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Integrated system for the treatment of blackwater and greywater via UASB and constructed wetland in Egypt

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ABSTRACT

Municipal wastewater separation into black and greywater proved to be an efficient system to prevent the contamination of greywater, reduce the volume of fecal contaminated wastewater as well as reducing the cost of treatment. Meanwhile, up-flow anaerobic sludge blanket (UASB) proved to be a cost effective pretreatment system for wastewater. On the other hand, constructed wetlands (CWs) offer a low-cost alternative for wastewater treatment in developing countries, particularly in the arid and semi-arid areas. In the present study, two separate UASB reactors were used as a primary treatment step followed by CW for the treatment of blackwater and greywater separately. The hydraulic residence time (HRT) of UASB was kept constant at 6 and 24 h for the two reactors, while the organic loading rates (OLRs) were 1.88 and 1.16 kg/m^3/day for the treatment of blackwater and greywater, respectively. The removal efficiency of chemical oxygen demand (COD) in the UASB reactor was about 60% for greywater and 68% for blackwater. Further improvement of the quality of the treated wastewater was obtained after the application of the horizontal subsurface flow CW. The overall results indicated that the integration between the UASB and the CW proved to be very efficient for the treatment of blackwater. The overall removal of the key constituents represented by COD, biological oxygen demand (BOD) and total suspended solids (TSS) in the final effluent was 87.7%, 89.5% and 94% for greywater and 94.2%, 95.6% and 94.9% for blackwater. It therefore, recommended that the combination of UASB and CW is an effective system for the treatment of blackwater and greywater.

Keywords: UASB; Constructed wetland; Blackwater; Greywater; Wastewater

1. Introduction

Sustainable water management in combination with highly efficient wastewater treatment and water recycling, wherever possible, is the only way to meet the challenge of water shortage in the arid and semi-arid countries. In addition, increasing scarcity of water in the world along with rapid population increase in urban areas gives reason for concern and the need for appropriate water management practices [1,2].

On the other hand, municipal wastewater separation into black and greywater proved to be an efficient system to prevent the contamination of greywater, reduce the volume of fecal contaminated wastewater as well as reducing the cost of treatment [3,4]. On-site greywater reuse has the potential to play a significant

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role. Indoor domestic water demand (excluding garden irrigation and other external uses) in developed countries usually ranges between 100 and 180 L/d PE or 36–66 m^3/y PE [5,6], comprising 30–70% of the total urban water demand. In urban areas the most feasible greywater reuse option is for toilet flushing, which can reduce individual in-house net water demand by 40–60 L/d PE. If this practice becomes widespread, reduction of 10–25% in urban water demand can be achieved. For example, Friedler and Galil [7] showed that in 2023, with a 30% penetration ratio (i.e., 30% of houses having greywater reuse units installed), greywater reuse for toilet flushing in the domestic sector could save about 50 MCM/y in Mediterranean countries [7]. This consists of about 5% of the projected national urban water demand and equals the capacity of a medium-size seawater desalination plant. The authors further demonstrated that reaching 30% penetration in 20 years is realistic if the government would promote and encourage such a practice [7]. Indeed on-site greywater reuse has been investigated extensively in the last decade, especially in the EU, Japan, USA and Australia. However, full-scale commercial systems are not getting common [3,6].

On the other hand, up-flow anaerobic sludge blanket (UASB) proved to be a cost effective simple and low energy consumption pretreatment system for wastewater [8,9]. It is the most widely and successfully high rate anaerobic technology for treating several types of wastewater. The success of the UASB reactor can be attributed to its capability to retain a high concentration of sludge and efficient solids, liquid and water phase separation. Moreover, the removed organic matter is converted into biogas, as a source of energy. In addition, due to the better stability and low production of the sludge under the anaerobic process, the cost involved in further treatment can considerably be reduced [8,9]. Nevertheless, the effluent from UASB does not, generally, comply with the local standards for treated effluent reuse.

Meanwhile, CWs offer a low-cost alternative for wastewater treatment in developing countries, particularly in the arid and semi-arid regions [9,10]. It has been proved that such CWs are simple in construction, low energy consumption, low cost in maintenance and operation [12]. The CWs are also recognized as one of the technologies that can be used in conjunction with or as an alternative to septic tanks, especially in small and isolated communities [9–13]. They have low investment and operation costs, produce high quality effluent with less dissipation of energy, and are relatively simple to operate [11–13]. Studies of CWs show that removal percentages of total suspended solids (TSS), biological oxygen demand (BOD), chemical oxygen demand (COD) and pathogens are generally high, whereas removal percentages of nutrients (N and P) are often lower and more variable. In addition, CWs have certain advantages over conventional treatment systems: that they can be established in the same place where the wastewater is produced; maintained by relatively untrained personnel; and have lower energy requirements [11–13].

The present study focuses on the treatment of greywater and blackwater by the UASB followed by constructed wetlands (CWs) as simple, low cost, low energy and friendly techniques for the urban and decentralized areas.

2. Materials and methods

2.1. UASB reactor

The research was carried out with the effluent of a 0.25 m^3 UASB reactor. The reactors were manufactured from non-transparent polyvinyl chloride (PVC) and fed continuously with wastewater through a connection from the manhole sewerage system. The effluent of UASB for either blackwater or greywater treated wastewater was fed to CW for further treatment. The operating conditions and the size of the substrate media of the UASB and the CWs for the both blackwater and greywater are given in Table 1. It is clear that the organic loading rate (OLR) was fixed for greywater and blackwater reactors at 1.88 and 1.16 kg/m^3/day, respectively (Fig. 1).

Table 1
Operating conditions the UASB and the constructed wetlands for the both blackwater and greywater

Item	Greywater UASB	Blackwater UASB	Greywater wetland	Blackwater wetland
HRT*	6 h	24 h	5 days	10 days
OLR** (COD)	1.88 kg/m^3/day	1.16 kg/m^3/day	61 kg/ha/day	70.15 kg/ha/day
OLR** (BOD)	1.1 kg/m^3/day	0.56 kg/m^3/day	33.24 kg/ha/day	31.4 kg/ha/day

*The hydraulic residence time (HRT) was calculated according to the equation given by Crites and Tchobanoglous [6].
**OLR, organic loading rate.

Fig. 1. UASB reactor used in the study.

2.2. Wetland units

The wetlands used in this study were horizontal subsurface flow constructed wetland (SSF-h CW). Schematic diagrams of the UASB and SSF-h CW are shown in Fig. 2. In addition, the design parameters of the wetland units are given in Table 2.

2.3. Plants

Phragmites australis is reeds that are planted in the studied CWs. The rhizomes were collected from a near-by marshland, and planted at a density of 3 rhizomes/m^2. The wetland units were fed continuously with the UASB reactor effluent.

2.4. Sampling and analytical methods

Composite samples of raw wastewater and effluents of the different treatment units were collected and analysed for the physical and chemical parameters namely; pH, COD, BOD, TKN, ammonia, phosphorus, total dissolved solids (TDS) and TSS. Determination of the colloidal fraction was carried out by filtration of the

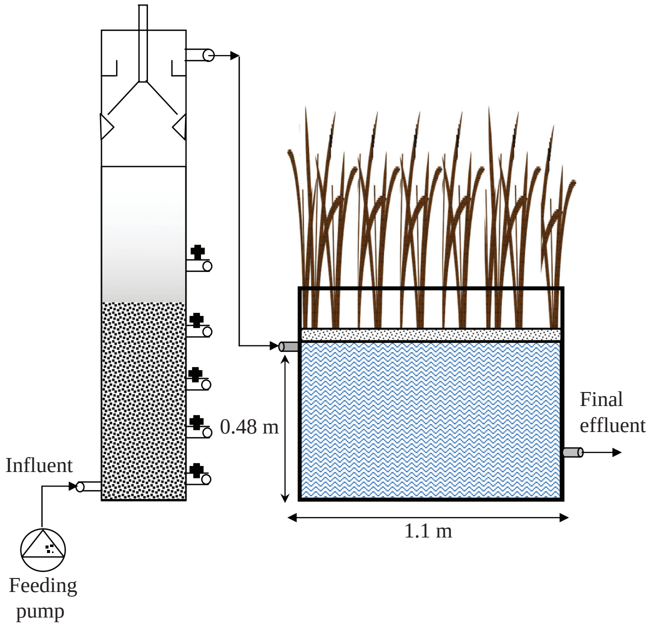

Fig. 2. Schematic diagram of the treatment units.

wastewater samples using filter paper having pore size of 4.4 µm. The difference between the total value (without filtration) and the colloidal part is identified in this study for simplicity as settleable. However, it represents the settleable as well as the supra-colloidal fraction of the concerned parameter. The soluble fraction was determined in the filtrate of the membrane filter paper (0.45 µm). Fecal coliform counts (FC) were carried out using grab samples. These parameters were carried out according to *Standard Methods for Examination of Water and Wastewater* [14].

3. Results and discussion

The main characteristics of 25 composite samples of raw wastewater (greywater and blackwater) are given in Table 3.

Table 2
Design parameter of the wetland units

Item	Greywater wetland	Blackwater wetland
No. of units	1	2
Substrate	Sand (0.5–1.0 mm)	Sand (0.5–1.0 mm)
Length (m)	1.1	1.1
Width (m)	1.0	1.0
Depth (m)	0.40	0.40
Plant	Reed	Reed
Water level (cm)	0.48	0.48

Table 3
Main characteristics of the wastewater (standard deviation in brackets)

Parameter	pH	COD	BOD	TSS	TKN	Ammonia	TDS
Unit		mgO_2/L	mgO_2/L	mg/L	mgN/L	mgN/L	mgN/L
Greywater	6.7–7.7	470 (±82)	267 (±50)	148 (±73)	9.8 (±1.6)	7.0 (±0.6)	519 (±98)
Blackwater	7.4–8.3	1160 (±391)	558 (±107)	363 (±131)	214 (±34)	150 (±16)	1401 (±256)

3.1. Greywater treatment

UASB reactor

The treated effluent showed that the COD, BOD and TSS were reduced from 470, 276 and 148 to 170, 98 and 50 mg/L, respectively. The data are presented in Table 4. The corresponding average percentage of removal was 63.8%, 64.5% and 66.1%, respectively.

CW

The effluent of UASB still does not complying with the National Regulatory Standards. Combining UASB and CW is well known practice [4,9,10]. Consequently, post treatment step is required by feeding the UASB effluent to the SSF-h CW. The overall removal of the CW in terms of COD, BOD and TSS was 65.9%, 70.3% and 82.2%, while the corresponding residual concentrations were 58, 29 and 9 mg/L, respectively. Fig. 3 reflects the performance of the combined UASB and SSF-h CW for the treatment of the greywater. Therefore, SSF-h CW unit was found to be efficient for the treatment of the UASB effluent.

The obtained results indicate that the combined treatment system (UASB followed by SSF-h CW) for the treatment of greywater is highly efficient as presented by the reduction in the COD, BOD, TSS and sulphides. The total removal rate was 87.7%, 89.5%, 94.0% and 77.8%, respectively. In addition, improvement in the turbidity of the final effluent was also achieved as it reduced from 126.7 to 8.4 NTU. Meanwhile, TKN and

Table 4
Efficiency of the combined UASB followed by CW systems for the treatment of greywater (concentration as mg/L)

Parameter	n^*	Greywater					
		Raw	UASB eff	UASB effluent %R	CW effluent	CW effluent %R	T %R
COD	25	469.9	170.0	63.8	58.0	65.9	87.7
BOD	25	275.9	98.0	64.5	29.1	70.3	89.5
TSS	25	147.6	50.0	66.1	8.9	82.2	94.0
Turbidity	25	126.7	60.3	52.4	8.4	81.3	93.4
Sulphides	25	5.7	12.1	−113.7	1.3	89.6	77.8
TKN	25	9.8	7.4	24.3	4.6	36.0	52.7
TP	25	3.1	2.5	18.4	1.7	32.4	44.0
FC	3	$<10^3$	$<10^3$		$<10^3$		

* Number of samples.

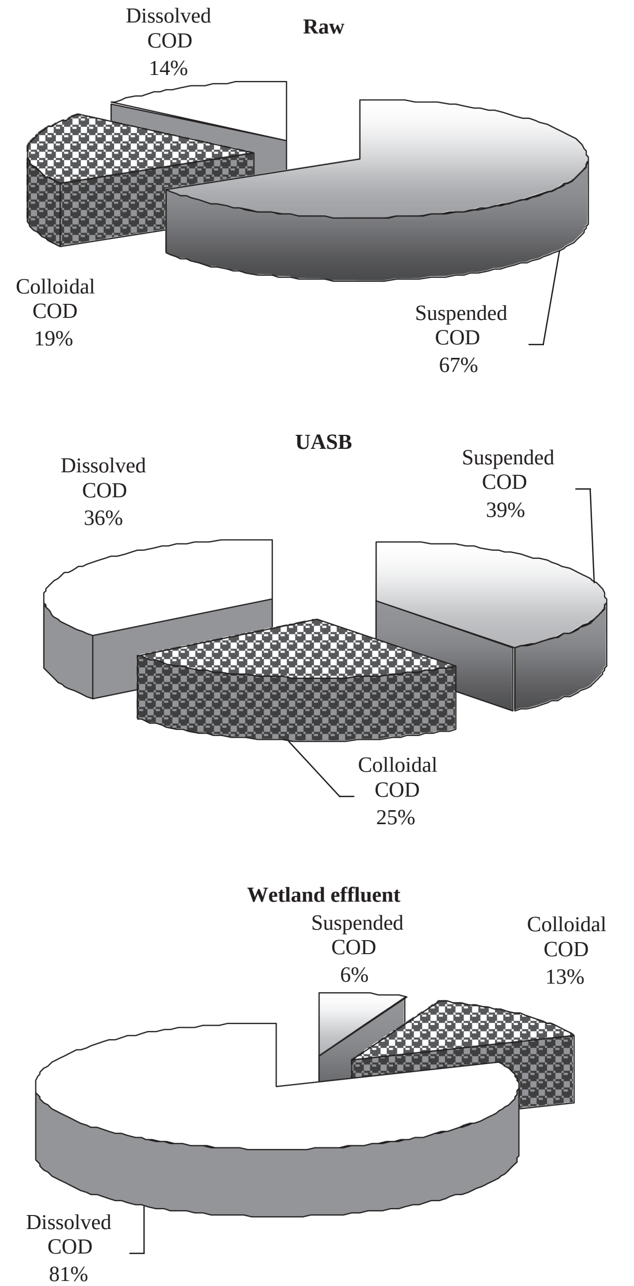

Fig. 3. COD fractions at different treatment steps for blackwater.

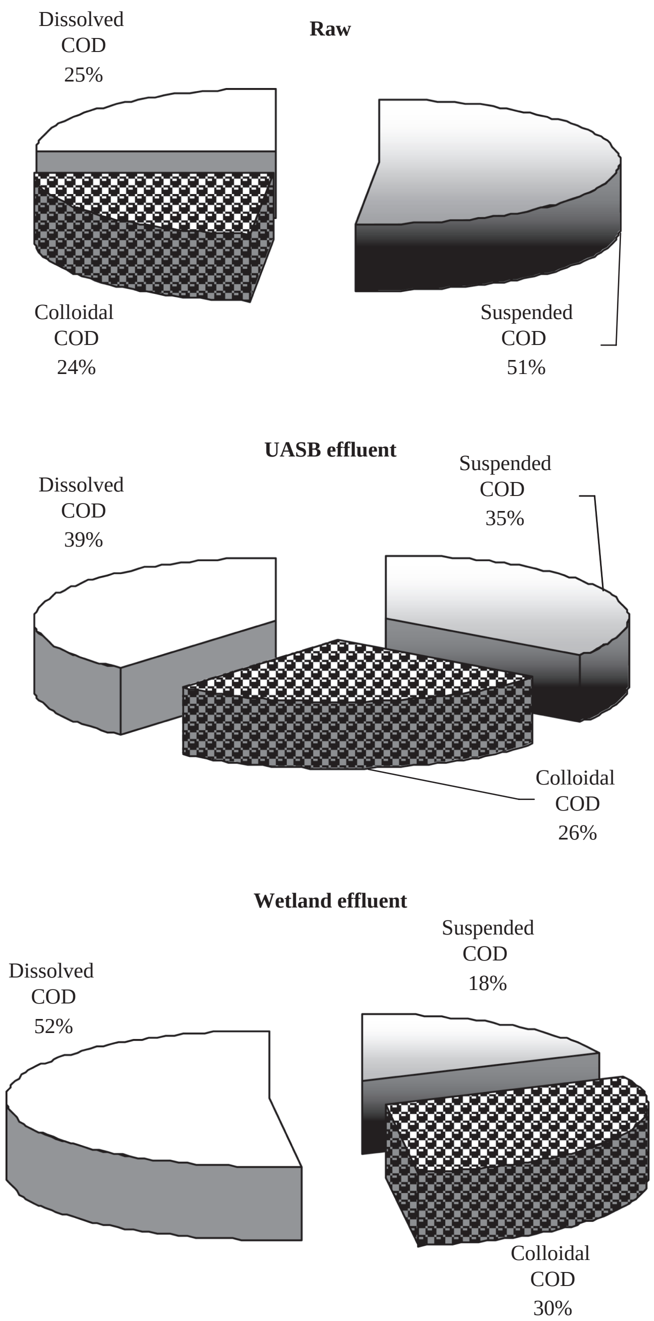

Fig. 4. COD fractions at different treatment steps for greywater.

TP were reduced by 52.7% and 44%, respectively. The corresponding concentration was 4.6 and 1.7 mg/L. The data are shown in Table 4. FC counts were found to be <10^3 MPN/100 mL.

Assessment of the COD_{tot} contributed by the different COD fractions indicated that the highest fraction in the raw sewage is the settleable part. Due to hydrolysis reactions which take place in the UASB, the soluble and colloidal fractions increased in the

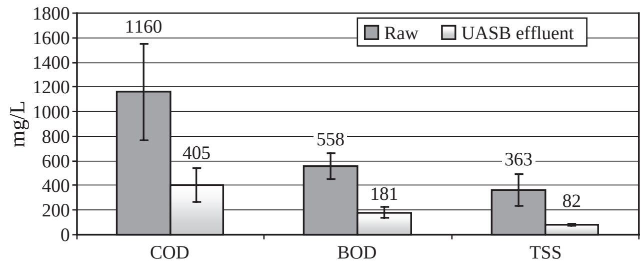

Fig. 5. Performance of UASB reactor for the treatment of blackwater.

effluent of the UASB reactor. Further increase of the soluble fraction has been recorded in the CW effluent (Fig. 4). This indicates the progress of biochemical reactions occurring under aerobic, anoxic and/or anaerobic conditions. These results are in a good agreement with that obtained by El-Khateeb and El-Gohary [9] and Abdel-Shafy et al. [11].

3.2. Blackwater treatment

UASB reactor

Fig. 5 shows the performance of UASB reactor for the treatment of blackwater. The average removal rates of COD, BOD and TSS were 65.1%, 67.5% and 77.4%, while the corresponding concentrations were 405, 181 and 82 mg/L, respectively.

CW

The UASB blackwater effluent was further treated with two stages SSF-h CWs. The percentage of reduction in the pollution parameters represented by COD, BOD and TSS reached 83.5%, 86.4% and 89%, respectively (Fig. 6). The corresponding residual concentration was 67, 25 and 9 mg/L (Table 5).

Table 5 shows the efficiency of the combined UASB and SSF-h CW for the treatment of blackwater. The residual concentration of COD, BOD, TSS and sulphides was 67, 25, 9 and 0.8 mg/L, respectively. The corresponding removal rate was 94.2%, 95.6%, 97.5% and 92.7%. The turbidity was reduced efficiently from 258.7 to 9 NTU with removal rate of 96.5%. TKN and TP were reduced by 81.8% and 74%, with residual concentration of 38.9 and 9.3 mg/L, respectively. FC counts were below 10^3 MPN/100 mL in the final SSF-h CW effluent. This may attributed to long retention time, which enhances the quality of the effluent [15].

As mentioned in COD fractions of the greywater, COD fractions of blackwater show the same behavior (Fig. 7).

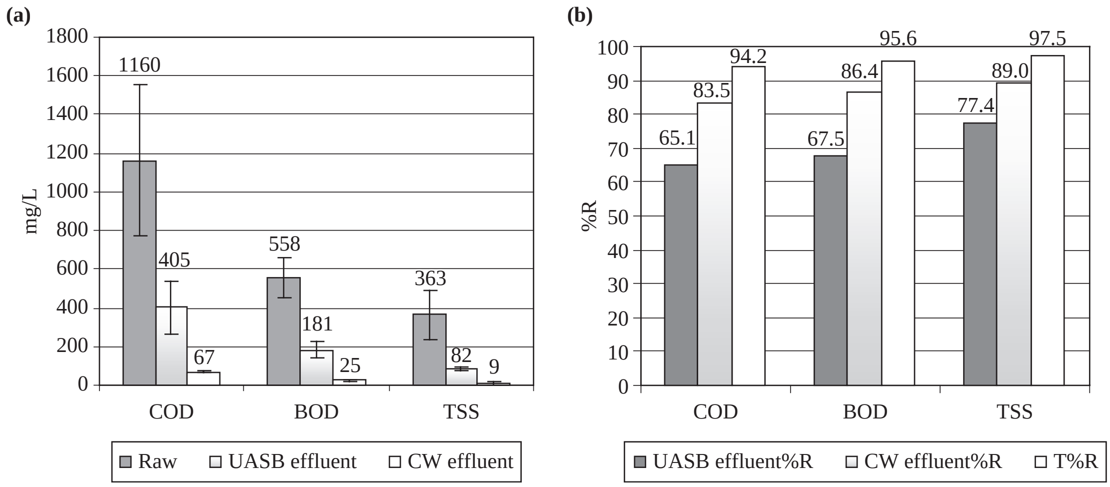

Fig. 6. Performance of the combined UASB and CW for the treatment of blackwater (a) characteristics of blackwater as well as treated effluents, (b) the corresponding percentage removal.

The overall results reveal that the enhancement of the effluent quality is due to the relatively low velocity and high surface area of the SSF-h CW media. Such wetlands act like horizontal gravel filter and thereby provide opportunities for TSS separations by gravity sedimentation, straining and adsorption on biomass film attached to gravel and root system as well as the uptake of certain nutrients by such biomass [14]. Consequently, the combination of UASB followed by SSF-h CW proved to promising technology for the treatment of either greywater or blackwater.

It is worth mentioning that the present investigation proved that the advantages of the UASB are a substantial saving in operational costs as no energy is required for aeration; on the contrary energy is produced in the form of methane gas, production. The process can handle high hydraulic and OLRs. Thus, the applied technologies are compact. The technologies are simple in construction and operation; so they are low cost. The systems can be applied everywhere and at any scale as little if any energy is required, enabling a decentralized approach for wastewater treatment application. The excess sludge production is low, well stabilized and easily dewatered so does not require extensive costly post treatment. Meanwhile, the valuable nutrients (N and P) are conserved which give high potential for crop irrigation.

4. Conclusions

From the available data it can be concluded that the use of CW as a post treatment step after a UASB reactor is a promising technology for wastewater reclamation and reuse in arid and semi-arid areas.

Table 5
Efficiency of the combined treatment system for the treatment of blackwater

Parameter	n^*	Blackwater					
		Raw	UASB eff	UASB effluent %R	CW effluent	CW effluent %R	T %R
COD (mg/L)	25	1160.3	405.0	65.1	67.0	83.5	94.2
BOD (mg/L)	25	557.6	181.0	67.5	25	86.4	95.6
TSS (mg/L)	25	363.2	82.0	77.4	9.0	89.0	97.5
Turbidity (NTU)	25	258.7	90.0	65.2	9.0	90.0	96.5
Sulphides (mg/L)	25	10.9	16.5	−51.3	0.8	95.2	92.7
TKN (mg/L)	25	213.6	126.4	40.8	38.9	69.3	81.8
TP (mg/L)	25	35.6	21.1	40.6	9.3	56.2	74.0
FC (CFU)	3	2.3×10^{11}	3×10^{10}	87	$<10^3$	99.99999	100

*Number of samples.

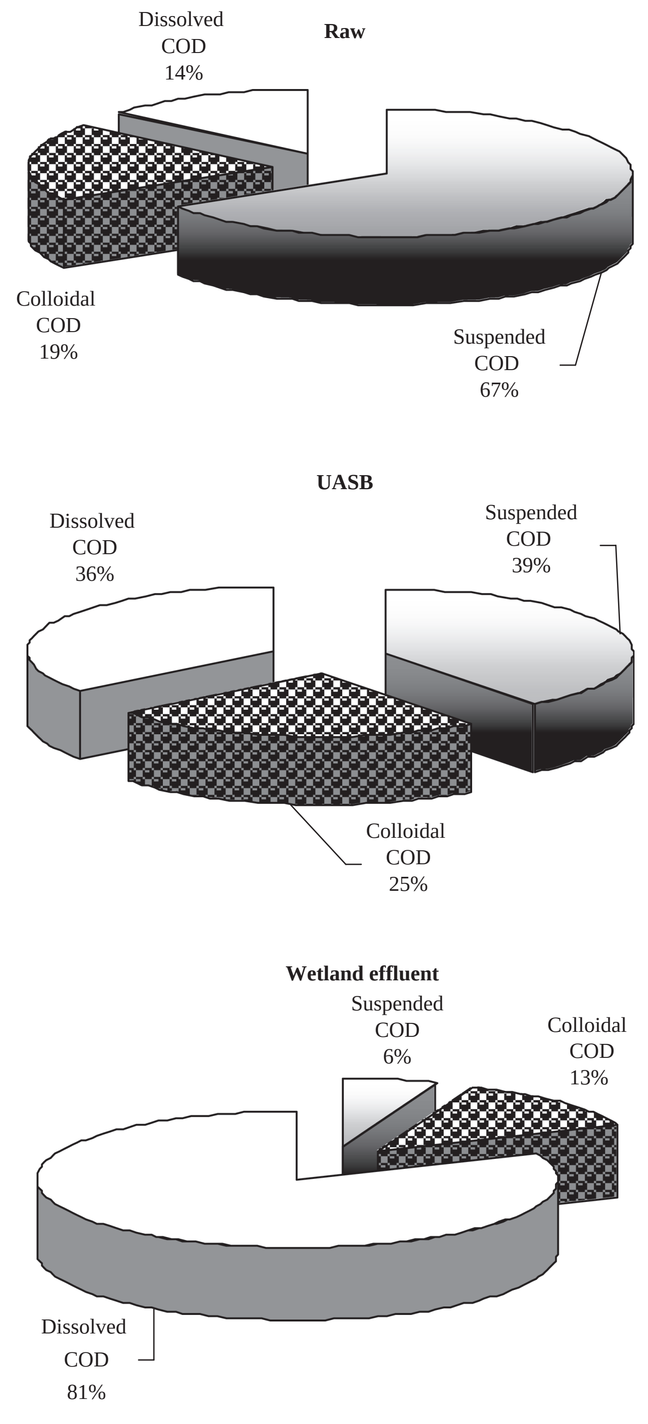

Fig. 7. COD fractions at different treatment steps for blackwater.

5. Future work

- The use of economic plant (instead of *P. australis*) will be considered.
- The work will be extended at different organic and hydraulic loading rates applied to both UASB and the wetland system.
- The evapotranspiration rates will be measured.

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