_5$ removal efficiency of 78.50% was achieved by the HSSFCW cell planted with *V. zizanioides* followed by HSSFCW cell planted with *C. alternifolia* (77.30%) and *P. purpureum* (76.20%). The order of COD removal efficiency followed the HSSFCW cell planted with *V. zizanioides* (80.10%), *C. alternifolia* (78.90%) and *P. purpureum* (77.40%).

### *3.3.2. Removal of nitrogen species*

Nutrients mainly P and N promote eutrophication in lakes, streams and estuaries are they are limited nutrients in aquatic environment [8]. HSSFCW cell planted with *V. zizanioides* showed better removal efficiency for $BOD_5$ (78.50%) and COD (80.10%) followed by HSSFCW cell planted with *C. alternifolia* with removal efficiency of 77.30% and 78.90%, respectively. Whereas HSSFCW cell planted with *P. purpureum* showed a removal efficiency of 76.20% and 77.40% for $BOD_5$ and COD, respectively. The minimum $BOD_5$ (61.70%) and COD (69.10%) removal efficiency were achieved by unplanted (control) HSSFCW cell. Finding from this study shows that most CW cells planted with rooted emergent plants lead to higher organic matter removal compared to unplanted CW cell. This indicates that the rooted emergent plants contribute to WCPWW treatment process in a number of ways including providing surface area for microorganisms responsible for biodegradation, increasing uptake of nutrients and trace elements and oxygen transfer [47].

The highest $BOD_5$ and COD removal efficiency of HSSFCW cell planted with *V. zizanioides* might be associated with the capacity to supply DO as the result of a massive, finely structured root system which are very important for the survival of microorganisms responsible for biodegradation of organic matter and aerobic oxidation in root zones. DO is an important parameter in a wetland since its amount is directly related to the population size and community of aerobic bacteria sustained by the system [47]. In this study, it has been revealed that DO variations in HSSFCW cells planted with rooted emergent plants and unplanted indicated that DO level increased from the influent to the effluent. An increase of DO level from 1.40 ± 0.35 mg/L to 4.10 ± 0.72 mg/L was observed in HSSFCW cells planted with emergent plants but it increased from 1.40 ± 0.35 mg/L to 1.60 ± 0.10 mg/L in unplanted HSSFCW cell. Wetland plants also improve organic matter removal as the result of growth of biofilms on the root surface, releasing chelating substances and enzymes by their roots which enhance adsorption and degradation of organic matter and adsorption onto soil and sand [23]. In the current study, the $BOD_5$ and COD concentrations of wet coffee processing effluent of the CWs failed to comply with the national discharge limits.

The mean influent $NO_3^-$–N and $NH_3$–N concentrations were respectively 37.70 ± 10.50 mg/L and 2.40 ± 1.0 mg/L. After 7 d the constructed wetlands were able to reduce the concentration of $NO_3^-$–N and $NH_3$–N. Table 6 shows the mean concentrations of $NO_3^-$–N and $NH_3$–N in the WCPWW of the system. Table 7 shows the removal efficiency of nitrogen species by the HSSFCW cells planted with rooted emergent plants and unplanted HSSFCW cell (control).

The maximum $NO_3^-$–N removal efficiency was achieved by HSSFCW cell planted with *V. zizanioides* (70.2%) followed by HSSFCW cell planted with *C. alternifolia* (63.10%), *P. purpureum* (58.3%) and unplanted HSSFCW cell (43.20%). Similarly, the maximum $NH_3$–N removal efficiency was achieved by HSSFCW cell planted with *V. zizanioides* (50.1%) followed by HSSFCW cell planted with *P. purpureum* (45.80%), *C. alternifolia* (41.60%) and unplanted (29.0%) cell. In general, HSSFCW cell planted with *V. zizanioides* showed better removal efficiency of 70.20% for $NO_3^-$–N followed by HSSFCW cell planted with *C. alternifolia* (63.10%) and *P. purpureum* (58.30%) for $NO_3^-$–N while HSSFCW cell planted with *V. zizanioides* showed better removal efficiency of 50.10% for $NH_3$–N followed by HSSFCW cell planted by *P. purpureum* (45.80%) and *C. alternifolia* (41.60%). Concentrations of $NO_3^-$–N and $NH_3$–N from the effluent of the study were compared with the national effluent discharge limits. The effluents from all the HSSFCW cells comply with discharge limits for $NH_3$–N except effluents from $HSSFCW_3$ for $NO_3^-$–N (21.40 mg/L). As shown in Fig. 9, the removal of $NO_3^-$–N was

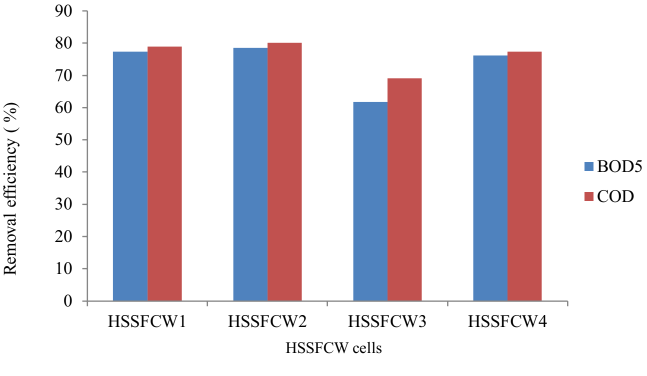

Fig. 8. $BOD_5$ and COD removal efficiency of HSSFCW cells.

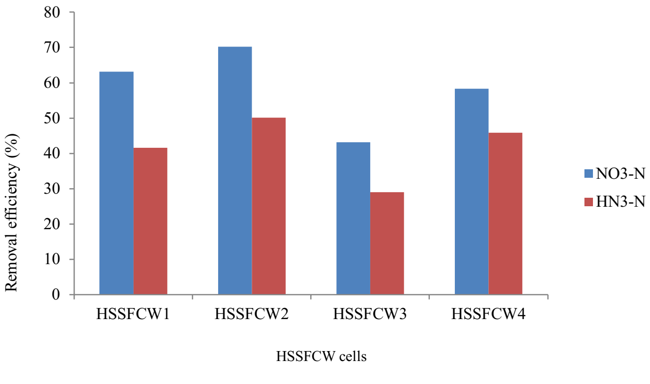

Fig. 9. Nitrogen removal efficiencies of the HSSFCW cells.

slightly higher in all the HSSFCW cells might be due to the transformation of nitrogen through nitrification process in the presence of high DO in the system. Ammonification process occurs under both aerobic and anaerobic conditions that improved removal of nitrogen species by HSSFCW cells planted with emergent vegetation might be associated with transport oxygen by macrophytes down to the roots where it diffuses into the sediment to produce an aerobic micro-environment [41]. In this study, the high nitrogen removal efficiency by HSSFCW cell planted with *V. zizanioides* might be due to its high biomass content and root mat, which enables it to uptake more soluble inorganic nitrogen species. However, the unplanted HSSFCW cell showed lower nitrogen removal efficiency. This shows that wetland plants can improve nitrogen removal of CWs. The possible reason for the lower removal of efficiency of $NO_3^-$–N and $NH_3$–N in the present study might be due to the fact that the HSSFCW cells only operated for short period of time, which is not sufficient for the plants to develop good root mat. This indirectly decreases the aerobic region in the constructed wetlands. Therefore, the short operational period, short HRT, high organic loading and less root mat development, might have lowered the aerobic region which accounts for the lower nitrogen removal efficiency.

### 3.3.3. Removal of phosphorus

Phosphorus is a limited nutrient that must be removed from wastewater as its disposal in water bodies causes eutrophication phenomenon [2]. In this study, the mean $PO_4^{3-}$–P removal efficiency by the HSSFCW cells was found to be 70.30% ($HSSFCW_1$), 79.60% ($HSSFCW_2$), 57.40% ($HSSFCW_3$) and 68.50% ($HSSFCW_4$) (Fig. 10).

It can be seen that all of the HSSFCW cells planted with emergent plants showed better $PO_4^{3-}$–P removal efficiency might be due to combination of mechanisms such as adsorption, complexation and uptakes. The maximum $PO_4^{3-}$–P removal efficiency of 79.60% was achieved by HSSFCW cell planted with *V. zizanioides*. The removal efficiency of $PO_4^{3-}$–P in HSSFCW cells planted with emergent wetland plants was found higher than unplanted HSSFCW cell (control). It might be due to the fact that phosphorus is removed by precipitation, adsorption onto the substrate, and biological uptake by the plants and microorganisms. As a result, the phosphorus concentration presented in the influent WCPWW decreased significantly in the effluent. Adsorption onto the substrate, complexation with organic matter, precipitation with multivalent cations (e.g., Al, Fe, Ca), and soil mineral constituents and uptake by the plants and microorganisms might be the dominant phosphorus removal mechanisms in the CWs [43]. However, most studies revealed that plant uptake and subsequent harvest is the only reliable long-term phosphorous removal mechanism. Harvesting is essential because plants detritus tend to release phosphorous into water during decomposition, thus, decreases the phosphorous removal efficiency of the system [23].

### 3.3.4. Removal of solids (TSS and TDS)

The mean influent and effluent concentrations and removal efficiency of the HSSFCW cells for TSS, TDS and EC are shown in Fig. 11. The better removal efficiencies for TSS (72.40%) and TDS (51.20%) were achieved by the HSSFCW cell planted with *V. zizanioides* followed by HSSFCW cells planted with *C. alternifolia* (67.50% for TSS and 47.80% for TDS), *P. purpureum* (66.90% for TSS and 46.90% for TDS). Whereas, the minimum removal efficiency was observed in unplanted HSSFCW cell with 65.8% removal efficiency for TSS and 42.80% removal efficiency for TDS. The maximum removal efficiency of EC was achieved by the HSSFCW cell planted with *P. purpureum* (31.10%) followed by the HSSFCW cell planted with *C. alternifolia* (30.4%), HSSFCW cell planted with *V. zizanioides* (29.70%) and unplanted HSSFCW cell (22.30%). These results indicated that the performance of HSSFCW cell vegetated with *V. zizanioides* showed higher removal efficiency for TSS (72.40%) and TDS (51.20%) compared to HSSFCW cell planted with *C. alternifolia* (67.50% for TSS and 47.80% for TDS) and HSSFCW cell planted with *P. purpureum* (66.90% for TSS and 46.90% for TDS). The roots of *V. zizanioides* are more diversified than the other two plants that block the movement of suspended solids which minimizes the effluent solids concentration, hence increasing removal efficiency.

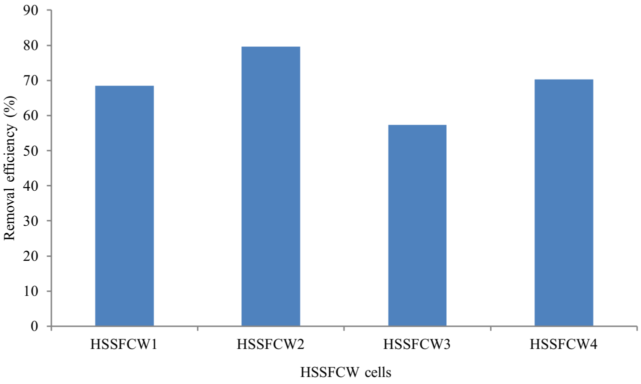

Fig. 10. Phosphorus removal efficiency of the four HSSFCW cells.

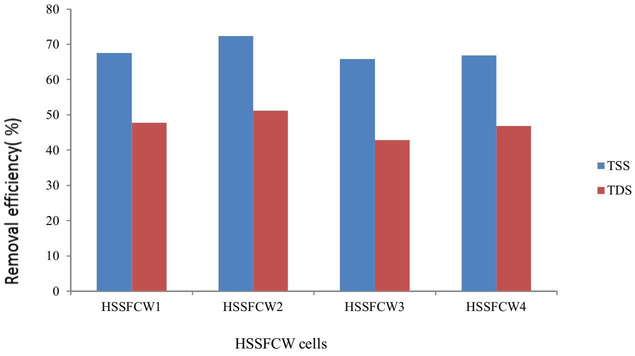

Fig. 11. TSS and TDS removal efficiency of the HSSFCW cells.

## 4. Conclusions

The selection of eco-friendly, cost effective, and adaptable wastewater treatment method is very critical to comply with the stringent discharge regulations. The WCPWW is medium to high strength agro-industrial effluent that needs proper treatment before discharged to the environment. In this study, an integrated system consisted of sedimentation, aeration, and HSSFCWs planted with different species of rooted emergent wetland plants was used to treat WCPWW. In order to avoid the poor growth conditions at the inlets of the HSSFCW cells created due to high strength WCPWW, the wetland plants (*C. alternifolia*, *V. zizanioides*, and *P. purpureum*) were fed with tap water: WCPWW mixture at different ratios (week 1: 75:25, week 2: 50:50, week 3: 25:75, and week 4: 0:100) for about 28 d until the plants establish themselves. The results of the study clearly demonstrated that the integrated treatment system achieved high retaining potential and removal efficiency of pollutants from the WCPWW. The HSSFCW cell planted with *V. zizanioides* demonstrated a high removal efficiency for $BOD_5$ (75.4%), COD (80.30%), $NH_3$–N (64.30%), $NO_3^-$–N (59.30%), $PO_4^{3-}$–P (85.70%), TSS (68.40%), and TDS (54.70%). A significant difference was observed between planted and unplanted HSSFCW cells in removing nutrients ($NH_3$–N, $NO_3^-$–N, $PO_4^{3-}$–P) from the WCPWW might be due to uptake by the wetland plants and microbial communities there. The three HSSFCW cells planted with rooted emergent wetland plants showed much high removal efficiency compared to the control. $HSSFCW_2$ showed better removal efficiency for the studied parameters and improved DO level (4.10 mg/L). Among the wetland plants used, *V. zizanioides* showed good potential of organic matter and nutrients removal might be due to better nutrient uptake and storage capacity, numerous root hairs that provided a better filtration, sedimentation, and adsorption of solids as well as higher surface area for the attachment of microbes responsible for pollutants biodegradation. The treated effluent meets the national discharge limits for most of the parameters studied. The performance of the integrated system might give an insight into the potential use of HSSFCW planted with appropriate wetland plant as an alternative eco-friendly and cost-effective treatment for WCPWW. It can be concluded that in a region where no land scarcity exist, treatment of WCPWW can be achieved using HSSFCW planted with carefully selected plant species and often very cost effective and environmentally friendly. The scaling up of the integrated system into a large industrial scale offers an attractive alternative for low-income countries such as Ethiopia to achieve environmental and public health benefits.

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