TECHNICAL DESCRIPTION

AFADS DEPURATOR

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1. SCOPE

The present document describes the technical features and potential of the biologic depurator **AFADS** (from the Spanish acronym of the 4-stage system **A**naerobic + **Phytodepuration** + **Aeration** + **Solar Distillation**). The same is a technology for the treatment of organic wastewater (pig manure, poultry dung, municipal or food industry wastewater, and with some modifications even olive mill wastewater) with null or even negative CO_2 emissions and low implementation cost. Generic values (Spanish averages) of temperatures, solar irradiation, composition of wastewaters and production of biogas and biomass were adopted for the calculations. The same can vary as a function of the site's climatic parameters and of the individual features of the wastewater to be treated, varying then as consequence the shape and dimensions of the depurator.

2. GLOSSARY

UW = Urban Wastewater
COD = Chemical Oxygen Demand.
Natural Solar distillation = consists in evaporating water inside a greenhouse with a sloped roof, and collecting the condensate that slips down the same in a trough installed on its perimeter.
Forced Solar distillation = idem, but forcing the moist air through a heat exchanger by means of an electrical fan. This way, the latent heat of condensation is recovered.
EGSB = Expanded Granular Sludge Bed.
Phytodepuration = utilization of plants to eliminate pollutants
HSB = Hydrolitic Sludge Bed.
SST = total soluble solids.
HRT = hydraulic retention time.
UASB = Upflow Anaerobic Sludge Blanket.
EDC = endocrine disruptive chemicals
PBR = photobioreactor
GAC = Granular Activated Carbon

3. ANTECEDENTS

For more than 100 years systems of decantation, filtration through sand bed, aerobic percolation and anaerobic digestion of sludge have been employed. The same are characterized by the need of big installation areas and long HRT, which means big volumes of accumulation, and hence high costs of land occupation and infrastructures. Another challenge these plants pose is their CO2 emissions. Till now this has never been an issue and present norms do not take it into account, but the scenario of the climatic change is becoming dramatic and **the following figures cannot simply be ignored**.

a) The treatment of municipal wastewaters in standard plants produces about **25 kg/inhabitant/year of CO_2**, and to these the indirect emissions (caused by the energy necessary for pumping, production and transport of the chemicals used…) must be added. If water is left untreated, the emissions are even worse, since 4 kg CH_4 / inhabitant/year are produced, which has 21 times more greenhouse power than CO_2 hence the equivalent emission is **84 kg CO_2 / inhabitant /year**.
b) In Western farms, the anaerobic treatment of pig manure and recuperation of the biogas produces **803 kg of CO_2/pig/year** , while the aerobic treatment produces **2,3 ton CO_2/pig/year** + the indirect emissions caused by the enormous amount energy needed for air blowing. If the manure is left untreated as is usually the case in the Developing Countries, and also in small farms in the Western Countries, its fermentation will produce up to 321 kg of CH_4/pig/year, equivalent to **6,75 tons of CO_2/pig/year**.

Similar calculations can be performed for cattle and poultry dung, slaughterhouse wastewater and other organic effluents of the industry. **The amount of greenhouse effect gases produced by the treatment of wastewater is enormous and results 21 times bigger when water is not treated.**

During the '70s prof. Lettinga et al. (University of Wagenigen, Netherlands) perfomed the first studies on vertical flow digesters (UASB and its variants EGSB and HSB). Said technology experimented a strong expansion on industrial scale and constant improvements since 1995. Its efficiency depends on the temperature. From the same studies of Lettinga et al. it can be deduced that with ambient temperatures below 15 ºC (59ºF) , either adding heat to the wastewater to be treated to allow the bacteria to keep their metabolism, or increasing the HRT (and hence the volume of the digester) is necessary. Said systems offer high efficiencies of organic matter elimination, but low efficiency of nitrates and phosphates elimination.

On the other side, the phytodepuration systems have been employed since the '60s, specially in U.S.A. and center - north of Europe. They feature high efficiencies of nitrites and phosphates elimination, but the efficiency of elimination of the organic matter depends of the solar irradiation received by the plants. Such systems are very economic, but of difficult application in hot – tempered and dry climates (like the Mediterranean area), which implies high evaporation losses and salinization of the water, which can even kill the plants. In cold climates their efficiency is severely hampered during winter. Furthermore they occupy big areas of land if seasonal growing species are employed. If the phytodepuration with aquatic plants is chosen (water lentil –*Lemna minor*- o water hyacinth –*Euphorbia crassipes*-) then shallow ponds with big extension should be employed, with risk to the nearby environment since said plants can be quite invasive. An example of this happened in Spain in 2005: an invasion of water hyacinth caused several environmental problem in the river Guadiana, probably because of leaks from a garden pond, (source *El País*, 30/12/2005). These plants depurate well in summer, but their metabolic activity is seriously impaired (or the plants even killed) in winter. In Kolding (Denmark) there is a phytodepuration plant shaped as a crystal pyramid with several stages of cultivation, which was a first attempt to solve the aforesaid problem by means of a greenhouse. Nevertheless, Kolding's pyramid was conceived in an era where energy was cheap. It cannot be considered sustainable with today's standards and some criteria of its design are questionable. In Portugal there are two artificial wetlands planted with bamboo for depuration of winery and UW.

The technology of the simple solar distiller (called "Chilean" o "Mexican" type) is known from one century and in practically all books or manuals on solar energy calculation formulas and sketches of them can be found.

4. GOALS OF THE AFADS DEPURATOR

The technical problem which the depurator AFADS intends to solve is the depuration of wastewater with minimal consumption of energy and environmental impact of the plant, and null or even negative CO2 emissions. The AFADS depurator has 4 stages (5 in the case of some recalcitrant wastewaters like the ones of the olive oil mills). The 4 stages contained in a compact unit (a greenhouse) are:

- Continuous vertical flow , high load anaerobic digestion.
- Phytodepuration, either by floating plants (*Lemna minor* o *Euphorbia crassipes)* or submerged ones (*Elodea canadensis*), or by microalgae.
- Airation (by trickling or packed bed percolation if macrophytes are used, by oxygen diffusion when growing algae).
- Solar distillation (natural o forced)

This simple disposition presents a series of advantages when compared to the traditional systems of wastewater biologic treatment :

- Low TRH and high elimination rate of organic matter, low land occupation, which are the typical advantages of the high load vertical flow digesters.
- Biogas production without the need of mechanical stirring of sludge (and consequent energy saving).

- Temperature stabilization of the digester by the combined greenhouse effect, latent heat transfer of the condensing moist and thermal inertia.
- Phytodepuration of the digestates in a closed environment, which avoids bad smells and leakage of the plants into lakes and rivers and their ecologic consequences this might carry.
- Aeration of the digestates by simple gravity in the case of trickling or packed bed percolation (the energy used for pumping is then partially recovered).
- Solar distillation of part of the effluent, with partial recuperation of the evaporation heat because the water condensation on the wall of the digester. This has a double benefit: the efficiency of the digester is raised since its temperature is kept more constant and at the same time the production of distilled water rises because the heat exchange area of the digester is added to the area of the tilted roof.
- High production of useful biomass throughout the year.
- More compact units, better use of the land and no odor.
- Lows pumping and maintenance costs.

5. DESCRIPTION

The AFADS depurator consists of a steel or aluminum, or even wooden structure with a transparent envelope of pyramidal or prismatic shape, which works as a greenhouse. It contains a vertical flow anaerobic digester (UASB, or EGSB, or HSB types or their variants and derivates depending on the case). The base of the structure forms a shallow (approx. 50 cm) pond, of volume greater o equal that of the reactor. It will be used for growing plants with high phytodepuration power (for instance, *Lemna minor* or *glabra* , *Eichornia crassipes,* or microalgae). Aeration is provided by trickling or percolation of the digestates, and by the oxygen production of the microalgae when these are used.

Logic consequence of the big quantity of water contained in the structure will be the abundant condensation on the transparent roof. This will be collected in a trough disposed along the internal perimeter of the structure (that's why a pyramidal, conic or however tilted roof shape is needed). The base of the digester will also have a trough for collecting the condensed water which will require just a light chlorination for being reused.

6. OPERATION PRINCIPLE

Please refer to Fig. 1. The wastewater (1) enters the digester (D) through its bottom and the particulars conditions of the flow (ascension speed < 1m/h) produce enough mixing while allowing the decantation of the solids together with the bacteria, which tend to form colonies shaped as granules and remain stable in the lower half of the digester. These granules offer the maximum contact surface with the liquid to be treated. The same is thus anaerobically digested in short time, yielding biogas (8) and stabilized sludge (9). The clarified effluent (2), still rich in nutrients, exits the upper part (about 2/3 of the digester's height) trickles or percolates a bed (B), being aerated (not necessay if microalgae are grown in the pond). When reaching the pond at the base, the water (3) is partly phytodepurated and otra partly evaporated by the sun (5). The vapor (5) will condense on the roof (P) and on the walls of the digester (D). Sliping down along the same it is collected in the troughs (C) and conducted to a tank for further use (7). The sludge that accumulates in the digester must e periodically removed, and the biomass produced in the pond must be harvested. Porbaly the easiest alternative for a farmer is just growing algae and concentrating the solution by means of a self cleaning filter. The concentrated algal solution can then be easily pumped into the digester. This has several advantages: improved robustness of the digester against EDC, higher yield of biogas, cheaper and easier automatic harvest equipment. The biogas extracted at the dome of the reactor can be cleaned and used in any suitable process. The water collected in the pond may still contain some nutrients, so it can be utilized for agricultural irrigation.

For CO_2 offset purposes, it is advisable to use the effluent water of the AFADS for cultivating bamboo. This plant grows 4 times faster and hence fixes more carbon than trees, and its biomass is suitable for the manufacture of furniture, flooring panels, fiber panels, paper pulp and many other uses that would reduce human pressure on forests. Since bamboo requires much water because of its high growth and transpiration rate, a sustainable cultivation of this plant is always the ideal complement of a wastewater treatment plant. The concept is illustrated in fig. 2.

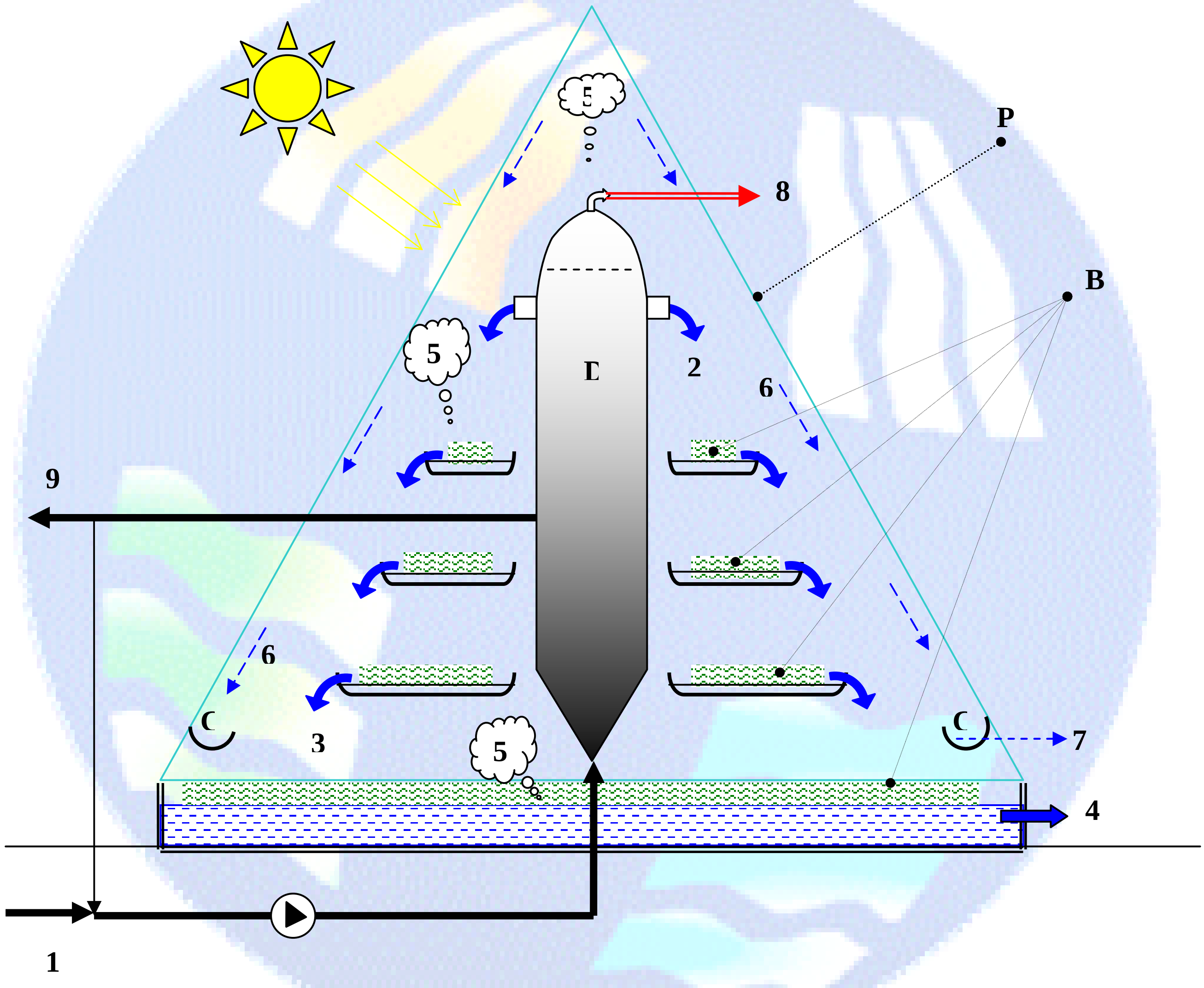
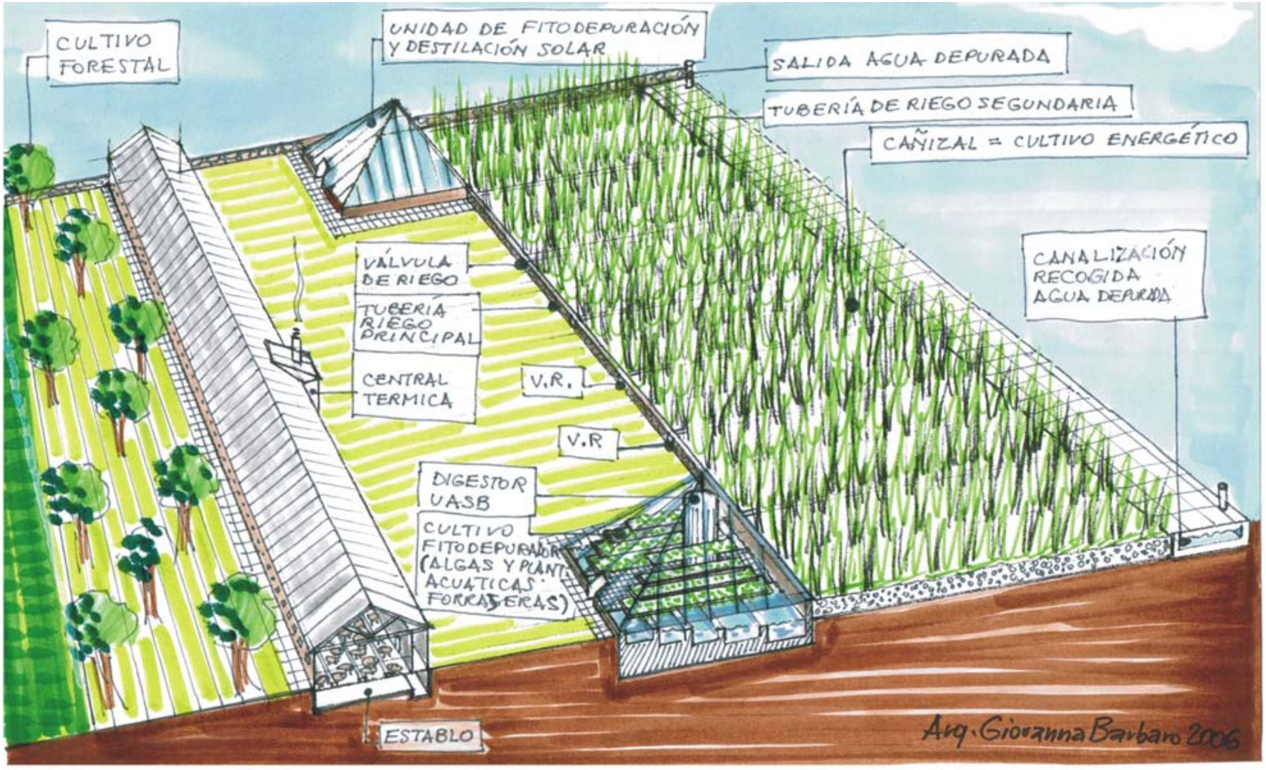


Fig. 1 – Working principle



Unidad de producción agrícola sostenible integrada con cultivo energético

Propuesta de Ing. M. Rosato y Arq. Barbaro (Col. Num. 37.658) - Barcelona 12/06/2006

Fig. 2. Sketch of a possible installation using the effluent for the irrigation of timber or fruit trees and bamboo plantations.

7. **TECHNICAL FEATURES - AFADS of 100 m^3 nominal capacity**

Square base pyramid, 22 m x 22 m, h = 20 m
Polycarbonate envelope, thickness 0,5 mm, wave of 25 mm.
Latitude of installation: 40 º (Mediterranean climate)
Daily average radiation = 15,4 MJ/m^2 / day
Yearly average temperature = 14 ºC
Working cycle: 12 hours loading, 12 hours of recirculating
Nominal flow of the of the load/recirculation pump: 2,31 l/s
Power of the load/recirculation pump = 500 - 750 W
Power of the ventilator to boost moisture condensation: 5 kW.

7.1. **1st Stage**: EGBS type digester with:
164 m^3, ∅ 4,3 m, h water = 11,3 m, h total = 16 m,
Nominal flow to depurate = 100 m^3/day
HRT = 24 hours (nominal),
$t_{nominal}$ = 20 - 30 ºC
Elimination of COD > 90% (for t >= 20 ºC and TRH > 18 hs)
Elimination of N < 25%
Production of biogas: depends on the affluent. Ranging between 0,20 to 0,25 kg CH_4 / kg of COD digested.

7.2. **2nd stage:** Aeration (trickling is assumed as minimum standard),
HRT = 11 hs., removes 0,005721 kg COD /m^3

7.3. **3rd Stage**. Phytodepuration

Phytodepuration pond: 440 m^2, depth 0,50 m, total volume 220 m^3.

This stage produces biomass with the following efficiencies (expressed as dry matter):

- *Eichornia crassipes* = 4,3 to 8,6 ton/year (10 -12 kg/day -conservative- up to 25 kg/day -optimistic- are possible)
- *Lemna sp.* = 2,98 ton/year (8 kg/day)
- Microalgae = 0,3 to 3,2 ton/year (0,9 to 8,8 kg/day assuming open pond productivity) 4,8 to 6,4 ton/year (assuming constant illumination and extrapolating from yields measured in small scale tests).

Its depuration power is the following (calculated with *Eichornia crassipes* and HRT approx. 36 hs):
Nitrogen: 1,7 Kg/day
Phosphor: 0,21 kg/day
Reduction of COD > 90%
The CO_2 fixing capacity can be estimated around 15 ton CO2 / year (assuming a dry biomass yield of 4 ton/year with 80% of C content). This means that the **AFADS process alone not only emits no CO2, but is able to fix 0,4 g of CO_2 / m^3 treated**.

7.4. **4th stage**: Solar distillation
The quantity of water evaporated (by natural evaporation + evapo-transpiration of the aquatic plants) and recovered by condensation is estimated in 1000 a 3000 l/day, depending on the adopted system of condensation (natural or forced). This water is 100% pure, apt for human or animal consume.

7.5. **5th Stage (optional for the water treatment, necessary for neutral CO_2 emissions):**
external bamboo plantation *Phyllostachys sp.*:

- up to100 ton/year/ha of dry biomass, (373 tons of CO_2 fixed / ha / year)
- edible shoot production from 1,2 to 6,7 ton/ha/year
- 100 m^3/day of effluent are enough for 18 ha of bamboo, hence can fix 6714 ton CO_2/year.

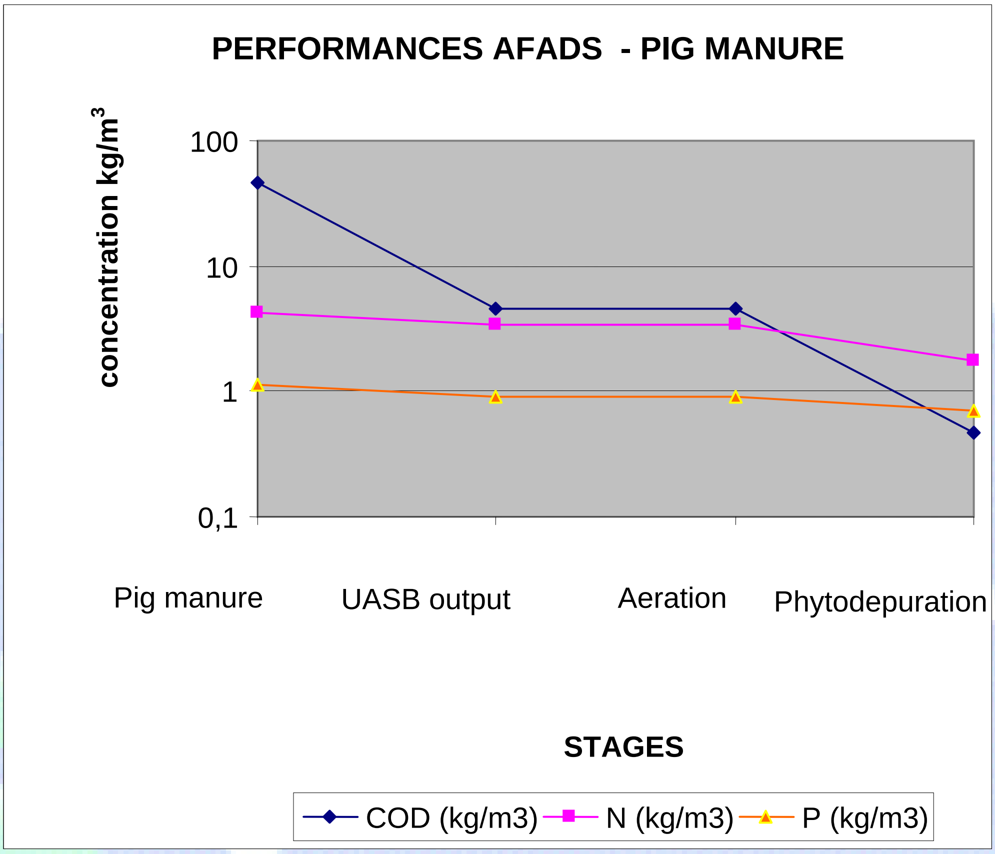
8. PERFORMANCES OF THE AFADS IN THE TREATMENT OF DIFFERENT TYPES OF WASTEWATER

8.1. Pig manure

Standard values adopted (Spain)
COD = 46.358,00 mg/l = 46,358 kg/m^3
Organic matter = 50 kg/m^3
total solids = 68,4 kg/m^3
suspended solids = 59,13 kg/m^3
volatile solids = 45 kg/m^3
N_{total} = 4,30 kg/m^3
P_{total}l = 1,15 kg/m^3
C_{total} = 17,38 kg/m^3
Ratio C/N/P = 17/4/1
PH = 7,20 (optimal for anaerobic digestion is 6,6 to 7,6)
Average t_{input} = 15 ºC
density= 1010 10 1050 kg/m^3
Net potential production of CH_4 = 8,34 kg/m^3

Assuming a 100 m^3 nominal capacity AFADS , the depuration of the pig manure in one day will be as follows (N.B. the diagram is logarithmic, phytodepuration with *E. crassipes*).

STAGE	COD (kg/m^3)	N (kg/m^3)	P (kg/m^3)
Pig manure input	46,358	4,3	1,15
UASB output	4,6358	3,44	0,92
Aeration	4,6298	3,44	0,92
Phytodepuration	0,46298	1,74	0,71



It can be noted from the table above that the effluent of the AFADS depurator is not suitable for dumping in water bodies because its contents of N and P overpass the (European) regulation limits. It is anyway suitable for its use in ferti-irrigation. As information, a commercial liquid fertilizer contains 70 g/l of N and 50 g/l of P (70 kg/m^3 and 50 kg/m^3 respectively). When diluted as per the manufacturer's instructions (about 1:50), the irrigation water will have similar concentrations of N and P to the pig manure treated in the AFADS.

Carbon offset
Assuming a production of 834 kg CH_4 + 556 kg of CO_2 per day (typical composition of biogas), the overall emission when the biogas is combusted amounts to 4448 kg of CO_2/day. The phytodepuration stage of the AFADS alone is not enough to offset such large amount of CO_2, hence an external plantation of bamboo (at least 4,5 ha) or an external system of PBR or algal ponds is needed.

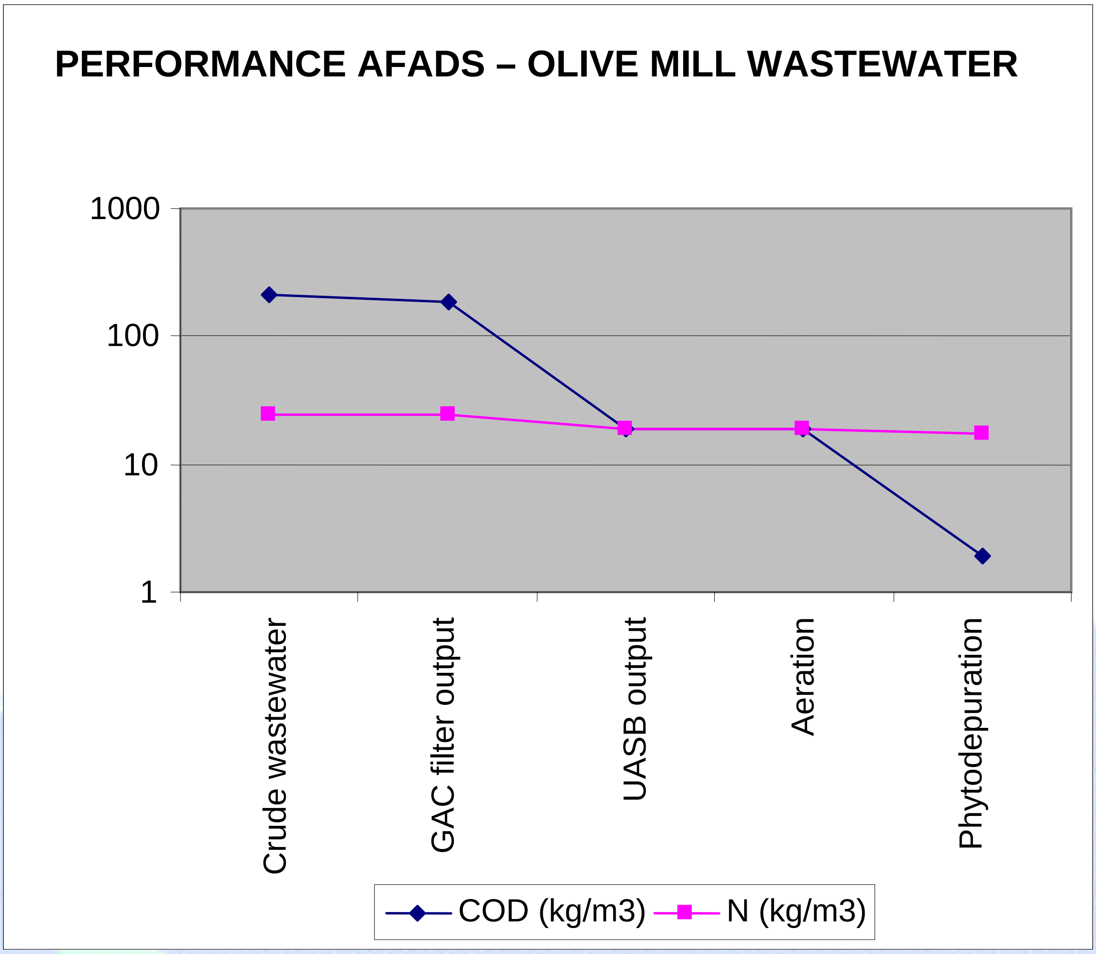
8.2. Olive mill wastewater

Average characterization values (Spain)
Water= 833 kg/m^3
Azúcares = 88 kg/m^3
N_{total} = 24 kg/m^3
organic acids = 15 kg/m^3
Polyalcohols = 15 kg/m^3

Phenols = 8 kg/m^3
Residual oil= 2,65 kg/m^3
Minerals = 18 kg/m^3
COD = 210.000 mg/l (210 kg/m^3)
C/N ratio = 78 / 24
PH = 5-6
Net potential production of CH_4 = 34 kg/m^3.

The olive mill wastewater is almost impossible to digest because of the high toxicity of the phenol. In order to process it in a AFADS depurator, a pre-treatment is necessary to eliminate the phenol. There are many possible systems, the adsorption with activated carbon is proposed here as probably the simplest and cheapest. Activated carbon can be prepared on site at low cost by carbonization of the granulated olive kerns (average diameter 2 mm) produced by the mill itself. The consumption of GAC has been estimated in about 100 kg / m^3 of wastewater. The performances of the AFADS depurator with pre-filtered wastewater are summarized as follows (100 m^3/day).

STAGE	COD (kg/m^3)	N (kg/m^3)
Raw olive mill wastewater	210	24
Output of GAC filter	189,6	24
Output of the UASB digester	18,96	19,2
Aeration	18,95	19,2
Phytodepuration	1,89	17,5



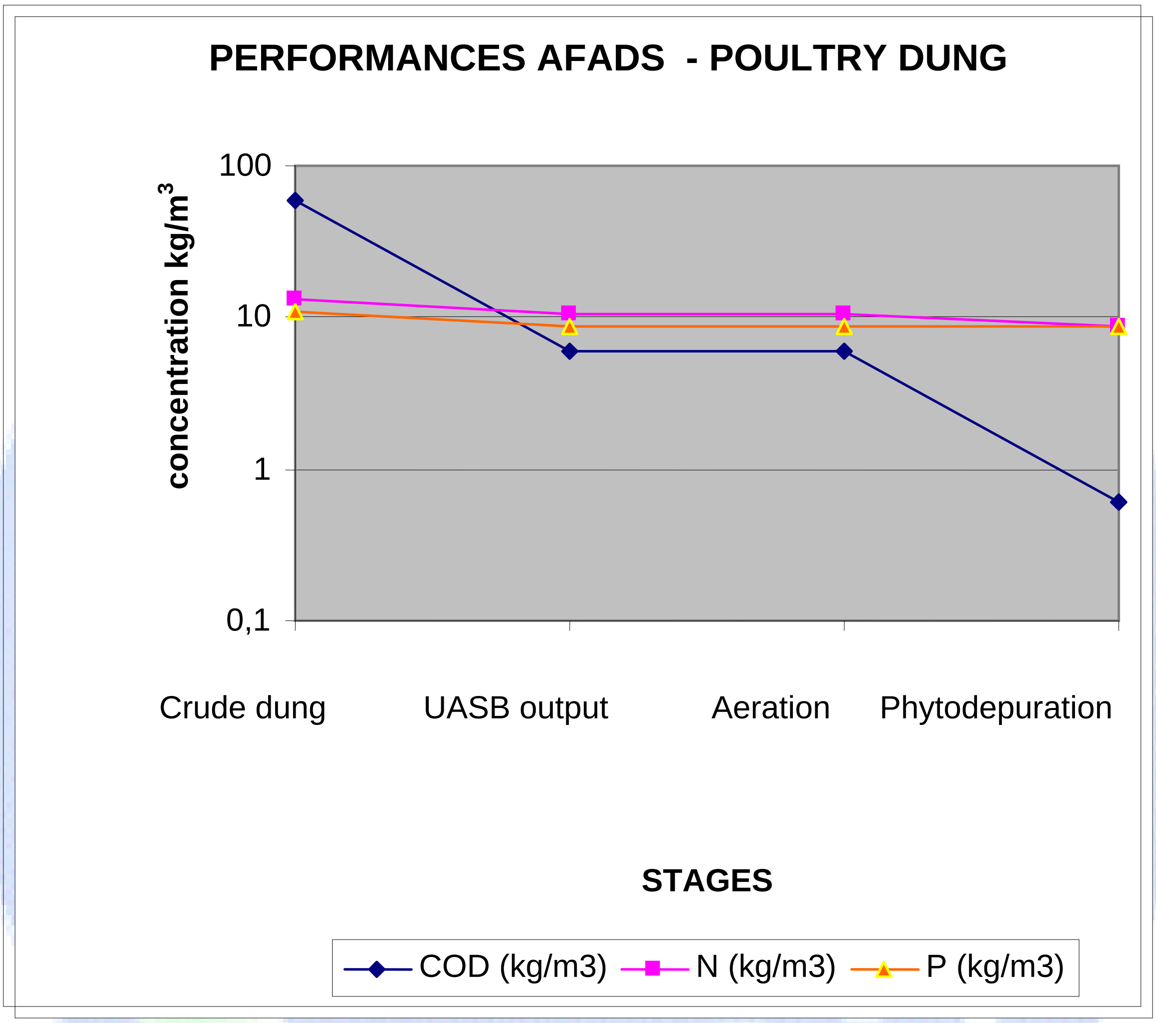
Because of the high COD and N_{total} of this special wastewater (respectively 4 and 6 times those of the pig manure), the depurator AFADS should work with at least the double of HRT or, even better, mixing the olive mill wastewater with pig manure or UW in order to optimize the digestion.

Carbon offset
Assuming a HRT = 4 days, the theoretica6 biogas production will be 850 kg CH_4 + 556 kg of CO_2 per day (typical composition of biogas), the overall emission when the biogas is combusted amounts to 6607 kg of CO_2/day. The phytodepuration stage of the AFADS alone is not enough to offset such large amount of CO_2, hence an external plantation of bamboo (at least 6,5 ha) or an external system of PBR or algal ponds is needed.

8.3. Poultry dung

Standard characterization assumed (fresh) :
COD = 60 g/l = 60 kg/m^3
total solids = 15 % = 9 kg/m^3
N = 13 kg/m^3
P = 11 kg/m^3
PH = 6
Relation C/N/P = 91/13/11
Potencial production of CH_4 = 10,8 kg / m^3 of poultry dung
N.B.: . Poultry dung is semisolid, so it should be diluted either with UW or pig manure. Experimental tests show that poultry dung mixed with pig manure with a ratio 60% / 40% or cattle dung 75% / 25% produces a higher quality biogas , with almost 70% of CH_4

STAGE	COD (kg/m^3)	N (kg/m^3)	P (kg/m^3)
Poultry dung	60	13	11
Output of the UASB	6	10,4	8,8
Aeration	5,994	10,4	8,8
Phytodepuration	0,5994	8,7	8,59



Carbon offset
Assuming a suitable dilution with UW, a production of 834 kg CH_4 + 556 kg of CO_2 per day (typical composition of biogas) can be attained. The overall emission when the biogas is combusted amount to 4448 kg of CO_2/day. The phytodepuration stage of the AFADS alone is not enough to offset such large amount of CO_2, hence an external plantation of bamboo (at least 4,5 ha) or an external system of PBR or algal ponds is needed.

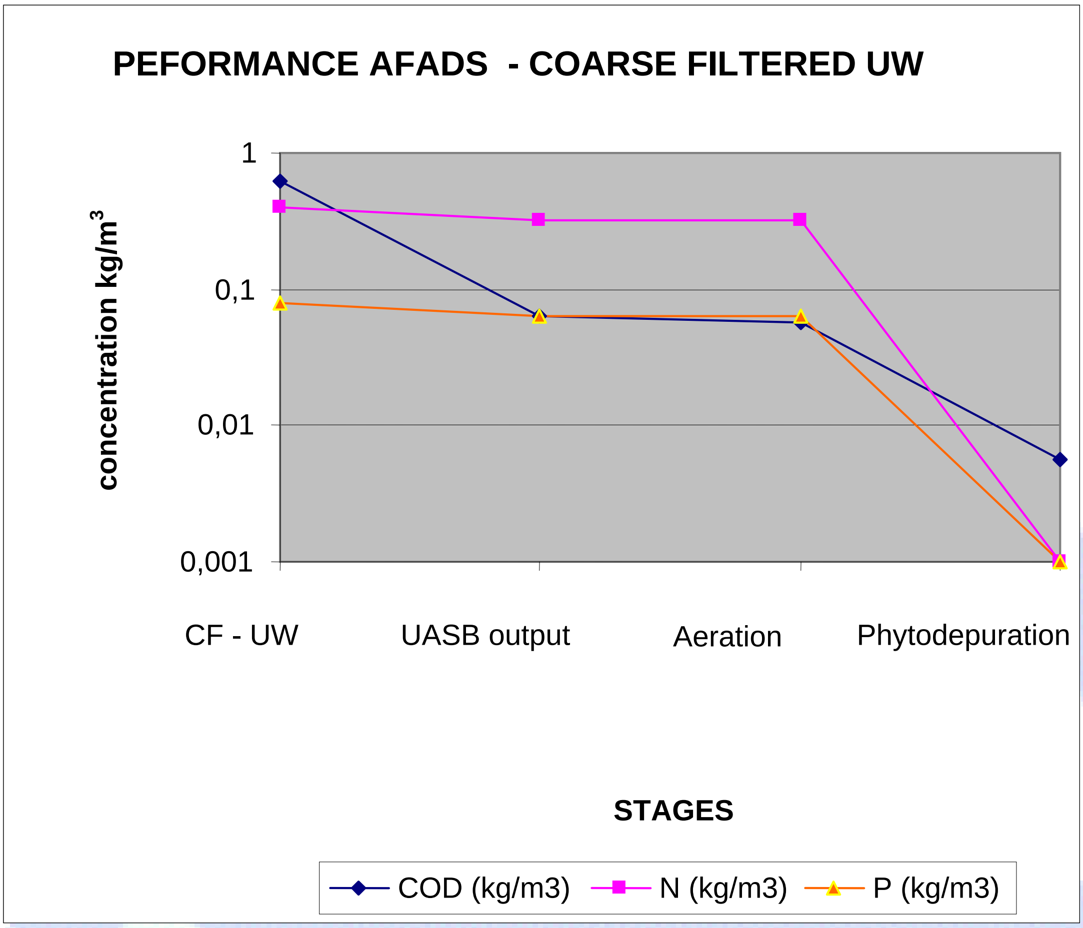
8.4. UW (coarse filtered).

The characterization of the same is very difficult and variable from place to place. The following table (Source: Metcalf & Eddy -1995) shows clearly the problem.

COMPONENT	CONCENTRATION			
	Unit	Fuerte	Media	Débil
Total Solids	mg/l	1200	720	350
Total Dissolved Solids	mg/l	850	500	250
Fixed	mg/l	525	300	145
Volatile	mg/l	325	200	105
Solids in Suspension	mg/l	350	220	105
Fixed	mg/l	75	55	20
Volatile	mg/l	275	165	80
Sedimentable Solids	ml/l	20	10	5
Biochemical Oxygen Demand	mg/l	400	220	110
Total Organic Carbon	mg/l	290	160	80
COD	mg/l	1000	500	250
Nitrogen (total as N)	mg/l	85	40	20
Organic	mg/l	35	15	8
Free NH_3	mg/l	50	25	12
Nitrites	mg/l	0	0	0
Nitrates	mg/l	0	0	0
Phosphor (total as P)	mg/l	15	8	4
Organic	mg/l	5	3	1
Inorganic	mg/l	10	5	3
Chlorides	mg/l	100	50	30
Alcalinity (as CaCO3)	mg/l	200	100	50
Greases	mg/l	150	100	50
Sulfates	mg/l	34	22	12
Coliforms (total)	N°/1	107 - 109	107 - 108	106 - 107
volatile organic compounds	μg/l	>400	100 – 400	<100

One of the fundamental problems for the anaerobic digestion of the UW is the content of greases (20% of total COD), which form a film around of the granules of bacteria colonies, hampering their exchange of nutrients and slowing down the methanogenesis. Furthermore, because of the low COD, the production of CH_4 is extremely low. Besides, the low organic load allows very short HRT. When treating UW in AFADS depurator the recommended HRT is 8 hs, so its real depuration capacity is triple of the nominal. The possible yield of CH_4 is 0,1134 kg / m^3 of UW , so with a flow of 300 m^3/day the total daily production will be only 34 kg. The water will exit almost clean, suitable for irrigation or even flushing in water bodies, as can be observed in the following table:

STAGE	COD (kg/m^3)	N (kg/m^3)	P (kg/m^3)
Coarse filtered UW	0,63	0,4	0,08
UASB output	0,063	0,32	0,064
Aeration	0,057	0,32	0,064
Phytodepuration	0,0057	0,001	0,001



Carbon offset
Assuming a production of 34 kg CH_4 + 23 kg of CO_2 per day (typical composition of biogas), the overall emission when the biogas is combusted amounts to 57 kg of CO_2/day (20,8 tons/year). The phytodepuration stage of the AFADS alone is almost enough to offset said amount of CO_2, With a few square m of external plantation of bamboo or a small external system of PBR or algal ponds is enough to reach null emissions.

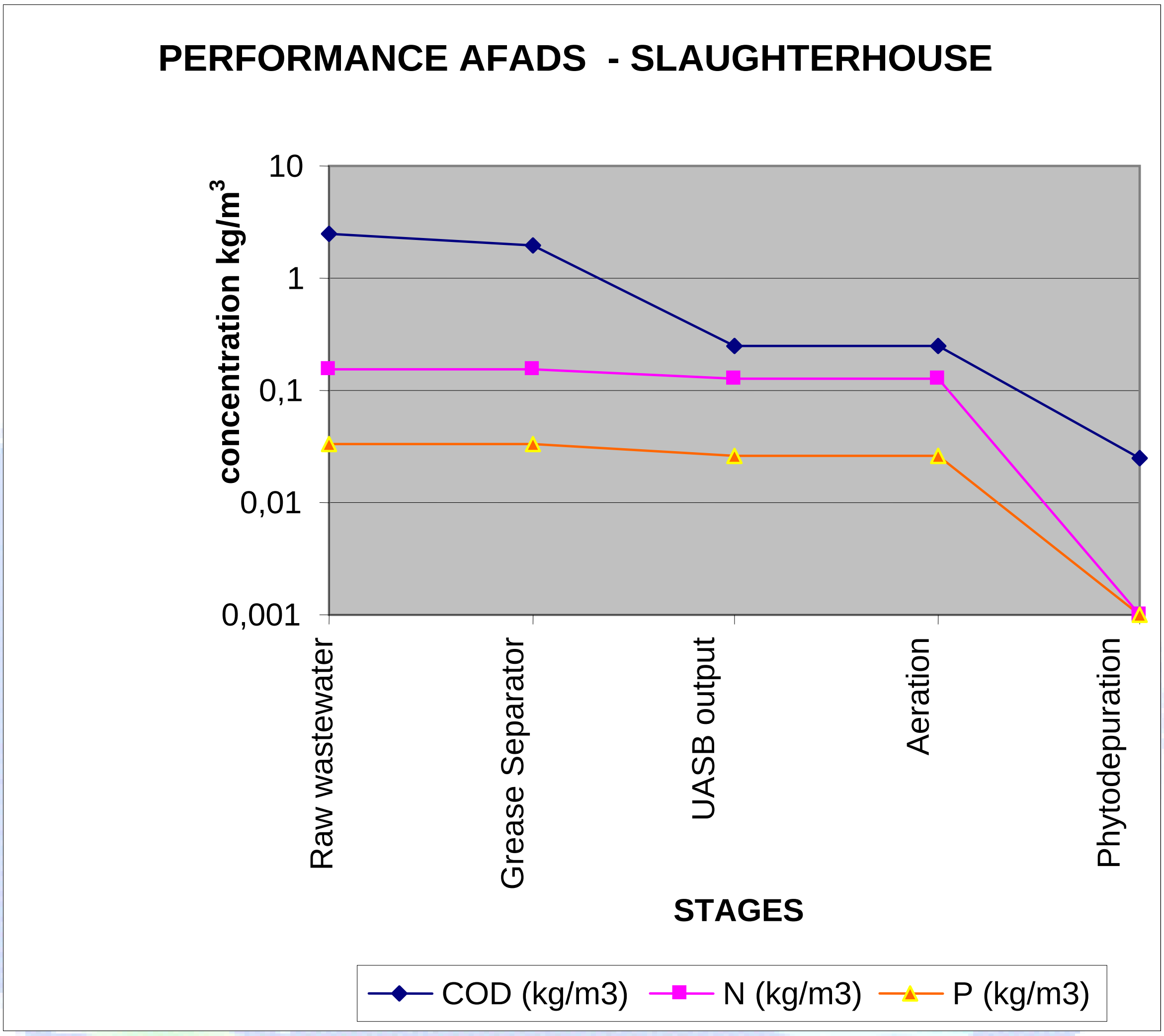
8.5. Pig Slaughterhouse Wastewater

They are difficult to digest because of the high content of greases (< 20%), and produces very little biogas, tough of good quality (75% CH_4). The options are 2: eliminate the greases with a pre-treatment or mix the slaughterhouse wastewater with other type of wastewater, dung, organic solid wastes, etc. , in order to reduce the ratio greases/COD.
The average characterization of this effluent is:
COD = 2,5 kg/m^3
PH = 7,2
Greases = 0,704 kg/m^3 (28% of COD)
N = 0,156 kg/m^3
P = 0,033 kg/m^3
Proteines = 0,073 kg/m^3

The performances of the AFADS depurator, assuming a previous stage of separation of greases and HRT 8 hours, will be the following:

STAGE	COD (kg/m^3)	N (kg/m^3)	P (kg/m^3)

Raw wastewater	2,5	0,156	0,033
Grease Separator	2	0,156	0,033
UASB output	0,25	0,1248	0,0264
Aeration	0,244	0,1248	0,0264
Phytodepuration	0,0244	0,001	0,001



The potential yield of CH_4 is near 0,45 kg/m^3. Because of the shorter HRT necessary for digesting this type of wastewater, the AFADS depurator can process up to 300 m^3/day with an average production of 135 kg/day of CH_4. The effluent is almost clean water.

Carbon offset

Assuming a production of 135 kg CH_4 + 90 kg of CO_2 per day (typical composition of biogas), the overall emission when the biogas is combusted amounts to 225 kg of CO_2/day. The phytodepuration stage of the AFADS alone is not enough to offset all that amount of CO_2, but 1500 m^2 of bamboo plantation or a small external system of PBR or algal ponds will be enough to reach null emissions.

9. CONCLUSIONS

The **AFADS** depurator is a versatile and sustainable wastewater treatment system. It offers high elimination rates of COD and nutrients in short times, production of biogas and biomass, with modest electricity consumption and lower land occupation than the traditional systems of depuration. Furthermore the process eliminates a small amount of CO_2. Its

effluent is divided in two separated flows: distilled water and water with some nutrients, which is suitable for ferti-irrigation. Said water can either feed a bamboo plantation (18 ha every 100 m^3/day treated) or be used for agriculture. When feeding a bamboo plantation, up to 0,183 ton CO_2 / m^3 of treated water can be fixed.
Excess sludge from the anaerobic stage can be dried and used in agriculture as the sludge of any digester, providing additional nutrients to the plants and soil bacteria.
Eichornia crassipes (water hyacinth) shows higher potential for the phytodepuration stage and higher CH_4 yield than other aquatic plants or even algae, but it must be harvested manually and energy is needed to triturate it in order to use the fresh biomass as methane booster in the anaerobic stage. Algae are easier to harvest by automatic means and need no energy expense in trituration. Anyway some energy will be required for CO_2 blowing and agitation. As a rule of thumb, *Eichornia crassipes* could be more suitable when installing AFADS in Developing Countries with low labor costs, and microalgae are the best candidates for installing AFADS in Industrialized Countries where labor rates are high.

