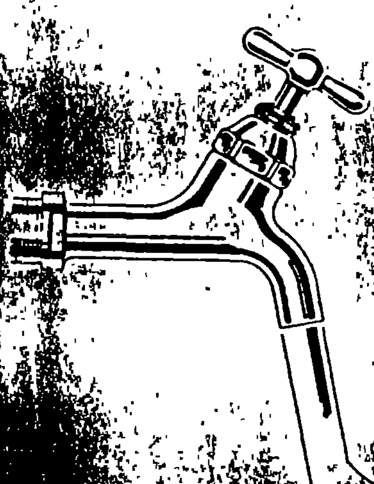
NOVEMBER 1986

anaerobic treatment of Coffee Wastewater at farm-level in matagalpa nicaragua



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This investigation has been performed as a graduate study of Chemical Technology of the University of Twente, and was executed within the Nicaraguan Ministry of Agriculture and Land Reform MIDINRA, Reg. VI, Matagalpa.

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summary and recommendations

1. introduction

Every year the drinking water supply of Matagalpa is polluted during the coffee harvest (october - april), with wastes produced by the coffee processing industries, which are located in the mountains forming part of the Rio Grande basin.

During the 1985-'86 coffee harvest the ministry of agriculture MIDINRA performed an investigation to the causes of this contamination with the objective to find short- and longterm solution to the problem.

2. wastewater characteristics

The coffee wastewater appeared to be a medium strength, easily degradable organic wastewater flow, which should be amenable to existing water treatment methods.

COD could be correlated to the coffee production (130 kg COD per metric tonne fo green coffee produced) whereas the wastewater flow varied between the various coffee farms. In practice, concentrations will be in the range of 3 to 15 kg COD/m^3.

The water appeared to have a strong tendency to form acids, probably caused by the presence of micro-organisms and enzymes from the coffee fermentation process. This accumulation of volatile fatty acids causes wastewater pH to decline.

It was estimated that anaerobic processes (such as anaerobic reactor technique and anaerobic lagoons) could provide a suitable treatment technique in the local situation in the long run.

3. Short-term solution

During the harvest 1985-'86 contamination of the water sources of Matagalpa was almost completely avoided through the application of a procedure that made controlled discharge by the farmers possible.
This solution was executed in a cooperative action of the coffee farmers, the drinking water institution INAA and MIDINRA, and was supported by public organizations in Matagalpa.

The procedure, however, is only recommended for a limited period: Especially at the end of the coffee harvest some contamination can be expected, while the consequences for the area downstream Matagalpa are still unknown.

It is recommended to continue this new procedure for controlled discharge until better and more permanent solutions are available.

4. long-term solutions

Treatment of the coffee wastes seems the only feasible solution on the longer term.

Two alternatives for pre-treatment were examined:
1. anaerobic reactor techniques
2. anaerobic lagoons.

It is not very probable that these treatment techniques will provide sufficient COD-removal. For that reason they should be considered as pre-treatment techniques, and post-treatment in the form of aeration and/or facultative lagoon treatment will be necessary!
This post-treatment was not considered in the investigation.

4.1 anaerobic reactor techniques

Anaerobic reactor techniques provide a possibility to join wastewater treatment with (rural) energy production.

From the investigation performed with the Upstream Anaerobic Sludge Bed reactor (UASB) it could be concluded that:

1. The start-up and operation seems technically feasible, although more research is needed before the process is ready for implementation. It is recommended:
   * to perform a complete process start-up at laboratory scale, to determine process parameters. This experiment can be terminated within one coffee season.
   * to build a pilot plant at a small coffee farm, to study scaling-up problems fo the technology.
     These experiments will take at least 2 years.

2. If it functions properly, a UASB can meet about 80-90% treatment efficiency, producing 0.7 kg CH_4-COD/ kg $COD_{removed}$; This implies, that during the coffee harvest all farms can provide in their energy needed for cooking.
   In the whole problem area about 10-25,000 m^3 of biogas, equivalent to 80-200 tonnes of firewood, can be produced.

3. Technical investigations should be directed to:
   a. The determination of design parameters;
   b. The development of sludge in the reactor;
   c. The die-off of sludge during storage, between the coffee harvests;
   d. Appropriate start-up procedures;
   e. Process stability if no neutralization is applied.

4. If it is decided to continue the investigations it should be born in mind that very much attention should be paid to the development of local expertise on planning, design, operation and maintanance of the plants: At this moment knowledge and experience of process planning, reactor construction and operation lack at every level in the local and national situation.
   The UASB is a new and unknown technology in this context, and many efforts will have to be spent to the development of local expertise.

   Furthermore it should be considered that local staff, at the moment, is hardly sufficiently educated for being trained as an operator or as a sanitary engineer.

5. Besides this, more efforts should be put to make people aware of the seriousness of the problems caused by the waste. The farmers don't fully realize the consequences of their actions when polluting the river, and sometimes are hardly willing to put more efforts to avoid the contamination.

4.2 anaerobic lagoons

Anaerobic ponds are the only treatment devices that have been applied so far to treat coffee wastewaters in Matagalpa.

The ponds are in a very poor condition: They lack every design, operation and maintenance and probably do more harm than good, since they function as breeding places for numerous insects.

Treatment performance of the lagoons is very poor.

From calculations performed in chapter 4 appears, that for satisfactory lagoon operation huge amounts of seeding sludge are needed: For the entire problem area annually about 130 mtonnes of fresh cow dung will be needed to start-up the lagoons.
For the first year this will be three times as much.

Considering further the expected mixing problems in the lagoons this alternative is not considered feasible for the treatment of coffee wastewaters, unless sludge seals and settling devices are introduced to prevent the sludge to wash out of the system.

List of abbreviations

INAA	Instituto Nicaraguense de Acuaductos y Alcantarillados; Drinking water institute
IRENA	Ecological institute
ISP	Interdisciplinaire Studiegroep Planologie; Student group from the Technical University Delft
MIDINRA	Ministerio de Desarrollo Agropecuario y Reforma Agraria; Ministry of agriculture and land reform
MINSA	Ministerio de Salud; ministry of health
UPE	Unidad de Porducción Estatal; state farm
BOD	Biochemical Oxygen Demand ($kg.m^{-3}$)
CFSTR	Continuous Flow Stirred Reactor
COD	Chemical Oxygen Demand ($kg.m^{-3}$)
GSS	Gas Solid Seperator
tgcp	metric tonnes of green coffee produced
TSS	Total Suspended Solids
UASB	Upflow Anaerobic Sludge Bed
VSS	Volatile Suspended Solids
A_m	Specific methanogenic activity (kg CH_4-COD.kgVSS^{-1}.d^{-1})
A_s	Lowest methanogenic activity for which the stability criteria are fulfilled
C_s	Lowest methanogenic capacity for which the stability criteria are fulfilled (kg CH_4-COD.m^{-3}.d^{-1}
G^o	Free enthalpy of reaction (kJ/kmol)
K_i	Substrate inhibition constante
K_s	Monod Constante, Concentration for which $u = 0.5\ u_{max}$
L	Organic load (kg COD.m^{-3})
Q	Flow ($m^3.d^{-1}$)
R	Retention time: HRT = Hydraulic Retention Time (d); SRT = Sludge Retention Time (d)
S	Substrate concentration
S_o	Influent substrate concentration
SVI	Sludge Volume Index (l/kg)
T	Temperature (K, °C), or dimensionless time ($u_{m,max}$*t)
V	Volume (m^3); Substrate utilization rate (d^{-1})
V_m	Substrate utilization rate of the methanogenic phase (d^{-1})
X	Biomass Concentration (kgBM.m^{-3})
Y	Yield Factor (kg/kg)
Y_A	($1 - y_a$), with y_a = yield factor for the acidifying phase.
Y_m	yield factor of the methanogenic phase
k	inhibition constant ($=K_s/K_i$)
m	retention time ($=u_{m,max}$ * R)
p	sluice fraction
t	time (d)
u	
u_m	growth rate of the methanogenic phase (d^{-1})
v	substrate utilization rate
v_m	substrate utilization rate of the methanogenic phase
x	sludge concentration (X/K_s * Y_m)
$x_{m,s}$	sludge concentration needed for 100% substrate conversion
x_s	sludge concentration at the steady state; lowest sludge concentration for which the stability criterium is fulfilled
x_{s1}	difference solution of the sludge concentration in the steady state
x_{s2}	sum solution of the sludge concentration in the steady state
y	substrate concentration (S/K_s)
y_s	substrate concentration in the steady state
y_{s1}	difference solution of the substrate concentration in the steady state
y_{s2}	difference solution of the substrate concentration in the steady state

Chapter 1: Introduction

1.1 Coffee production and the dinkingwater supply in Matagalpa

The drinkingwater supply situation of Matagalpa presents several problems: Besides the fact that the quantity of the liquid supplied is far from sufficient, quality of the water is also very poor. In a study, performed by the Interdisciplinary study-group Planology (ISP) (1) the causes of this water quality problem are mentioned:

1. Erosion of the soils in the areas surrounding Matagalpa contaminates the raw water with soil- and humus-products, resulting in high turbidity, high colour-values and a bad smell and taste to the water;
2. The water of the rivers is seasonally polluted during the coffee harvest: The water gets a bad smell, a dark green colour, and a white scum layer can be observed in the Rio Grande.
   This contamination is a product of the coffee processing industries, that are located in the mountains, close to Matagalpa. These industries drain their process waters, more or less untreated, in the nearest streams, forming part of the Rio Grande river-basin.

Investigations of INAA (the drinking-water institution), ISP and a Nicaraguan consultants agency PROCONSULT, have concluded that the water of the rivers concerned will be indispensable for the water supply in the nearer future (10 years or more).

1.2 Objectives of this investigation

During 10 months (from august 1985 until june 1986) I had the opportunity to perform my doctoral-investigations at the Nicaraguan Ministry of Agricultural Development and Land Reform (MIDINRA, Region VI, Matagalpa). Here I studied the problems caused by the contamination of surface waters in the area surrounding the city of Matagalpa, with emphasis to the coffee pollution problem.
Goals to which I developed my activities were:

1. An investigation into the causes of the contamination;
2. To find a short-term solution to avoid, as far as possible, contamination of the drinking water of Matagalpa;
3. For the long term: To start an investigation to find technical and (in the local situation) economically feasible solutions to purify the water;
4. This work was to be conducted with personnel from involved institutions, in such a way, that after I had gone people would be able to continue the activities or, at least, to avoid contamination of the city's water supply;
5. If necessary for the continuation of the activities, (external) support should be found to prevent a silent death of the results of the examinations. This also, because the pollution-problems of Matagalpa are not unique for Nicaragua, but also apply to other coffee producing countries in Latin-America, Asia and Africa: From various countries environmental problems due to processing of coffee were reported.

1.3 Coffee production around Matagalpa

In the region of Matagalpa (Region VI) about 60% of Nicaraguan national coffee production is cultivated, in state-owned and private coffee farms.
In general, the wet part of the coffee process (see chapter 2) takes place in the farms where great quantities of clean water are used to transport and wash the coffee.
In the basin of Rio Molino Norte and Rio San Fansisco (see fig. 1) about 1,000 metric tons of green coffee is harvested and processed annually. In fig. 2, a list of the coffee producers is given, with their productions in 1980 and 1983 (2).

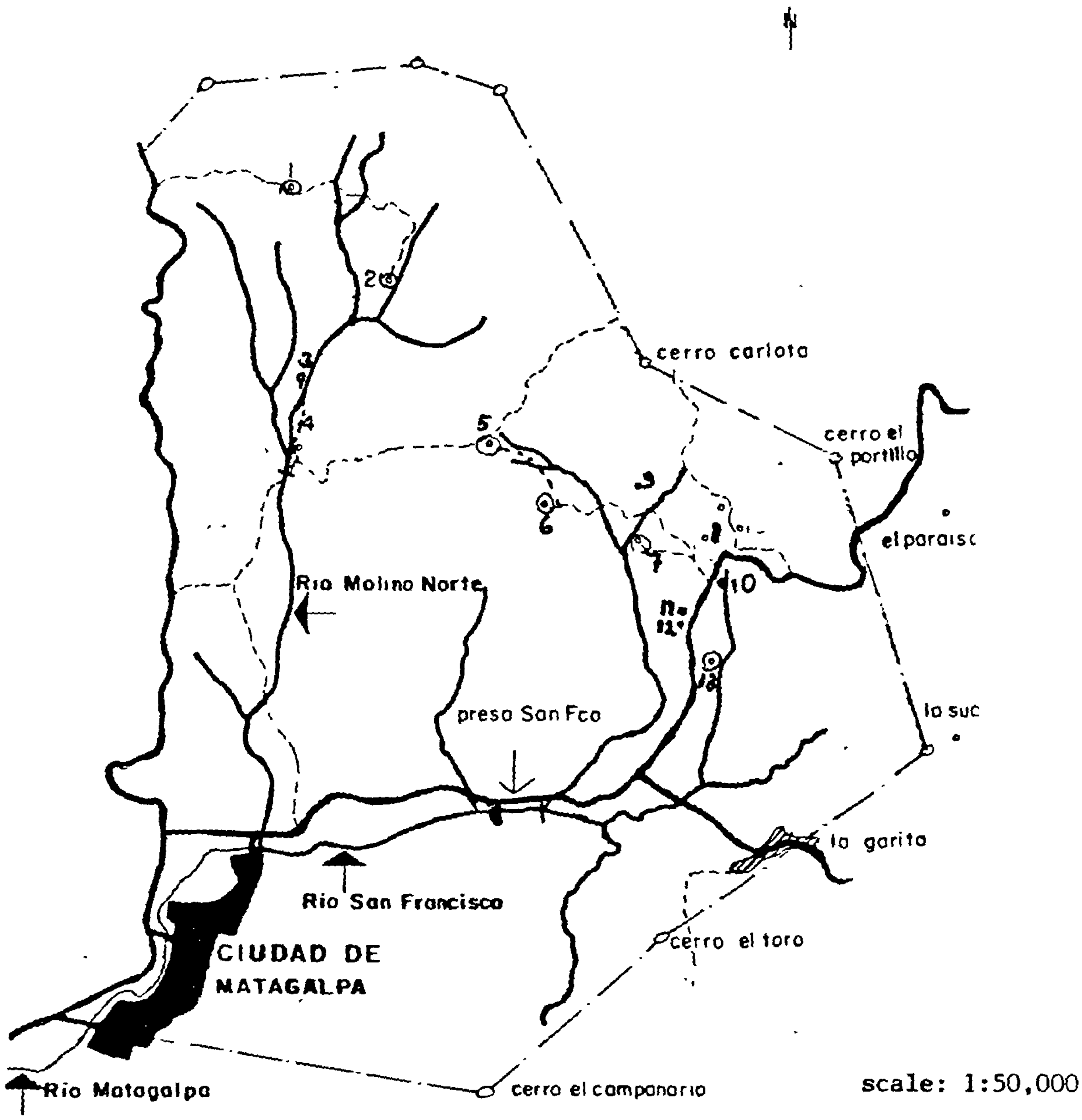


fig. 1: The Rio Grande (= San Fransisco-Molino Norte) river basin

	coffee production (tgc/year) 1980	1983
Rio Molino Norte:		
1. La Hamonia	137	137
2. San Luis	170	227
3. La Gloria (APP)*	68	70
4. La Ponderosa	9	nd
Rio San Fransisco:		
5. La Cuesta	160	80
6. Los Alpes (APP)	93	83
7. San José(APP)**	80	58
8. La Suiza(APP)**	23	35
9. La Chiripa	18	16
10. San Pablo	3.4	nd
11. La Cueva del Tigre	14	14
12. Quinta Praga	18	14
13. San Fransisco	68	34

* State owned farms (UPEs)
** These UPEs process their coffee in "Los Alpes"
nd No data available
tgc (metric) tons green coffee

fig. 2: Main coffee farms around Matagalpa

In general, the bigger properties do have a waste-water treatment, in the form of oxydation lagoons. It appears, however, that these ponds do not function very well, and that the water that leaves these lagoons still contaminates the rivers.
For that reason, part of this investigation is dedicated to the functioning of these (mainly anaerobic) lagoons, to identify the reasons for deficiencies in their performance.

1.4 The application of a short-term, temporary solution

During the harvest-season 1985-'86, contamination of the raw water sources was almost completely avoided, through the application of a temporary solution that was conducted, as a cooperative action, by the Ministry of Agricultural Development and Land Reform (MIDINRA), the water institution (INAA) and the coffee producers, who agreed on a procedure to control the contamination.

The causes of that contamination were:
1. The absence of oxydation lagoons or some other treatment device at a (small) number of properties;
2. The poor functioning of the existing oxydation ponds;
3. The limited capacity of these lagoons, and the consequent necessity to discharge (treated or un-treated) process waters into open streams.

Lack of coordination between the involved parties, as well as unconsiousness of each others problems, caused the relations between the coffee producers and pressure groups in Matagalpa (like the CDS-es, la Junta de Reconstruccion, INAA, el Gobierno Regional, the Ministry of Health (MINSA), a.o) to worsen, and the search for common solutions to be restricted to sharper government control on contamination.

During the season that lasted from october '85 to march '86, INAA and the coffee producers, with MIDINRA as an important party involved, decided to use the lagoons as storage-basins, in which the process waters were to be collected. These would be emptied collectively, upon reaching full capacity of the ponds.
During the discharge, INAA shut off the captation of raw water to avoid contamination of the drinking-water system, with as a consequence the absence of drinking water in town during 12-24 hours.
During the periods of most intensive coffee production, this procedure was needed once in 2-3 weeks.
Especially in the Molino Norte basin, where 80% of the drinking water was captured, the discharge could easily be performed, because of:
- the limited number of coffee producers (4 producers above water-captation, from which the three largest produced 98% of the coffee);
- the presence, and relatively reasonable state, of the lagoons at these farms;
- The limited distance from the farms to the Molino Norte dam: From flow- and flow-velocity-measurements it was predicted that the discharged water would reach the dam within 2-3 hours. This proved to be correct.
  In the wet months (november, december) all water discharges from the ponds passed the captation dam within 9 hours.

In the San Fransisco basin, the situation was somewhat more complicated, but since only 20% of the water for Matagalpa was captated here, no serious problems arose.

Although the water quality was relatively good in 1985-'86, the applied procedure should not be considered as a permanent solution, because:

1. The coffee harvest was relatively short in 1985-'86: At the end of february, almost all coffee already had been processed. In longer harvests, processing will go on until april, the dryest month; The rivers contain very little water in this period, so that an absolute water shortage takes place. Besides this quantity problem, it will take more time for the water to pass the captation dam. It is not unthinkable that the town will be without water for 36-64 hours;
2. Relatively little coffee was harvested in 1985-'86, so that in other years more process waters will flow into the ponds. A number of farms will need pond extension;
3. The procedure is relatively vulnerable and labour intensive, because of the poor means of communication in the local situation;
4. Since a few years INAA is trying to increase the amount of water to be captated from the San Fransico basin. In this way, a greater part of the water for Matagalpa will be from this basin, where water pollution control is more difficult due to the more divers location of the farms, and the absence of lagoons in some situations.
5. It is not sure what influence the discharges will have downstream. It is sure, however, that the organic matter in the water breaks down slowly, also in case of good water reaeration and thus will be affecting the oxygen regime, and influence the re-use possibilities.

For these reasons, solutions with a more permanent character were looked for, in the form of waste-water treatment. Other solutions like concentration of all coffee-processing units into one central plant, or the substitution of coffee for other crops have been investigated but were rejected for high costs (2).
In the case that centralization of the coffee processing would be carried out, treatment of the waste-waters would still be needed anyway.

1.5 The structure of the report

The present report discusses on the water treatment aspects of the performed investigations. Economical, organizational and social feasibility will be discussed elsewhere.

The study at the composition and treatability of coffee waste-waters is described in chapter 2; In chapter 3 the technical feasibility of the anaerobic reactor process as a (pre-)treatment method for coffee waste-waters is examined, whereas in chapter 4 the performance of (existing) anaerobic oxydation lagoons is studied, and a design model for these lagoons is developed.

Chapter 2: Coffee waste waters: composition and treatability

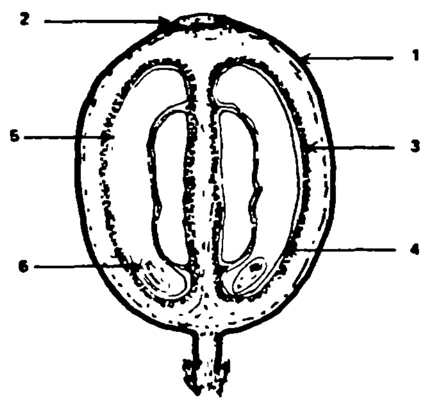
2.1 The processing of coffee berries

The process of coffee production consists of agricultural and agri-industrial processes, which are partly performed in the countries where the coffee is grown. Mixing and roasting generally is performed in the consuming countries.

Depending on altitude, coffee berries are harvested in Central America from late august until march, with lowland coffee maturing earlier than highland coffee. The berries are harvested upon reaching maturity, such as indicated by an intense red or yellow color of the fruit, depending on its variety.

In cross section the coffee berry (fig. 3) shows four anatomical fractions: The coffee bean proper or endosperm (6); The hull or endocarp (5); A layer of mucilage or mesocarp (4) and the pulp, or esocarp (3).
The processing of the berries merely consists of removing all fractions from the bean in such a way that quality of the resulting "green" coffee is maintained.

Basically, coffee-fruit processing to obtain the commercial beans consists of two operations. The first is a wet processing step, yielding coffee pulp, mucilage and waste-waters on the one hand, and coffee beans covered with hulls on the other. The second operation is a dry processing step that seperates the hulls from the coffee beans (see fig. 4).



Longitudinal section of a coffee berry (Coffea arabica) 1 epicarp 2 disk or "navel"; 3 mesocarp. 4. endocarp (coffee hull) 5. spermoderm or "silver skin". 6 embryo

fig. 3: Cross-section of a coffee berry

For this investigation, however, only the wet processing step is important (see fig. 5).

After harvesting, the coffee berries are transported to the coffee processing plant, where they are dumped into the receiving tank. From there the fruit is led to the pulpers, which seperate beans from the pulp by mechanical friction.
The pulp is transported by water to a disposal system, or simply piled for later removal, and the beans are transported (by water also) to the first classification step, usually consisting of a rotating sieve (pregrader). The heavier coffee fraction is transported directly to the fermentation tanks, while the lighter fraction first is "repassed" in a second pulper, to remove also the pulp of those berries that passed the first pulping units unpulped.

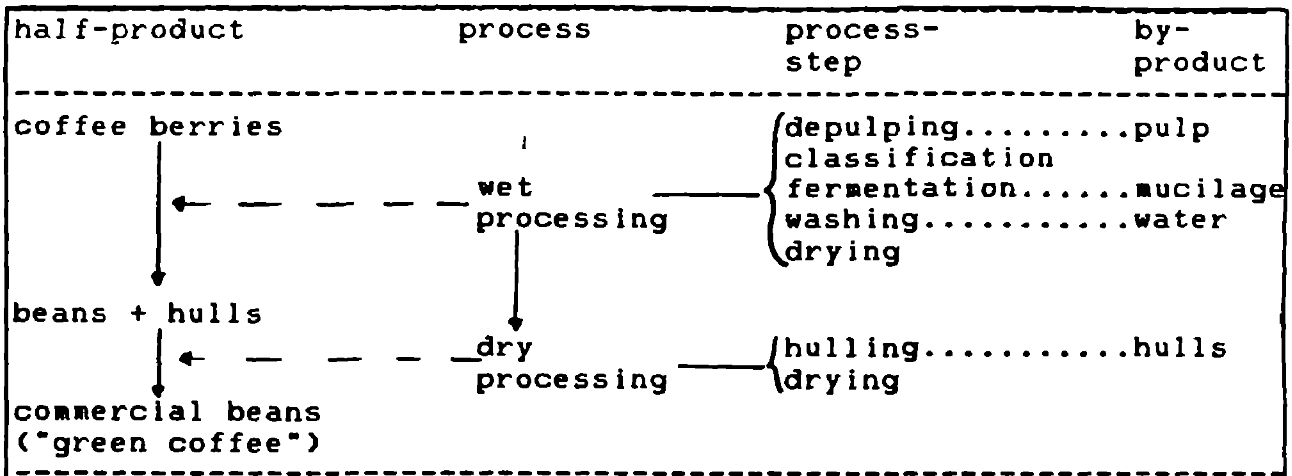


fig. 4: Steps involved in coffee processing

The fermentation process, which is mainly anaerobic in nature, is carried out for 24-48 hours, and causes the degradation of the mucilage. The products of this hydrolysis ("miel", or honey) remain in the water, and form the second by-product of the coffee process.

After this fermentation process the coffee beans are washed extensively, prior to dehydration (drying) in the sun or mechanically, and they are transported to the centralized "beneficios" where hulls are removed and the coffee is dried resulting in "green coffee" or "cafe oró".

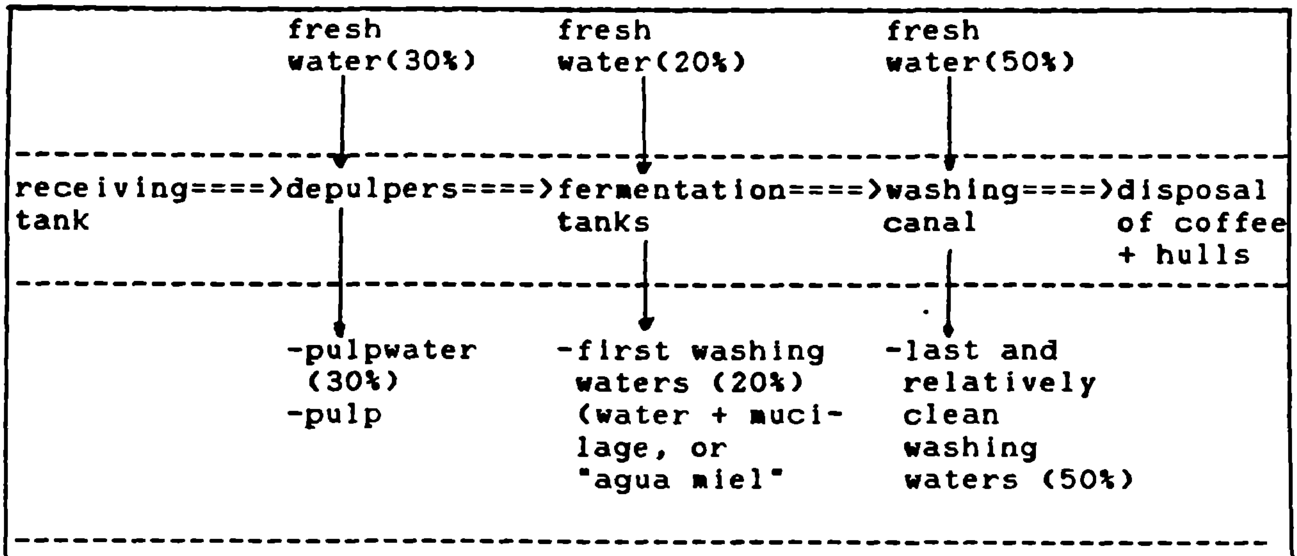


fig. 5: The wet process

In terms of the yield of coffee beans and the other fractions, besides the water, the material balance of the process as obtained in laboratory tests is shown in fig. 6.

	fractions by weight (%)	dry fraction (%)
intermediate		
berry	100	34.5
by-product		
pulp	43.2	9.9
mucilage	11.8	1.7
hull	6.1	4.1
green coffee	38.9	9.1

fig. 6: Material balance of the coffee process.
Source: (3)

Research on the re-use of by-products of coffee-processing mainly was performed from the view of waste-disposal: The great amount of wastes are a menace to human environment. When fresh pulp for example, is stored in open piles, its sugar is attractive to flies which could be a nuisance. When the pulp begins to ferment, a repulsive odor is emanated.
Nowadays, however, the availability and utilization of great amounts of coffee pulp and coffee hulls is also considered to have economic importance, and research is directed to the development of profitable uses for these products. Coffee pulp generally can easily be collected and used as fuel, fertilizer or animal feed. Application as material for anaerobic fermentation, resulting in the production of methane gas, is propagated by various Latin-American research centers (4,5). A good overview of this research can be found in literature (3).
In Matagalpa, in a number of cases the re-utilization of coffee by-products is not (yet) applied, probably due to lack of knowledge and motivation (especially in state-owned farms).

2.2 Composition and natural fermentation of coffee wastewater

2.2.1 Theory

As shown in fig. 4, coffee wastewaters are produced in the depulping and washing part of the coffee process.

Depulping wastewaters are known for their high concentrations of organic contaminants: Using the water to transport the pulp from the pulpers to pulp storage, fractions of the pulp are extracted into the liquid, giving the water a deep-brown color, a penetrating odour, and high COD-values.

Wastewaters originating from the washing process are contaminated with the end-products of the coffee fermentation, in which process the mucilage, surrounding the coffee-bean, is removed. Especially during the first part of the washing process, concentrations of suspended and dissolved solids are very high, but they decrease rapidly in the course of the washing process.

The quantity of water used in the processes is not constant, but will vary considerably per coffee mill and with season. It depends on:

- The availability of sufficient clean water;
- The application of water recirculation (see fig. 7): Pulping- and first washing waters may be re-used to depulp coffee, while last washing waters, that hardly have been contaminated, can be used in the first washings.

The minimum use of water is about 10-15 m^3/tgcp (6), which can mean a saving of water up to 70-80%, compared to the actual situation.

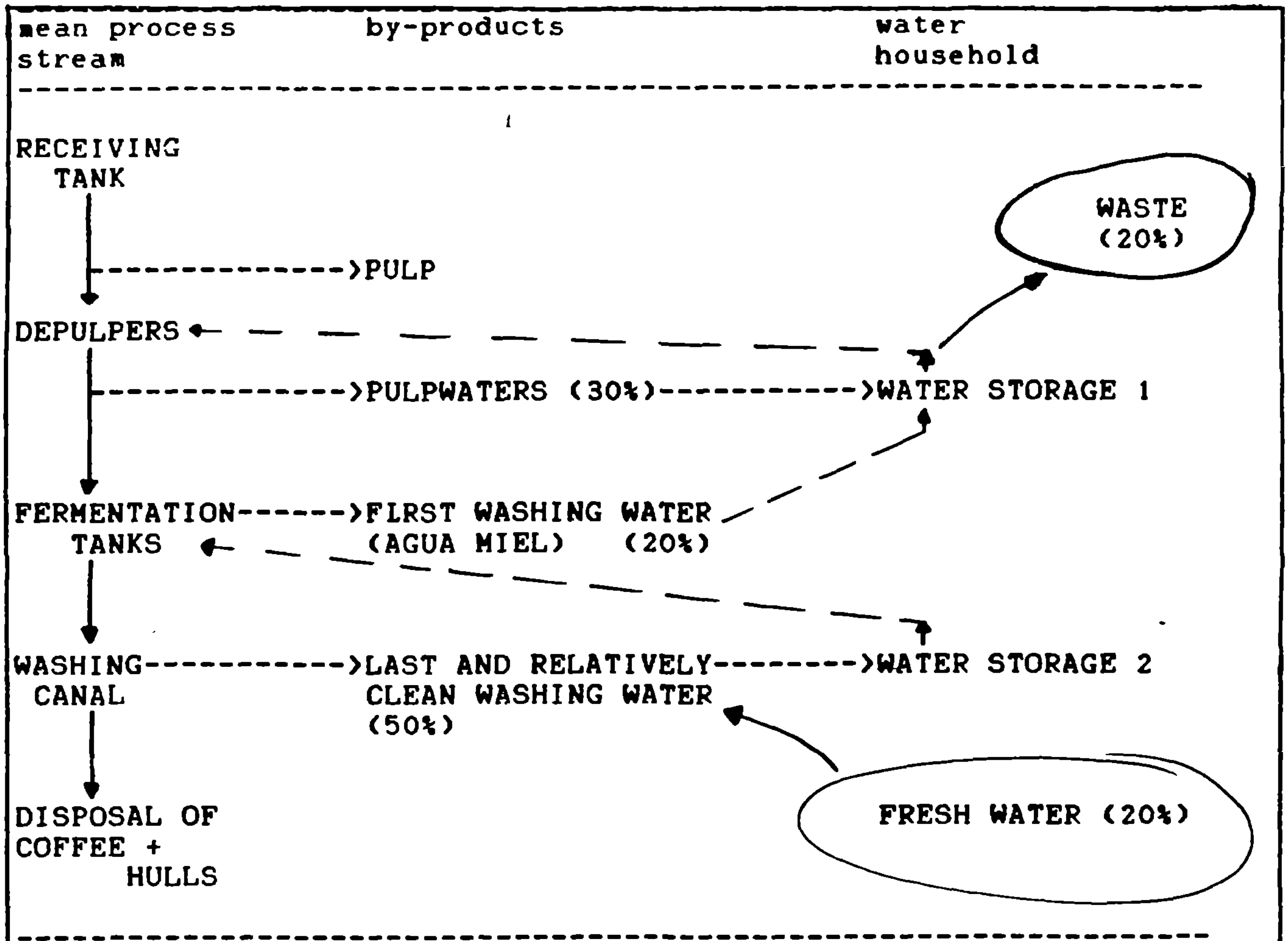


fig. 7: An example of recycling of process water

In literature, few data on the composition of the wastewaters were found: Only basic contamination data (COD, BOD, Total Solids) have been encountered (see fig. 8), showing wide ranges, probably mainly due to variable amounts of water used.

Particularly the problems of UASB reactor start-up (see chapter 3) called for a closer investigation on the composition of the wastewater and the biochemical processes in it: Acid formation appeared to be extraordinarily rapid.

1. P.C. Ward (1945) (7)

	BOD_5 (20 °C) (g/l)	sedimentable matter (g/l)	soluble matter (g/l)	suspended matter (g/l)
Pulpwaters	1.8-2.9	0.06-0.13	5.0	0.8
Washing waters	1.3-2.2	0.7	4.3	2.1

2. R.K. Horton (1947) (8)

	BOD_5 (20°C) (g/l)	pH	Turbulence (g/l)	suspended matter (g/l)	soluble matter (g/l)
Pulpwaters	3.3-15	4.1-4.7	1.5-4.0	0.6-1.1	10.1-12.3
Washing waters	0.3-3.6	4.1-5.5	0.3-4.0	0.2-2.4	0.9-3.1
Combined waters	2.5-8.0	4.3-4.7	1.5-2.5	0.5-0.8	6.8-7.2

3. P.C. Ward (7) (1945)

pulpwaters	32	kg BOD/ton green coffee
washing waters	4.4	kg BOD/ton green coffee

4. A.R. Adams (1981) (9)

combined waters	80	kg BOD/ton green coffee

5. P. IJspeert (1984) (10)

washing waters	12	kg COD/m^3

fig.8: Literature review on the composition of coffee wastewaters

2.2.2 Composition of the wastewater

In this paragraph the composition of the coffee wastewater is estimated through the investigation of two processes:

1. The extraction of soluble matters from coffee pulp, as a simulation of the depulping process, to estimate the composition of the pulpwater;
2. The fermentation of the pulped coffee, to estimate the composition of the first washing waters ("aguas mieles").

pulp waters

Ellis (11) gives information about the organic components in coffee pulp, based on a literature review. These components are probably extracted form the pulp during the pulping process, and in this way they form the high contamination levels of the water.

Molina (12) investigated the extraction of these organic components from the pulp, using different extraction liquids, such as water (at different temperatures) and alcohol.
In fig. 9, the results of extraction with water at 25 and 96 °C are given; It appears that a significant part of the soluble components were removed from the pulp (and thus dissolved into the water).

component	presence in pulp (% dry weight)	extract in water (% of fraction in pulp) (96 °C)*	(25 oC)**
total proteins	12	6	5.5
pectic substances	6.5	-	-
tannins	1.8-8.6 (assume 2.4)	88	25
chlorogenic acid	2.6	87	45
total caffeic acid	1.6	88	32
soluble sugars	8.3	83	58
caffeine	1.3	98	76

* percolation: in three stages of 1h duration each
** extraction : with constant agitation

fig. 9: Composition of coffee pulp, and of extracts of pulp

Assuming an extraction with water at 25 °C as a simulation of the pulping process, semi-quantitive data can be calculated on the composition of the pulping wastes (see fig. 10).

component	presence in pulp (% of dry weight)	extracted matter (kg/tgcp)	COD-conversions reference component	kg COD/ tgcp	COD (%)
total proteins	12	3.4	glutamat	5.4	8.9
tannins	2.4	3.1	cathechin	5.9	10.0
chlorogenic acid	2.6	6.1	chl.ac.	8.8	14.5
caffeic acid	1.6	0.3	caf.ac.	0.4	0.7
soluble sugars	8.3	24.9	glucose	27.4	45.3
caffeine	1.6	6.3	caffeine	12.6	20.3
	total			60.5	100.0

Assumptions: 518 kg dry weight pulp/tgcp (see fig. 6)
8.8 m^3 water/tgcp (see fig. 13)
extraction at 25 °C, see fig. 9

fig. 10: Composition and COD of pulpwater, based on extrapolation of data from fig. 9.

It shoud be considered that Molina did not report on some components such as fats and cellulose. For that reason no 100% precise composition can be given. However, these fractions in pulpwaters will be small, since they cannot easily be extracted.

washing waters

The mucilage , surrounding the coffee bean, is a hydro-gel containing pectins, sugars and organic acids (see fig. 11), and apparently is free of tannins and caffeine (11).
An estimation of COD of the fermentation products, based on the mucilage composition, is shown in fig. 11.

component	mucilage composition (% of D.M)*	kg/tgcp	COD-conversions reference component	kgCOD/ tgcp	COD (%)
pectic substances	35.8	31.9	D-galacturonic acid	26.3	29.4
total sugars	45.8	40.8	glucose	44.9	50.2
cellulose	17.0	15.1	cellulose	18.2	20.4
total	98.6			89.4	100.0

assumption: 89 kg mucilage/tgcp (see fig. 6)
* source: (11)

fig. 11: Composition of mucilage and estimation of its COD.

During the fermentation process, the hydrogel is digested to pectic acid to an extent that all mucilage is dispersable in water (see also annex 1).
Bacteria and fungi, able to perform these processes, are present in coffee pulp and mucilage.
The formation of pectic and volatile acids cause the pH to fall, and acidity of the coffee to increase. Fermentation time is rather critical: Volatile organic products, formed during fermentation, may affect final coffee quality.

Chemical reactions during fermentation can be summarized as follows (15):

1. Pectin degradation by natural enzymes present in the mucilage and/or microbial action;
2. Ethyl alcohol production from carbohydrates (sugars, and pectin-reduction products);
3. Microbial production of organic acids (acetic, propionic, buturic, lactic and valeric acids).

The latter reaction takes place under aerobic and anaerobic conditions, with reduction velocities depending on coffee variety and altitude of the coffee cultivation.
Bacteria, able to perform these processes, were reported by various authors (13,14,15,16).

In laboratory, attemps were made to verify the supposed composition and microbiological processes that occur in the coffee process. However, limited technical means made it impossible to design experiments in such a way that sufficient proof for the hypotheses could be found. They were therefor tried to be made plausible with available means: COD-production was measured, and compared to the expected values, as shown in figs. 10 and 11.

2.2.3 Methods and materials

1. Chemical Oxygen Demand (COD)

COD determinations were performed according the description in annex 2.
COD of suspended matter were performed using Whatman nr 42 paper filters.

2. Volatile acids:

Individidual volatile acids, nor total volatile acids could be determined according to Standard Methods, by lack of necessary laboratory-equipment.
As an alternative, total alkalinity was taken as a measure for total VFA. Determination was performed by titration with 0.1N NaOH, using phenophtaleine as an indicator, or pH-meter (Fisher 6025). One sample-analysis was performed at the Agricultural University of Wageningen, using gaschromatografic methods.

3. Acidification

To determine the velocity of the natural acid-producing processes in the wastewater, a sample was left to stand during some weeks. Daily acidity was determined, as described under VFA. 1-2 times a week, COD of the sample was also determined, to get insight in the COD-reduction due to aerobic processes.

4. Total Solids

Total solids (TS) were determined according to "Standard Methods" (48).

Total protein, caffein, tannins, chlorogenic acid, caffeic acid and total sugars could not be determined, due to a lack of equipment, chemicals, materials and information.

2.2.4 Results and discussion

2.2.4.1 Waste production

Results of the determination of COD- and waterquantities in the depulping process as observed in "Los Alpes" are given in fig. 12. Data on the washing waters were obtained in laboratory tests (oxydizable matter and suspended solids) as well as observations in situ (amount of used water).

	quantity (m^3/tgcp)	oxydizable matter (kgCOD/tgcp)	suspended matter ($kgCOD_{ss}$/kgCOD)
pulpwater	8.8	57	0.052
washing water	22	72	0.18
total	30.8	129	

fig. 12: Water quantities and oxydizable matter produced in coffee processing

Comparing these results to the literature values (fig. 8) it can be remarked that:

- The results fit rather well with Adams results of 80 kg BOD/tgcp (9), assuming a COD:BOD relation of 2:1 (10);
- Especially the contamination produced in the washing process is higher than reported by the other authors. Reasons for this can be that in research so far mostly concentrations of contamination in the wastewaters wash measured (kgCOD/m3) and not the total amount of contamination produced (kgCOD/tgcp).

The results show a good fit with the extrapolated values as obtained in 2.2.2: In fig. 13 the predicted and obtained values are compaired showing for pulpwater as well as washing water a slightly lower value than was expected from the literature extrapolation.

	COD-values (kg COD/tgcp) extrapolated (a)	research (b)	b/a*100%
pulpwater	64	57	89
washing water	89	72	81
total	153	129	84

fig. 13: Comparision of extrapolated and research results

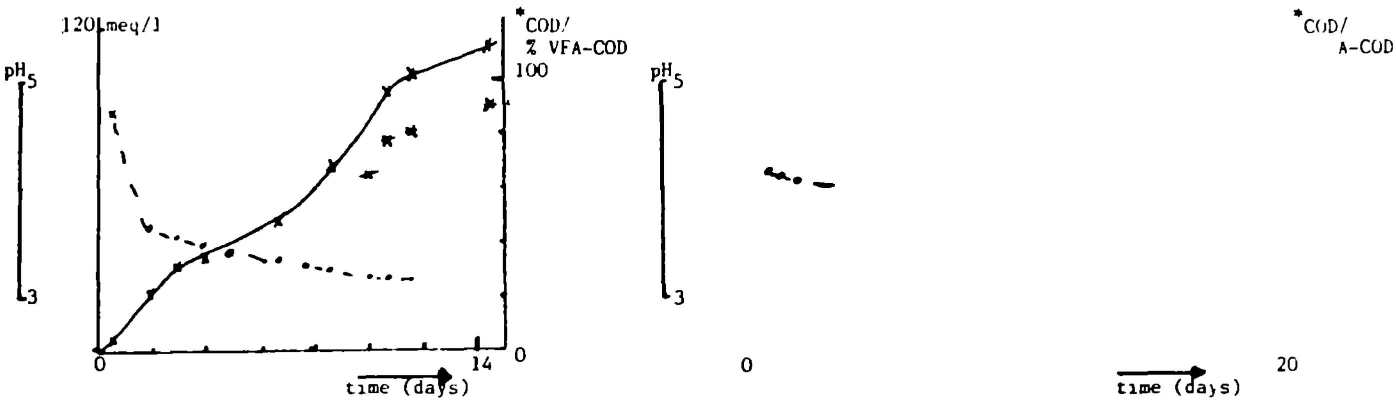
Main explanations for these differences are:

1. The global character of the calculation of the extrapolated values. Especially in the case of the estimations for pulpwater COD, the calculation was based on a rather approxi mative assumption;
2. Especially in the execution of batch fermentation tests in the laboratory, COD might have been lost due to evaporation or aerobic decomposition of volatile fatty acids and other lighter organic fermentation products, such as methanol (that is released during the breakdown of pectic substances) and ethanol (a product of sugar decomposition).

2.2.4.2 Acidification of pulpwater

In 2.2 the probable cause of an increasing acidity of the wastewater with time is discussed.
Experiments were done to determine the velocity of this acidification, and the extent to which the organic components in the wastewater actually are acidified, or, how much of the COD is conversed to volatile fatty acids in these, largely anaerobic, conditions.

Results are shown in fig. 14 for concentrated pulpwater (16-18 gCOD/l) showing an increase of the total acidity during 13-16 days, from 0 to 120 meq/l.



Exp. 1: 4.2-18.2.'86

Exp.2: 27.2-15.3.'86

fig. 14: Acidification as a function of storage time (T = ± 25 °C)

To find an indication of the significance of these data, use is made of a VFA-analysis of fermented pulpwater that was performed at the Agricultural University of Wageningen. Results of this analysis are shown in fig. 15, resulting in a mean COD of 128.5 gCOD/eq. acidity.

	mg/l	acidity (meq/l)	COD (mg/l)	% COD
Acetic acid	146	2.42	155	8.2
propionic acid	402	5.43	608	32.3
n-butyric acid	541	6.15	904	52.2
n-valeric acid	67	0.66	137	7.3
total	1156	14.66	1884	100

fig. 15: VFA analysis of fermented pulpwater

Using this result in the evaluation of the two acidification tests performed, it is found that about 90% of the total COD is transformed to volatile fatty acids (fig. 16). These are very easy degradable compounds, but cause low pH-values. The maximum acidification velocities are around 20 meq/l.d, or 2.6 gCOD/d or, related to the concentration of the waste, about 1 meq/gCOD.d or 0.13 kgVFA- COD.kgCOD^{-1}.d^{-1}.

	time (days)	COD (g/l)	maximum acidity (meq/l)	extrapolated VFA-COD (mg/l)	COD/ VFA-COD
Exp. 1	13	16	116	14.9	0.93
Exp. 2	16	18	125	16.1	0.89

fig. 16: Estimation of eventual VFA forming

The acidification products are mainly propionic- and butynic acids, which is in accordance to the results of Zoetemeyer (17) who reported on the fermentation of glucose under various pH-conditions.

2.2.5 Conclusions

From this paragraph can be concluded that in the coffee process a medium concentrated, easily (bio-)degradable wastewater is produced, which should be amenable to existing treatment methods.

The COD-production was quantified per amount of coffee produced, and the results from the determinations could be fitted well with the expected values which could be derived from literature data.

The data on the amount of wastewater used (and thus on the COD-concentrations in the wastewater) are based on data from one coffee mill only. It is probable that in other mills different amounts are found, depending on:

- the amount of clean water available;
- the application of water saving techniques.

This parameter should be determined in every case separately.

2.3 Reducing contamination by decreasing water consumption

Many authors (6,7,9) mention the reduction of waterconsumption in the coffee mills as one of the possibilities to reduce contamination. In this way, recycling wastewater (see also fig. 7) would offer a (partial) solution to the pollution problem.
However, a reduction of the total amount of produced COD would only take place in the case of saturation of the wastewater.

To test whether this actually was the case 7 batches of pulped coffee plus its pulp were treated, in laboratory, with the same water (at 22 °C) to extract oxydizable matter from the mixture. In this way, the pulping process was simulated.

The results are shown in fig. 17 and 18, and show a linearity in the total amount of COD and the quantity used for pulping coffee. It can be concluded that the total amount of COD produced in the pulping process will not be reduced by the re-use of the process waters: The concentration of COD in the water is proportional to the quantity of the coffee treated, and the amount of COD produced (kg COD/tgcp) is constant.

number of recirculations	amount of coffee treated (kg berries/l)	amount of water used (m^3/tgcp)	COD (kg/m^3)
0	0.3	17.5	7.8
1	0.6	8.8	15.2
2	0.9	5.8	25.3
3	1.2	4.4	33.6
4	1.5	3.5	36.1
5	1.8	2.8	50.0
6	2.1	2.5	56.0

fig. 17: Extraction of coffee pulp with different amounts of water

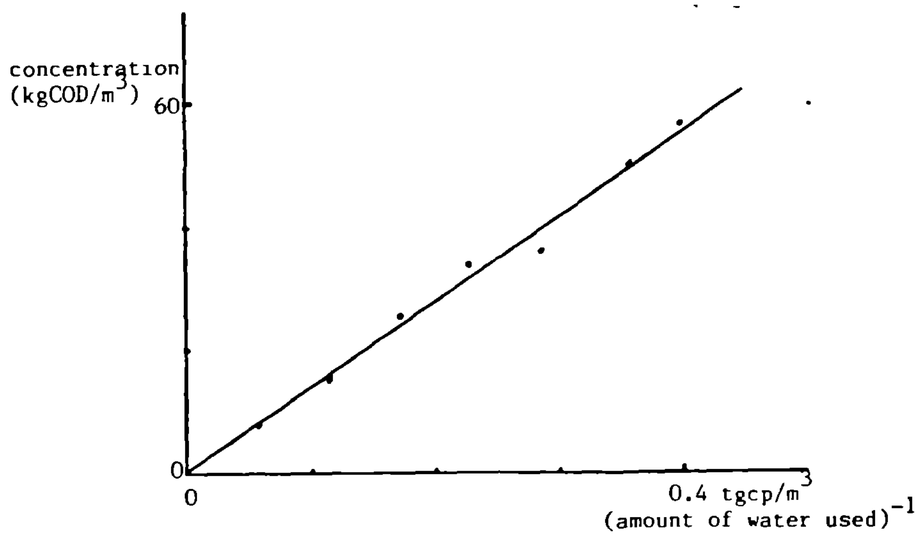


fig. 18: COD-concentration and water recirculation in coffee processing

For the washing process it can be remarked that all fermentation products have to be washed from the coffee, which represent a certain amount of COD. For that reason, no reduction of the total amount of COD removed can be expected from the application of water saving techniques.

From the results it can be concluded that water re-use can be useful in the following cases:

1. In the case of untreated disposal of the waste, as is applied at the moment in Matagalpa. In this way volume of storage lagoons needed to collect the process water, is saved. At the same time, water to be used for other purposes can be saved.
2. In the case of insufficient watersupply for the mill;
3. In the case of aerobic wastewater treatment, that usually is described as a first order oxydation process, where higher concentrations of the waste will lead to a faster COD-elimination.

In these cases, care must be taken not to use the polluted water in delicate process-steps, such as the washing process, in order not to effect the coffee quality (6). Re-use, as shown in fig. 7 can be recommended.

In most cases of biological wastewater treatment of medium and high strength wastes, the maximum allowable organic loading rate (kg COD-BOD.$m^{-3}.d^{-1}$) rather than hydraulic loading rates ($m^3.m^{-3}.d^{-1}$) determine the demensions of the treatment process. Further concentration of the waste will result, in these cases, in very low hydraulic loading rates, and (in case of oxydation beds or anaerobic reactors) to non-optimal process conditions (18,19).

2.4 Discharge standards.

Pickford (20) poses that discharge quality of wastewaters should meet standards of biological quality, toxic substances, organic matter, suspended matter, taste, odour and smell.
Because of the fact that these norms hardly can be correlated to COD-terms, it will be difficult to put standards on the effluent quality of wastewater treatment systems, treating coffee wastes; However, drinking-water purification techniques applied in Matagalpa (chlorination, a.o) generally require clean water: The organic contamination of the water used should not exceed 25 mgBOD/l (≈50 mgCOD/l (1)). We suppose, that at this level the wastewater will be stabilized.

ISP-Matagalpa gives data on the expected minimal water supply in the affected rivers Rio Molino Norte and Rio San Fransisco (1), and with data as found in 2.2 and dilution rates (as they result from these data) the minimum treatment requirements can be calculated (see fig. 19). Supposed are:

- A coffee production in the river basin of 1225 tgcp/year (see fig. 2);
- A maximum daily coffee production of 2.5% of the yearly production (2);
- COD-production of 130 kgCOD/tgcp (see fig. 12);
- A maximum allowable river contamination of 50 mgCOD/l (1);
- The driest harvest month: February.

probability of minimum water supply (%)	minimal supply in febuary (m^3/s)	max. dischargeable COD (kgCOD/d)	min. needed treatment efficiency (%COD)
70	0.17	734	82
80	0.12	518	87
90	0.08	346	91.5
95	0.04	173	96

fig. 19: Needed performance of purification systems for various values of water supply.

In this report, a probability of contamination, >50 mgCOD/l once in 10 years, is considered acceptable. Counting the minimal dilution rate in the driest month, the treatment technology applied should be able to meet 92% total-COD-removal efficiency.

2.5 Treatability of the waters

Many alternatives are available to reduce the contamination of the coffee wastewaters. In theory, a classification can be made with physical-chemical and biological treatment methods as most important alternative groups.
In this paragraph, a summary will be given of the technical possibilities of these technologies resulting from the wastewater characteristics as determined in 2.2. Furthermore, an overview will be given of the application of these technologies in coffee wastewater treatment, as they appeared in literature.

2.5.1 Physical-chemical treatment

Major alternatives in this group of technologies are the sedimentation of suspended solids and coagulation, flocculation, followed by sedimentation (or filtration).

Sedimentation
The process of sedimentation, as it is applicable for wastewaters with high concentrations of settleable suspended solids, is not very suitable for the treatment of coffee wastewater: In fig. 12 appears the small quantity of suspended solids in pulp- and washing waters, and it appeared that suspended solids are, for the larger part, present in the dispersed, colloidal form.

Coagulation, flocculation and sedimentation
Coagulation-flocculation is the process in which colloidal and some soluble compounds are removed from the water, by destabilization of dispersed particles and the formation of flocs using coagulants such as ferric chloride, hydrated lime or alum. Especially fermentation wastes, which contain colloidal gels of pectine fermentation products, could be treated well with this process. However, as is shown in fig. 10 and 11, complete removal of pectic substances would result in a mere 37% COD-reduction of the washing water, and 17% of total theoretical COD.
Horton (18) applied coagulation-flocculation in the treatment of coffee wastewaters, reporting settling of coagulated matter, but no data were given on the reduction of oxygen demand.
In general can be remarked, that a 17% COD-reduction would be far from sufficient for coffee wastewater treatment, so the technical feasibility of this alternative should be strongly doubted.

2.5.2 Biological treatment

High COD- and BOD-levels of the wastewater make it probable that biological purification methods are the most suitable to treat coffee wastewater. Successful treatment was reported with oxydation beds (18) and anaerobic treatment techniques (10), while also stabilization of the water in lagoons (7) and land-treatment (22,23) of the waste has been reported.
For that reason, special emphasis was put on biological treatment during this investigation, considering local farm-conditions in the choise of the subjects of investigation.

2.6 Choise of technology

In Nicaragua, (but also in many other countries) coffee is processed on the farms where it is cultivated. This decentralized way of production results in the requirement of decentralized wastewater treatment.

Conventional sewage treatment (oxydation beds, activated sludge techniques, a.o) rely heavily in advanced equipment that require considerable skill in installation, operation and maintenance. This skill is not readily available in many of the tropical developing countries, let alone at the farm level(24,25).

For water purification at the farm level, in general, a.o following circumstances should be considered in the choice of technology:

- Scarcity of educated, local staff personnel makes simple and, if possible, endogene technologies necessary;
- Scarcity of capital calls for cheap treatment methods, which involves (because of other cost-relations in these countries) the use and knowledge of locally produced (or at least: locally available) materials;
- Variable costs of scarce goods (energy, chemicals) should be avoided as much as possible.

These criteria, that strongly emphasize the local conditions, are used in fig. 20 to assess a number of "conventional" and more or less "appropriate" technologies of biological wastewater treatment. The "scores" in fig. 20 give some indication of the suitability of the process for the treatment of coffee wastewaters in these circumstances.

	A.S	O.B	O.D	A.L	S.L	A.R
BOD-removal (90%)	2-3	2	3	3	3	2c
Bacteria-removal	1	1	2	2	3	1
Simplicity of						
- construction	1	2	2	2	3	2
- operation	1	2	2	1	3	2
Costs of						
- construction	1	2	2	2	2-3	2
- operation	1	1	1	1	3	2
Necesity of land	3	3	3	2	1	3
Demand of energy	1	2	1	1	3	3a
Applicability in case of:						
- farm level	1	2	2	2	3	2
- effluent re-use	1b	1b	2	2	3	3b,c
- seasonal use	1	2	1	2	2	3
- coffee wastewater (experience)	1	2	1	?	2	2
Total score	15.5	22	22	20	31.5	27

a. production of biogas, demand of energy is negative
b. high amonia and faecal bactery concentrations
c. post-treatment necessary, but suitable for irrigation-ends

1 = poor
2 = average
3 = good

A.S: Active Sludge Process
O.B: Oxidation Bed
O.D: Oxidation Ditch
A.L: Aerated Lagoon
S.L: Stabilization Lagoon
A.R: Anaerobic Reactor

fig. 20: Approximative comparison of some biological wastewater treatment methods for application on farm level in developing countries.

2.7 Conclusions and consequences for the investigation

Investigating the possibilities of the treatment of coffee wastewaters on farm level, the waste, containing high concentrations of easily biodegradable matter like polysaccharides, sugars and pectins, will be treated best with biological wastewater treatment methods.
Considering the local situation (application of this process on farm level in a developing country) it can be concluded that the most promising alternatives to treat the waste are oxydation lagoons and anaerobic reactor processes. These alternatives were investigated further in this report.

In chapter 3, the feasibility of anaerobic reactor techniques will be studied, using an Upflow Anaerobic Sludge Bed Reactor.
In chapter 4, further study will be made on the technical feasibility of (anaerobic) oxydation lagoons, as a first phase in the purification process. Performance of existing lagoons will be studied, and a design method for anaerobic ponds will be developed.

Because of the limited time available, this investigation did not treat on the applicability of the various post-treatment methods. In general it should be remarked, however, that an (aerobic) post-treatment of the effluents of the anaerobic treatment techniques will be required in order to obtain the set effluent standards (see 2.4).

Chapter 3: Anaerobic pre-treatment with the UASB-process

3.1 Introduction

Anaerobic digestion of wastewater has its potentials from the point of view of wastewater treatment, and of energy production. The anaerobic digestion processes offer a simple (pre-)treatment method, able to remove a significant part of the biodegradable fraction of (medium and high-strength) wastewaters, resulting in 80-95% COD-removal.
The main advantages in comparison with many aerobic wastewater treatment techniques are:

- The low energy requirements combined with the production of biogas (up to 0.8 kg CH_4-COD*.(kgCOD-removed)$^{-1}$;
- The much lower production of excess sludge;
- The possibility to perform the process in an uncomplicated way, requiring little expertise to perform the process;
- The conservation of valuable compounds for fertilization, like ammonium- and phosphate salts.

Especially in developing countries, these characteristics make the application attractive, albeit that anaerobic treatment essentially represents a pre-treatment method, and some sort of post-treatment is needed before the water can be discharged into receiving waters.

Essentially, anaerobic treatment of wastewaters can be applied in two main process methods:

1. The anaerobic wastewater stabilization ponds: A low rate process, which is the most simple, and in many cases the cheapest form of anaerobic wastewater treatment;
2. The anaerobic reactor process, handling high loading rates. Advanced methods were developed after the energy crises of 1973, such as various fixed-film reactor types and the Upflow Anaerobic Sludge Bed (UASB)-process, allowing high hydraulic loading rates in combination with long sludge retention times.

Both methods have been studied to treat coffee wastewaters.

In this chapter, the anaerobic reactor is studied, while in chapter 4 a study will be made of the anaerobic lagoon system, although many of the theoretical aspects of the processes have common features, such as microbiology (3.2.1) and a number of process parameters (3.2.3).
In 3.2.2 different processes to perform anaerobic reactor treatment will be studied, justifying the choice of the UASB-technique, while in 3.2.4 the theoretical aspects of the start-up of this process will be treated.
In 3.3 a literature review will be given on aspects of the application of hte anaerobic reactor on coffee wastes.
In 3.4 and 3.5 the design and results of the experiments, performed in laboratory and on technical scale, are described and discussed.

*1 Nm^3 ≙ 2.62 $kgCH_4$-COD, 298K

3.2 Theory

3.2.1 Microbiological aspects

Anaerobic digestion of biodegradable wastes involves a large spectrum of bacteria. Generally three main groups are distinguished, each of which is connected with part of the total digestion process (see fig. 21).

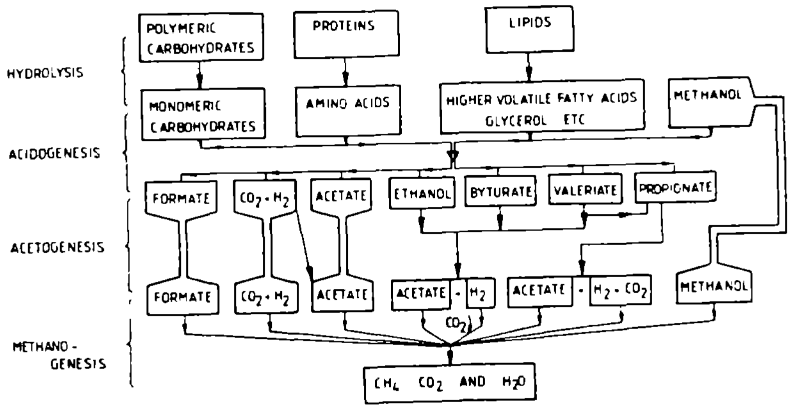


FIGURE 21 Schematic survey of the main processes involved in anaerobic digestion.

Fermenting bacteria perform the first two subprocesses, i.e. hydrolysis and acidogenesis. They hydrolyze dissolved or undissolved polymers like proteins, lipids and carbohydrates through the action of exo-enzymes into smaller units, that can enter the cells. In the cells, an oxydation-reduction process results in the formation of carbon dioxide, hydrogen and mainly volatile fatty acids (VFA). The environmental conditions determine to what extent other, more reduced compounds like ethanol are formed. Because of their production of VFA the fermenting bacteria are usually designated as the acidifying population.

The second group of bacteria, which break down the products of the acidification step, are called the acetogenic bacteria, after their main product acetate. Besides acetate, hydrogen and, in the case of odd-numbered carbon compounds, CO_2 is also formed in this phase.
Fig. 22 shows that the breakdown of volatile fatty acids into acetate and hydrogen does not yield energy under standard conditions.

The acetogenic bacteria only perform these reactions when the concentrations of acetate and, more specifically, the partial pressure of hydrogen in the liquid are kept sufficiently low by methanogens or sulphate reducing bacteria (26). The acetogens are therefore obligate syntrophic bacteria and depend upon an effective interspecies hydrogen transfer.

substrate	reaction			$\Delta G^{0'}$ (kJ)
METHANOGENIC				
acetate	CH_3COOH	→	$CH_4 + CO_2$	- 31
hydrogen	$4H_2 + CO_2$	→	$CH_4 + 2H_2O$	-131
methanol	$4CH_3OH$	→	$3CH_4 + CO_2 + 2H_2O$	-312
ACETOGENIC				
ethanol	$CH_3CH_2OH + H_2O$	→	$CH_3COOH + 2H_2$	+ 9.7
propionate	$CH_3CH_2COOH + 2H_2O$	→	$CH_3COOH + 3H_2 + CO_2$	+76
butyrate	$CH_3CH_2CH_2COOH + 2H_2O$	→	$2CH_3COOH + 2H_2$	+48
$CO_2 + H_2$	$2CO_2 + 4H_2$	→	$CH_3COOH + 2H_2O$	-95

fig. 22: Free energy changes of some methanogenic and acetogenic catabolic reactions

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Of the acetogenic reactions commonly observed in anaerobic digestion, propionate oxydation is thermodynamically the most unfavourable reaction (27). Yet, propionate represents an important intermediate. It is formed in the break-down of odd-numbered fatty acids from certain amino acids, as well as from carbohydrates. Unfavourable process conditions will lead to the increase of propionate-producing bacteria (28,29).
Accumulation of hydrogen (which might be caused by an unbalance between the acidification and the methanogenesis) can rapidly inhibit the turn-over of VFA higher to acetate. Propionate degradation will be affected first.

The third group are the methanogenic bacteria.
They convert acetate or hydrogen and carbon dioxide into methane (fig. 22). Other possible methanogenic substrates, like formate, methanol, CO and methylamines, are of minor importance in most anaerobic digestion processes.
In the anaerobic digestion processes, the methanogenic step is most critical to environmental factors; Inhibition of these bacteria in a more or less stable anaerobic process may cause VFA-accumulation and possibly an acidification of the process. Furthermore, the methanogenic step is most sensible to environmental factors (30).
In a stable methane digestion of dissolved organic matter, the acetate conversion to methane is the rate limiting step. In cases of hard hydrolizable, and/or suspended organic matter, however, the first step of the fermentation process may define the maximum digestion rate (31).

3.2.2 The retention of biomass, and the UASB process.

The successful performance of high-rate anaerobic processes depends on the retention of a high concentration of active biomass in the reactor, despite high superficial gas and liquid velocities. The low maximal growth rate of the rate limiting bacteria in the methane digestion process (u_{max} is in the order of 0.40/d) requires minimal sludge retention times of 3 to 12 days. In the treatment of low concentrated wastewater with normal organic loading rates, the hydraulic retention time will be considerably lower than this period. For that reason equal retention of sludge and wastewaters has to be abandoned. Methods to improve the sludge retention in the treatment systems are summarized in fig. 23.

The UASB reactor is one of the reactor types with a high loading capacity. The sludge retention method (granulation and/or flocculation of biomass) implies no need for filter or carrier material (as is the case for anaerobic filter or fixed fils reactor types) nor exists need for sludge or effluent recirculation and concomitant pumping energy (as in the anaerobic contact process and the fluidized bed reactor).
This simplicity of design makes the UASB process suitable for application in cases where process costs are a dominant criterium in the choice of purification technology (32,33).

reactor type	sludge retention method	achievable load ($kgCOD/m^3.d$)
conventional (completely stirred)	none	± 1
anaerobic contact process	separate settling tank with sludge return	± 5
anaerobic filter	bacterial immobilization on filter material combined with sludge particle retention in filter interstices	10 - 15
UASB	granulation of bacterial mass and an internal settling compartment	20 - 50
fixed-film processes	bacterial immobilization on static surfaces, or on particles (expanded or fluidized mode)	20 - 40 20 - 50

fig 23: Comparison of various anaerobic wastewater treatment concepts. Source: (19)

For that reason, the investigations described in this chapter are based on the UASB process.

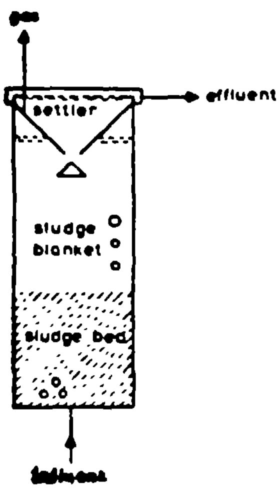


fig 24: UASB-reactor with internal settler

Figure 24 shows a schematic diagram of an UASB-plant.
In general, three zones can be distinguished in the reactor:

1. The sludge bed, formed in the lower part of the reactor, consisting of a densely packed mass of granulated sludge with good settling characteristics;
2. A much less concentrated, fairly well mixed sludge blanket fills up the space above the sludge bed and beneath the gas collector system;
3. Above the gas collectors a gas bubble free zone permits sludge particles to settle out and to slide back into the digesting compartment.

Main objectives of the Gas-Solid Separator (GSS), installed in the top of the reactor, are (34,49):

a. The separation of the biogas from the mixed liquor and from floating particles;
b. The separation of dispersed sludge particles and flocs by settling, flocculation and/or entrapment in a sludge blanket, if present in the settler compartment;
c. To enable the separated sludge to slide back into the digestor compartment;
d. Restriction of excessive expansion of the sludge blanket.

A properly functioning UASB reactor needs an even distribution of the wastewater at the bottom of the reactor. The extent to which a satisfactory distribution of influent can be obtained depends on various factors: The sludge bed volume, the hydraulic retention time, the division of the influent over the reactor, and mixing (35,36).
In general, no mixing device is needed in UASB reactors.
At higher gas production rates (> 10 kgCOD.m^{-3}.d^{-1}) the biogas production guarantees sufficient contact between substrate and biomass.

3.2.3 Environmental factors

<u>Temperature</u>

Temperature has a major effect on the bacterial growth rate and activity. In general, three temperature ranges are distinguished to classify anaerobic processes, each of them allowing certain maximum loading rates:

In the psychrofilic range (8 - 20°C), as has been applied in treatment of diluted domestic wastewaters, gas is still produced at temperatures as low as 10 °C. Organic loading rates of 0.7 - 2.8 $kgCOD.m^{-3}.d^{-1}$ were applied, with a treatment efficiency of 60 - 80% COD (37).

In the mesophilic range (20-40 °C) allowable organic loading rates depend strongly on wastewater composition.
Nowadays most processes are applied in the mesophilic temperature range, with organic loading rates varying from 25 to 50 $kgCOD/m^3.d$ (38).

The application of thermophilic digestion (50-60 °C) might be interesting for certain industrial wastewaters (39). Extremely high organic loading rates (up to 150 $kgCOD.m^{-3}.d^{-1}$) can be applied, with good treatment efficiencies (80-95% COD-reduction) and consequential gas productions.
Energy demand, however, will make the process attrictive to only a limited number of applications.

	temperature	max. loading
psychrophilic	8 - 20 °C	- 3.5 $kgCOD.m^{-3}.d^{-1}$
mesophilic	20 - 40	15 - 50
thermophilic	50 - 65	80 -150

fig. 25: Temperature ranges and maximum organic loading rates

<u>pH</u>

Anaerobic digestion is rather sensitive to pH-conditions.
The optimum pH for the mesophilic methanogenic process step lies between 7.0 and 7.2 (26), while the acidification process finds its optimum at pH 6.0-6.5 (40).
Complete inhibition of the methanogenic process-step was encountered when pH fell below pH=6, or above pH=8, during a considerable length of time. Buffering should be applied, if necessary.

Nutrients

Compared to aerobic bacteria, the anaerobic bacteria need relatively small amounts of nutrients. Nitrogen and phosphate are required in relation to the COD of the waste,
COD : N : P = 350:5:1 (19).
Trace nutrients, like Iron, Cobalt, Nickel and other metals are needed in low concentrations (1-250 mg/kgCOD), as was shown in a study by Speece (41).

Toxic substances

Free heavy metals, chloroform, cyanide compounds and some other chemicals are considered as highly toxic to methanogenic bacteria.
However, process inhibition can be caused by a lot of other (organic and inorganic) substances. In most cases adaptation of the anaerobic sludge can be forced.

3.2.4 UASB process start-up

The most critical period in a UASB lifetime is its start-up period, defined as the time after which the sludge characteristics do not change anymore, when treating a wastewater of a constant composition under fixed conditions, or the time required for the development of the first macroscopic sludge granules (19).
Especially when no adapted UASB sludge is available performance of the start-up procedure will be a critical factor in later process performance.
According to de Zeeuw (19), who made a major study on reactor start-up, a number of phenomena are important in the first reactor start-up:

1. Nature of the seed sludge:
   In general, UASB reactor start-up will proceed more easily and more quickly when the quality of the seed sludge in one or more aspects exceeds that of unadapted seed material, as defined in fig. 24.
   Sludge can be characterized by the following parameters:
   a. TSS and VSS contents ($kg.m^{-3}$);
   b. Methanogenic activity ($kgCH_4$-$COD.kgVSS^{-1}.d^{-1}$).
      As the volatile fraction of unadapted seed sludges often mainly consists of non-bacterial organic mass, methanogenic activity yields a better characterization of bacterial concentrations than VSS-contents.
   c. Settleability, characterized by SVI (Sludge Volume Index) (ml/g).
2. Lag phases:
   The response of an unadapted sludge to a new waste generally will include a lag phase. Among the factors influencing the occurence and the length of the lag phases are the concentration of active biomass (methanogenic activity), the mixing intensity, the initial substrate concentration and the environmental factors (temperature, pH, toxic substances);
3. Growth velocity;

a. The seed material is obtained from an anaerobic treatment system without biomass retention, such as conventional mixed digesters, ruminants, septic tanks or fresh water sediments;

b. The sludge exerts a specific methanogenic activity of less than 0.2 kgCH_4-COD/kgVSS.d;

c. The settleability of the organic fraction of the sludge is poor;

d. The bacterial population of the sludge is unbalanced with respect to the composition needed for the simulateous degradation of all waste ingredients;

e. The sludge is not adapted to specific inhibitors in the wastewater (such as sluphide, ammonia, etc).

fig. 26: Characteristics of unadapted seed sludge for UASB reactor start-up.

4. Sludge wash-out and sludge retention:
   During the start-up of a UASB-reactor the upward velocity of both water and gas causes finely dispersed and poorly settling particles to wash out from the reactor. This wash-out may be part of a key feature of the UASB concept, i.e. the selection pressure exerted upon the sludge particles. This selection ultimately leads to the development of highly settleable, granular sludge.

The phenomena outlined above are described by de Zeeuw in start-up experiments using digested sewage sludge as an inoculant. The use of cow manure as seed sludge is said to be possible too. However, for reasons of low initial methanogenic activity, it should be counted with longer start-up periods.
In thermophilic processes, on the other hand, start-up is faster using fresh cow-dung than digested sewage sludge or fermented sewage sludge (42).

3.3 Aspects of coffee wastewater treatment with the UASB-process

3.3.1 The application of the UASB process on coffee wastes

In two cases the anaerobic wastewater treatment was applied to coffee residuals. These investigations were performed in Colombia and Guatemala, respectively.

IJspeert (10) reports the troublefree application of the UASB concept to undiluted wash and fermentation waters in Cali, Colombia.
The reactors (23 and 270 litres) were seeded with sludge from a 64 m^3 UASB reactor treating domestic wastewaters, which showed a low specific methanogenic activity (0.1 g CH_4-COD/kgVSS.d) and a good settleability (SVI = 10 ml/g).
During the start-up phase the applied organic loading rate followed the total methanogenic capacity of the reactor, so that eventual overload was avoided.
Organic loading rates up to 15 kgCOD/m^3.d with COD reductions of 80-90% could be handled easily, with hydraulic retention times as low as 6 hours. Gas production was round 0.3 Nm^3/$kgCOD_{rem.}$ methane.
Further research was needed, according to this report, to determine the maximum loading rate and the necessity of (automatic) influent pH-control (10).

Calzada a.o (45,47), treating coffee pulp juice that was obtained from the mechanical pressing of fresh pulp to remove water and soluble compounds, had various problems treating the water in UASB reactors (0.15 and 12 litres of volume), functioning according to one- and two-phase systems.
The methanogenic reactors were seeded with cow-manure, to which coffee pulp juice was added to adapt the inoculant to the waste to be treated. No data were given dealing with the initial methanogenic activity of the inoculum. Acidogenic fermentors were seeded with sludge from non-controlled, fermented piles of pulp in the coffee mills.

In single phase digestion finally acidification of the process occurred: Hydraulic retention times of 5-10 days, corresponding to organic loading rates of 2.5-5 KgCOD/m^3.d, could not be handled (see fig. 27).

Also in the two-phase system the pH-control of the methanogenic reactor turned out to be difficult: Two reactors had a fatal pH-drop, at hydraulic retention times of 6 days and organic loading rates of $\pm$ 6 kg COD/m^3.d. Unfortunately, data on the reactor start-up are not available.

The same investigators reached better results using poly-urethane foam packings in the methanogenic ractor in two-phase systems (46,47).

Reviewing the data available, it would be interesting to know more about the start-up methods applied in these experiments. If the experiments would be executed (and thus, also be started up) for only 30 days (as should be concluded from the publications) serious doubts should be put on the start-up modes applied. To reach a loading rate of 2.5 $kgCOD/m^3.d$ with poorly adapted inoculum in less than 30 days is a rather fast start-up, and it is likely that the loading rates dit no follow the methanogenic capacity of the reactor.

Possible causes of the encountered reactor break-downs are:

1. Inhibition of the methanogenic phase because of the treatment of the seeding material with coffee pulp juice, that contains high concentrations of tannins (see next paragraph);

reactor	retention time (d)	derived organic load ($kgCOD/m^3.d$)	gas production ($kgCH_4COD/m^3.d$)	CH_4-COD/COD_{rem} (%)	rem
1-phase (46)	20	1.25	1.2	96	
	10	2.5	1.7	68	*
	5	5.0	1.9	38	**
2-phase (45)	5	7.7	6.2	81	
	4	9.7	8.5	88	
	3	12.9	5.3	41	*
	2	19.4	13.1	68	*

remarks: * problems in pH-control in the methanogenic reactor
** process stop due to fatal pH-drop

fig. 27: UASB-experiments by Calzada a.o

2. Overloading of the reactor: The organic loading rates that were applied in the single phase system were higher than the gas production, and thus the specific methanogenic capacity of the reactor.
   Low initial organic loading rates should be applied when cowdung is used as inoculum, because of its low methanogenic activity ($\pm$ 15 gCH_4-COD/kgVSS.d). An overload will cause the process pH to fall because of the rapid acidification of the wastewater.

In the application of the two phase UASB-system probably also a structural overload of the methanogenic phase took place. This explains the problems that occured in the control of pH. Inhibition of the methanogenic phase due to tannin inhibition might also have been the case: Coffee pulp juice will contain tannin concentrations up to 5 times higher than is the case with "normal" pulpwaters, with tannin concentrations that might give more than 90% methanogenic inhibition (see 3.3.2).

However, as with the single phase system, no definite conclusions can be drawn, because of the lack of sufficient data.

3.3.2 Tannin inhibition

As remarked in 2.2.2, pulping wastes contain polyphenolic components that are known as inhibitors of enzymatic processes. Field (43) performed an investigation of the toxic capacities of ta nnic substances at anaerobic (hydrolytic and methanogenic) processes, and reported a strong reduction of the methanogenic activity of granular sludge (50 to 90% or more) in the presence of moderate concentrations of tannins (0.7-2 g/l).

The polymeric structure of these phenols are regarded as the prerequisite for their "tannic" qualities, since the polymer provides multiple phenolic groups which can form hydrogen bonds with the proteins.
In doing so, the formed protein-tannin complexes flocculate and are sedimentated. If they stall are fed into the reactor, tannins may be set free if the protein-part of the complex is digested and converted to smaller VFA.
Tannins can be oxydized, as many phenolic compounds, to pigments, melanines or humus in alkaline conditions, as oxydation of phenolic compounds require the presence of neighbouring hydroxyl groups. Oxidation of the tannins generally will lead to their detoxification, because of the formation of less effective inhibitors.

In coffee wastewaters the presence of tannins can be expected. As shown in fig. 9, extraction of coffee pulp with water at 25 °C will lead to 25% tannin removal from the pulp or, which is the same, the dissolution of 2-11 kg tannins/tgcp. Using water quantities as indicated in fig. 12, this would mean that tannin concentrations of 0.2-1.3 g/l in the wastewater (pure pulpwater) or 0.1-0.4 g/l (washing water included) can be expected.
According to Field (44), inhibition of the methanogenic activity up to 90% (for pure pulpwater, with tannin concentrations of 2g/l, or COD > 8g/l) could occur in cases of high tannin concentrations. Little problems are to be expected in case of moderate tannin concentrations in the pulp (up to 3.5% of pulp dry matter contents), and normal water use, as was the case in "Los Alpes".

3.4 The design of experiments

3.4.1 Objectives of the experiments

Aim of the program is to determine the process parameters determining the design of a full-scale UASB treatment system for coffee wastewaters. Next to this problems in the start-up and operation of the system were to be identified and treated.

The major process variables that characterize the UASB start-up and determine the later process performance are the amount and quality of the seeding sludge, the organic load and the hydraulic retention time.
Parameters to determine the process performance are the COD-removal, the gasproduction, sludge development and the process (pH-)stability.

The experiments were to be carried out considering the local constraints: Seeding sludge should be locally available, and the use of neutralizer or other chemicals should be avoided as much as possible.
Furthermore, the socio-technical conditions to implement UASB-reactor technique in a farm should be indicated, considering:

- the complicateness to construct a UASB-reactor;
- the complicateness to control the process;
- the need and availability of local (specialized) personnal, for design, construction and control of the process.

3.4.2 The 9 m^3 UASB system

To determine these technical and socio-technical parameters, an existing biogastank of 9 m^3, perviously used for the fermentation of coffeepulp (see fig. 28), was used to test the feasibility of the UASB process in the purification of coffee wastewaters. For that purpose, the reactor was modified (see fig. 29).

The influent is collected from the depulping process (see fig. 30), which produces the highest concentrated wastewaters ($\pm$ 6.5 kgCOD/m^3). The influent enters a buffer tank (36 m^3) by gravity, from where it is pumped to the bottom of the UASB reactor. The inlet distribution system has only one inlet point (at the center of the bottom) for the 3.5 m^2 reactor surface, which is rather poor (38), although good results have been reached with one inlet point per 2-5 m^2 (19).

Neutralization of the water is performed in the tube, just before entering the reactor, in order to minimize the use of neutralizer.

Sodium hydroxide (50% technical grade, Pennwalt Managua) is used as neutralizer.

The use of lime or calcium carbonate was considered for its better buffering capacity. However, this idea was rejected for two reasons:

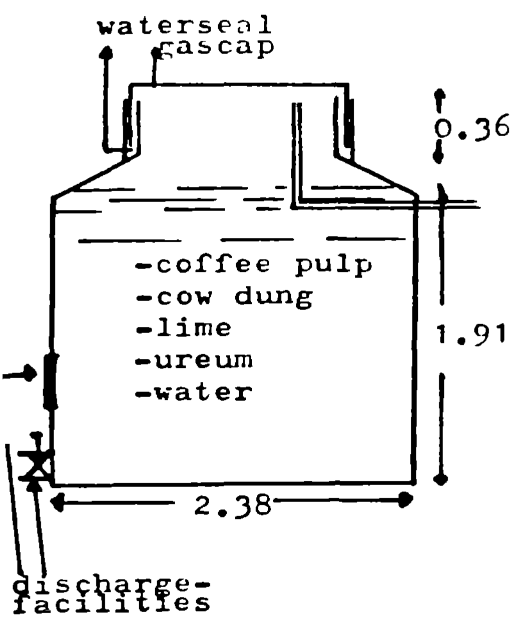


fig. 28: Biogas tank
"Los Alpes"

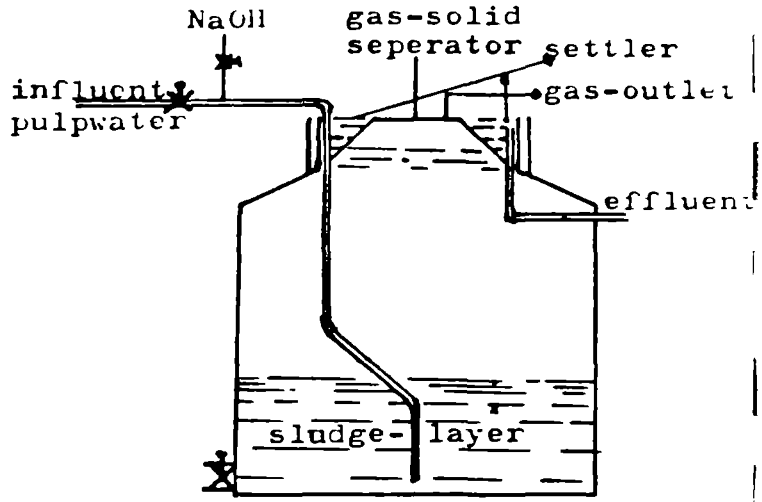
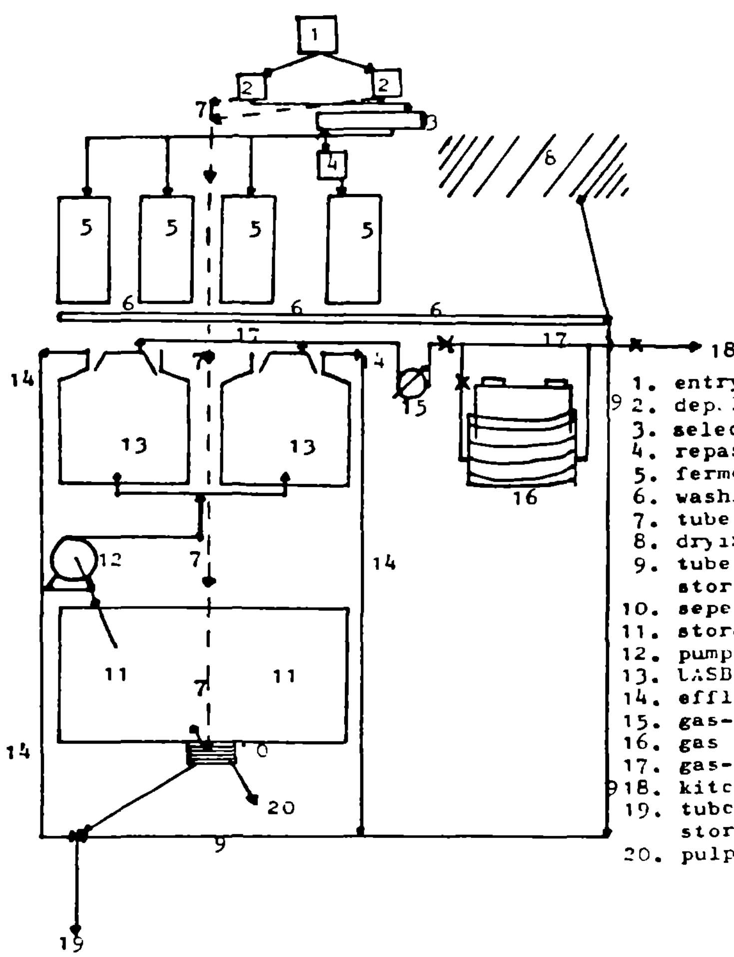


fig. 29: The modified tank,
used as UASB-reactor



1. entry of water and coffee
2. dep. lpers
3. selector
4. repasser
5. fermentation tanks
6. washing canal
7. tube for pulp
8. drying patio
9. tube for wastewaters to storage ponds
10. seperation of water and pulp
11. storage of pulpwater
12. pump
13. UASB-tanks
14. effluent UASB-tanks
15. gas-meters
16. gas holder
17. gas-tube
18. kitchen
19. tube for wastewaters to storage ponds
20. pulp storage

fig. 30: Coffee mill and experimental UASB-system at "Los Alpes"

a. The application of calcium- and carbonate salts would lead to the formation of suspended salts, that would settle down on the sludge particles. This would have a negative effect on the sludge development (10,34).
b. Lime nor calcium carbonate were available in a sufficiently pure form in the local situation. Because of the needs of the process after this experimental stage, the idea of importation of the chemicals was rejected.

The effluent was discharched into oxydation ponds, the gas was storaged, via a wet gasmeter, into a metal gas holder.

Loading of the reactor took place 1-2 times a day, during 1.5-3 hours.

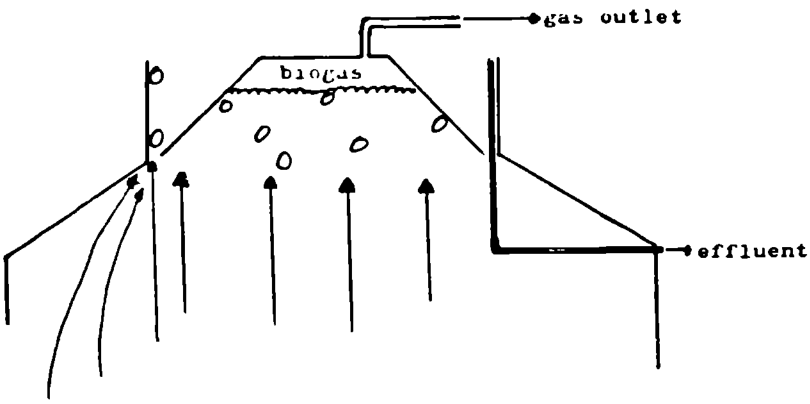


fig. 31: The gas-solid seperator device
scale: 1 : 200

In fig. 31 a schematic digram is given of the location of the Gas-Solid-Separator (GSS) in the reactor.
Dimensions of this GSS and the settler are given in fig. 32.

- volume of GSS : 0.16 m^3
- % of reactor area cover by GSS : 25%
- volume of the settler compartment : 0.24 m^3
- area in settler compartment : 0.2 - 1.1 m^2
- upward velocities in the settler :

flow (l/h)	reactor retention time (h)	settler retention time (h)	upward velocities in GSS bottom (m/h)	half-way (m/h)	top (m/h)
0.2	44	1.2	1	0.3	0.2
0.4	22	0.6	2	0.5	0.4
0.6	14.7	0.4	3	0.8	0.5
0.9	9.8	0.3	4.5	1.2	0.8
1.2	7.3	0.2	6	1.6	1.1

fig. 32: Dimensions of GSS and settler compartment

Major deficiencies of the device are:

1. The limited area the GSS covers: Assuming an equal gasproduction over the reactor area, at the most 25% of the gas produced is captured and, consequencially, registered;
2. The lack of gas seals, causing the floatation of sludge particles and gas bubbles into the GSS-device. Hence, especially at moments of high gas production and at high loading rates, large quantities of sludge were present in the settler compartment and (unnecessarily) washed out of the reactor;
3. The small volume of the settler compartment, with a consequently small residence time and high surface load (up to 3 m/h at an applied loading rate of 600 l/h).
   According to Lettinga a.o, the surface load in the settler compartment should not exceed 1-1.5 m/h for flocculant sludge bed systems (34).
   The fact that the ractor was operated in a semi-continous way re-inforces this effect: During the loadings (1.5-3 hours/day) a sudden high hydraulic load was applied.

3.4.3: Materials and methods

Performances of the 9 m^3 Los Alpes installation were followed in the physical-chemical laboratory of the Soils Department of MIDINRA VI-regiôn in Matagalpa.

During the first 30-100 days, a UASB system is starting-up: Sludge has to develop, and to adapt slowly to the feed and loading rates that eventually will be applied. To assure a stable process, optimal circumstances should be installed during this stage of the process.
Regular monitoring consisted of 4-6 times a week monitoring of the systems performance, expressed as efficiency in COD-removal, temperature, pH, acidity and gas production.
Sludge development was monitered in TSS, VSS and specific methanogenic activity. Sludge profiles over the reactor were made every 14-28 days.

- Determination of COD

The micro-COD-determination that was applied, is described in annex 2.

- Determination of the specific methanogenic activity:

The methanogenic activity was determined in standardised batch activity tests, as described in annex 3.

pH-values were determined by a field- and laboratory pH-meter (Hanna instruments and Fisher 6025 respectively), gas production with a wet gasmeter (Saõ Paulo, Brazil), TSS and VSS were determined according to Standard Methods (48).
For photospectrometric analysis a Spectronic 20 was used.

3.5 Results

3.5.1 First reactor start-up (10.1.'86-25.1.'86)

seeding sludge

The reactor first was inoculated with a mixture of septic-tank sludge and coffee-process residual sludge, found on the bottom of process water drains and anaerobic stabilization lagoons. Quantities and initial methanogenic activities are shown in fig. 33 and 34, and resulted in a total initial methanogenic capacity of 1.7 $kgCH_4$-COD/d in the reactor.

SLUDGE	kg TSS/m^3	kgVSS/m^3	meth. act. ($kgCH_4$-COD/kgVSS.d)
coffee residual sludge	90	31	0.027
septic-tank	24	14	0.066
fresh cow-dung	180	125	0.015
flocculated cow-dung	53	31	0.022

fig. 33: Seeding sludge characteristics

SLUDGE	1st start-up 1st load	2nd start-up 2nd load	3rd load
coffee residual sludge	1	3	-
septic-tank	4	-	-
fresh cow-dung	-	0.1	-
flocculated cow-dung	-	-	1.2

fig. 34: Quantities of seeding sludge, in m^3

process performance and process stability

During this start-up, literature guidelines for start-up procedures were applied. De Zeeuw gives as a general recommendation to start-up at a loading rate of 0.1 kgCOD/kgVSS.d, with a mean sludge concen-tration of 10-15 kgVSS/m^3.

During start-up, the COD-removal efficiencies declined rapidly, the pH was very difficult to control and, at the end, acidifica

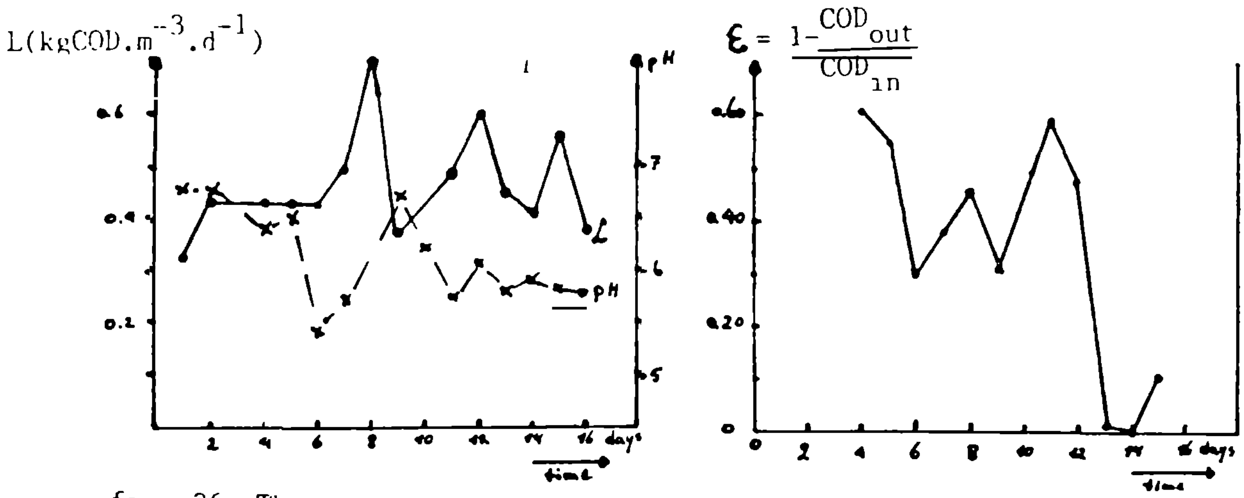


fig. 36: The results of the first reactor start-up

tion of the process took place (see fig. 35). This, in spite of attempts to neutralize the reactor with large quantities of sodium hydroxide (day 9 and further).
At day 14 a sludge profile and a methanogenic activity test were performed. Although no change in the methanogenic activity was registered (21 gCH_4-COD/kgVSS.d) the total methanogenic capacity of the process had declined because of a considerable sludge wash-out. VSS-contents declined from 42 to ± 20 kgVSS(2.2 kgVSS/m^3).
Because of this low concentration a new sludge load was considered indispensible.
During this period, the gas production could not be measured, because of the lack of a gas meter.

3.5.2: Second reactor start-up (28.1.'86-12.3.'86)

seeding sludge
A mixture of coffee-process residual sludge and cow-dung was used in the 2nd load, with a total of 106 kgVSS and 2.7 kg CH_4-COD/d methanogenic capacity of the reactor as a whole (see fig. 33 and 34).

process performance and process stability
The organic loading rates applied during this period were lower; It was tried to follow the maximum methanogenic capacity of the reactor sludge as a start-up guideline; In reality, still a 25% overload took place.
Problems arose in this period with the determination of process performance: Because of wash-out, COD-samples contained much cow-dung, making the measurements useless.

Gasproduction still could not be measured.

The pH stayed between allowable limits (6.5-7.0 with some falls to 6.3) wich indicates some process stability.

Because of the heavy dung wash-out, and the doubts about process stability, it was decided to load flocculated sludge (see fig. 33 and 34, 3rd load), using aluminium sulphate as a coagulant.
In this way, settleability of the sludge was improved, and the bacterial mass was avoided to wash out of the reactor.
By this load, VSS contents increased from 105.5 to 143 kgVSS, and the methanogenic capacity from 2.7 to 3.5 $kgCH_4$-COD/d.
A reactor profile, 1 day after this sludge load, is shown in fig. 36.

date: day 16				date: day 42			
level (m)	TSS (g/l)	VSS (g/l)	VSS/TSS (%)	level (m)	TSS (g/l)	VSS (g/l)	VSS/TSS (%)
0	147	59	34	0	148	54	34
0.2	134	55	41	.2	139	55	37
0.4	124	53	34	.4	112	45	47
0.6	83	37	45	.6	1.5	nd	nd
0.8	2	nd	nd	.8	nd	nd	nd

fig. 36: Sludge profiles over the reactor.

day	date	sludge amount (kg VSS)	mean meth. activity ($g\ CH_4-COD.kgVSS^{-1}.d^{-1}$)	meth. capacity ($kg\ CH_4$-COD/d)
1	28.1	106	25.4	2.7
15	11.2	105	53.3	5.6
16*	12.2*	143	45	6.4
42	10.3	115	59	6.7

* 3rd sludge load

Fig. 37: sludge development during 2nd reactor start-up

Methanogenic activity of an average sludge sample was 45 gCH_4-COD/kgVSS.d, signifying that a total methanogenic capacity of the process of 6.4 kg CH_4-COD/d was found (see fig. 37). The difference with the calculated value (=3.5 kg CH_4-COD/d) should be attributed to an increased sludge activity, due to a good sludge development: The activity of the sludge, present in the reactor, doubled in 15 days (2.7-5.6 $kgCH_4$-COD/d) which indicates a net average sludge growth of the methanogenic phase of 0.046/d.

Results of the ultimate sludge profile at 11.3.'86, day 42 of the second reactor start-up (fig.36,37) indicate that the total sludge amount declined from 143 to 115 kg VSS, while the methanogenic activity of an average sludge sample was determined at 59 g CH_4-COD/kgVSS.d. This results in a total methanogenic capacity of the process of 6.7 $kgCH_4$-COD/d.

The average loading rate in this ultimate week was 5.0 kgCOD/d.

The gas production, registered during this week, was 2.4 m^3/d (compensated for losses), or (with an assumed 70% methane contents of the gas) 4.4 kg CH_4-COD/d. This implies 88% conversion of substrate to methane, which is a very high value.
This can be explained with the poor precision of the measurements.
Process pH during this week was maintained between 6.8 and 7.0, without extra NaOH addition.

3.6 Discussion

process performance

It appeared that the process performance was very closely related to the applied loading rate: Overloading immediately led to instability, shown by a fall of the pH (see the 1st start-up). This can be explained with the characteristics of the wastewater: The presence of acidifying enzymes and micro-organisms in the wastewater causes the acidifying phase of the digestion process to be stronger developed than the methanogenic phase. Overloading (i.e. loading so much waste that the methanogenic phase cannot transform the VFA produced by the acidifying population) will lead to accumulation of VFA and, consequently, inhibition of the methanogenic phase.
For that reason, literature guidelines as given by de Zeeuw could not be realized, since he used digested sewage sludge as inoculum, which has a methanogenic activity ± 5-10* higher than cow dung.

An indication of the process stability was obtained from the determination of the pH profile over the reactor. In this way, overloading easily could be detected, and the necessary measures could be taken. In this way the lack of data on process performance could be overcome.
During the experiments, several circumstances caused that very little data on the process performance could be obtained:

* Until day 42 of the 2nd reactor start-up, no gas flowmeter was available to measure the gas-production;
* No CO_2-meter was available;
* From the 2nd reactor start-up on, wash out of cow-dung caused the COD-efficiency measurements to become useless.

Inhibition of the methanogenic phase, caused by the presence of tannins (43) has not been registered yet. An explanation can be found in the following:

- low tannin concentrations in the influent: Since medium-strength wastewaters were applied (up to 6 $kgCOD/m^3$) not many problems arose. The application of the same UASB process to pulp-juices, which are up to 10* more concentrated, will give more reasons to fear inhibiting effects;
- flocculation of the tannins with protein ,that sedimented to the bottom of the storage tank. This was registered at tests at the Agricultural University of Wageningen;

sludge development

From the 2nd start-up on, the process showed all the characteristics of a "normal" UASB start-up, which can be described as follows:

- During the first stage the lightest, more or less colloidal fraction of the seeding sludge was washed out of the reactor: During day 3 and 4, a wash-out of black colloidal particles was registered, probably originating from the septic-tank

seeding sludge of the first reactor start-up;
Large amounts of dispersed cow-dung left the reactor for more than two weeks.

- During the second stage, sludge wash-out should continue, due to sludge bed erosion. This wash-out should resulted in a decreased average concentration of the retained sludge (see fig. 37), but increasing specific sludge activity could compensate for this wash-out.

- During stage 3, a further increase in the gas-production rate may cause the sludge bed to be pushed out of the reactor (expansion wash-out). Floating sludge actually was observed, but this probably was caused by the poor construction of the GSS-device (see 3.4.1).

Later in the start-up of the reactor, sludge growth will occur more and more on the heavier sludge particles in the sludge bed, which results in an increasing amount of sludge in the reactor enabling further increase in the loading rate.
It is clear that the experiments performed with the 9 m^3-reactor had to be stopped while the process was still starting up: Using poorly active seeding sludge the process start-up takes much time.
For that reason, it is strongly recommended to perform reactor start-up again during the next coffee harvest, from the first moment the coffee is processed: The whole season should be utilized.
It is possible that too much sludge was washed out of the reactor; Between day 16 and day 42, 28 kg VSS (net, or 20% of the reactor contents) was lost. At least part of this wash-out is due to the poor functioning of the settling device (see also 3.4.2).

<u>applicability on farm level in Nicaragua</u>
The applicability or feasibility of the UASB process using this wastewater should, in the present state of the investigations, strongly be doubted, and application should be dissuaded, for several reasons:
1. Lack of knowledge on every level of process planning, reactor construction and operation in the local and national situation. The UASB is a new and unknown technology in the local context, and much efforts would have to be spent to the development of local expertise;
2. Lack of sufficiently educated staff, able to be trained as an operator or sanitary engineer;
3. Lack of materials, needed to build a reactor (steel, gas flowmeters), to use the produced biogas (kitchens, motors) or to run the process (during all experiments, the influent was neutralized with a 50% sodium hydroxide solution; this implies the need of some basic chemical knowledge from the operator)
4. Lack of awareness at farm-level of the seriousness of the problems caused by the wastes. People don't fully realize the consequences of the river contamination, and sometimes are hardly willing or able to put more efforts to avoid the contamination.

3.7 Conclusions

It appeared that a regular UASB-start-up can be expected, as was described by de Zeeuw (19). A constraint is a good and accurate organic load, that should not exceed, nor be much less than the methanogenic capacity of the reactor.

Because of the composition of the waste, high applyable loading rates can be expected: The waste is easily degraded to lower volatile fatty acids, and a sludge development like in the treatment of sugar beet waste can be expected. This implies the formation of granular sludge, and eventual loading rates of 1-2 kg COD/kgVSS.d (19) easily should be achieved.
More optimistic values as given by de Zeeuw (sludge activities between 5-15 kgCOD/kgVSS.d) should, in my opinion, be doubted given the local situation: The poor quality of the seeding sludge, in combination with the limited and seasonal use of the reactor, are less favourable circumstances that cause that the prediction on the process performance should be a little less optimistic. An assumed applyable load of 7.5-15 $kgCOD/m^3_{reactor}$ at a sludge concentration of 7.5 kg VSS/m^3, seems a reasonable target. This would implicate a needed reactor volume of 10 m^3 per tonne coffee produced per day.

Regarding the objectives of the experiments (3.4.1) it should be remarked that the main objective, determination of the main process parameters, has not been achieved.

The applicability of the process at farm level is also treated in the former paragraph. In the follow-up of the experiments, socio-technical, socio-economical and organizational conditions will seriously have to be considered. As it seems at the moment, these factors probably will have a greater impact on the application of the UASB-process than technical factors. In many implementations of technologies in the different circumstances of developing countries, cultural and management aspects appear to be at least as important and limiting as the technical qualities of an innovation.
Education and training programs on the technical, managerial and economical aspects of the technology as well as studies of the cultural limitations of its applications, should be included in future activities.

Technical recommendations for next seasons experiments are the following:

* A complete UASB start-up under laboratory conditions should be reached, to determine the maximum achievable performances of the system;
  In these experiments, use should be made of the sludge produced this year;

* Under the condition of revision of the GSS device the experiments with the 9 m^3 reactor can be continued, in which experiments much attention should be paid to:
  - sludge development
  - hydraulic characterization of the reactor;
  - effects of sludge storage on its activity at various temperatures;
  - the application of un-neutralized influent at a full-scale reactor, in combination with the hydraulic characteristics of the reactor;
  - composition and use of the gas;
  - transition of the technology to local staff, including government tecnicians and farm-workers.
* In the nearer future, these activities should lead to a full scale pilot reactor, that should treat all wastewaters of a minor coffee mill (± 500-1000 qq oro or up to 50 tonnes of green coffee per year).

Chapter 4: Anaerobic waste stabilization ponds

4.1 Introduction

Stabilization of wastewaters in anaerobic or facultative lagoons is the only treatment technology so far applied in Nicaragua. The technology is mainly used to treat the domestic wastewaters of a number of medium-big cities in Nicaragua, such as Masaya, Granada, León, Ocotal and Rivas. They are under the responsability of INAA, the water institution, and are designed according to the internationally accepted design methods of E.F.Gloyna and D.D.Mara (50,24), and a modification of these models by the Central American Center for Sanitary Engineering (CEPIS). Some of these lagoons function satisfactorily, others are overloaded, underloaded or lack maintenance (51).
At this moment, 2 lagoon systems are being constructed, i.e. a system of two facultative ponds in series in Estelí, and a major extension of the Masaya lagoon system.
In Nicaragua, little or no experience exists in the treatment of industrial wastewaters.

Around the city of Matagalpa, 85% of the coffee wastewaters are discharged via ponds, most of which are largely anaerobic. In these lagoons, no pond-design whatsoever was applied, which resulted in poorly functioning, stinking pools that hardly deserve the name "oxydation lagoon". The introduction of these lagoons hardly has relieved the situation of the poor water quality of Matagalpa in the form of reduction of the total contamination. In the best case they did not further increase the bad environmental effects of the coffee waste discharges through their function as a breeding place for numerous insects.

In my investigations some time is spent at a needed study of the lagoon systems. However, because of the importance of the subject in the local situation, and the lack of knowledge about the technology in the responsable institutions, a global evaluation of present lagoons was made, resulting in a number of critics on design, operation and maintenance of the systems in the local situation (4.3).
So far, very little is written on the design and operation of anaerobic lagoons systems. A literature review on the subject shows, that authors restricted themselves to the presentation of some empirical values, that lack theoretical background (4.2).
In 4.4 a model is developed to identify minimal requirements to be put to anaerobic lagoons treating coffee wastewaters, whereas in 4.5 the results of the simulations of 4.4 are compared to the actual situation, and conclusions are drawn.

4.2 Theoretical aspects

4.2.1: Design of anaerobic lagoons

The underlying processes in this purification technology are largely the same as in anaerobic reactor techniques: An anaerobic fermentation takes place in which the waste is hydraulized, acidified, transformed to acetate and, ultimately, reduced to methane and carbon dioxide in a methanogenic step that performs COD-removal (see 3.2.1).
Also the influence of the environmental factors on the process (temperature, pH, nutrient composition, toxic substances) are the same as in the anaerobic reactor technique.
The major difference between the two processes, however, is the design of the reactor: In anaerobic reactor techniques the sludge retention time is increased through biomass attachment or the introduction of a gas-solid seperator. Consequences of this extended sludge retention are:

* Hydraulic retention time can be diminished ($HRT_{reactor} \cong 8-24$ h; $HRT_{lagoon} = 3-10$ days);
* Higher organic loading rates can be applied;
* Reactor capacity can be decreased ($L_{reactor} \cong$ 10-25 kgCOD/m^3.d); $L_{lagoon} \cong 0.4-1$ kgCOD/m^3.d).

In literature, few guidelines to design anaerobic lagoons can be found. As most of the publications discuss the treatment of domestic wastewaters in facultative systems, anaerobic lagoons are considered as "simple pre-treatment techniques reducing the necessary area of a facultative lagoon to a large extent" (24). They will function as settling tanks, in which the sedimentated matter will be accumulated and wwill be digested anaerobically at the bottom sludge layer.

Anaerobic lagoon designs are based on volumetric loads (kgBOD-COD/m^3.d). In practice, the values of these loading rates for domestic wastewaters are around 0.1 to 0.4 kg BOD/m^3.d, between 12 and 27 °C, in which a linear relationship is supposed (25). Mara (24) reports a maximum applicable load of 0.4 kg BOD/m^3.d, to avoid odour problems. However, safety margins should be accounted for.
BOD-reduction of anaerobic lagoons are hard to predict. Mara (24) poses it depending on the hydraulic retention time (see fig. 38), while Gloyna gives the next empirical relation (50):

$$L_i/L_e = 1/[\, k_N * (L_i/L_e)^n * R + 1],$$

with:

- L_i = influent BOD-concentration
- L_e = effluent BOD-concentration
- R = retention time (d)
- k_N = design coefficient (≅ 6)
- n = exponent (for Zambia: n = 4.8)

R (d)	BOD-red. (%)
1	50
2.5	60
5	70

fig. 38: Efficiency of anaerobic lagoons, treating domestic wastewaters (24)

The Gloyna method leads to somewhat more conservative estimations. In high strength wastewaters, such as coffee wastewaters, the applicability of these relations should be doubted: They do not offer a sufficient accurate design method, and do not consider important factors, such as waste- and sludge composition. A different approach, describes the processes that actually occur in the lagoons, is needed to give a more reliable prediction of anaerobic lagoon functioning (see also 4.4), especially for the treatment of industrial wastewaters. Such models do exist for facultative lagoons (52), but in general remain restricted to the aerobic part of the process.

4.2.2: Mixing Aspects

Uhlmann (53) reports the hydrodynamic properties of sewage ponds as one of the major causes of scaling-up problems in the lagoon process. Tracer tests in many cases have shown high peaks of exit concentration of the tracer at times not exceeding 0.1 or even 0.05 of the theoretical retention time.
The cause of this phenomenon may as well be lack of horizontal, as vertical mixing in lagoons:

* Horizontal mixing:
  Shindala (54) reports on the influence of the shape of sewage lagoons on mixing and permittable loads of stabilization ponds. Especially in large area lagoons, the distribution of influent over the lagoon is of influence on the lagoon performance. It is important to prevent short-circuiting and dead space, as unwished causes of an uneven residence time distribution. It appears, that rectangular facilities (length to width ratio 1:1 to 2.5:1) enhance better distribution than circular or irreguar shaped lagoons.
  Polprasert and Bhattarai report the results of their dispersion model for waste stabilization ponds, that offers a simple structure that relates the value of the dispersion number in lagoons to the retention time, kinematic viscosity and the pond geometric shape, i.e, length, width and depth (55).
* Vertical mixing:
  As a consequence of low permissable loading rates, the gas production rate often is too low to perform sufficient vertical mixing as is the case in (for example) UASB-technology. Still vertical mixing is important to facilitate the necessary mass-transfer processes between biomass and wastewater.
  Stratification is a process that often prevents vertical mixing in lagoons: Differences in temperature between the (warmer) surface layer and the deeper water layers cause a density gradient over the lagoon, which is intensified by the accumulation of dissolved reaction products in those deeper layers. A consequence of stratification is, that water flow to a large extent takes place in the surface layers of the lagoon (surface flow). This type of flow behavior may be interpreted as a combination of bypassing (short-circuiting) and dead space (56).

In many situations, stratification is a phenomenon that is limited to daylight hours. After nightfall, the air can cool as such that the surface becomes denser than the deeper layers, resulting in nocturnal inversion (57). However, this is not always the case in warmer climates; Sometimes the nights are still too warm to permit the necessary cooling of the surface and inversion does not occur (58).
Wind is the means by which stratification can be overcome, as is acts against stratification by surface cooling and by the frictional effect creating turbulence. Hence, wind action should be promoted in lagoon processing.
In cases of long residence times and regular nocturnal inversion or strong wind effects, flow pattern may approach complete mixing, and effects of stratification might be neglectable.

4.3 Evaluation of the existing lagoons

In this paragraph the existing oxydation lagoons will be described with regard to their design, operation and maintenance, and data on their performance will be discussed.

4.3.1 Design and site-selection

In fig. 39 a description is given of all encountered lagoons regard to their dimensions and location.

system	production 1985-'86 (tonnes green coffee)	number of lagoons in series	sizes (lxwxh)	Volume (m^3)	min. ret. time* (d)	wind acces
1. La Hamonia	137	2	Ø=21m;h=1.3	433	4	+
			60x30x1.5m	2700	26	±
				3133	30	
2. San Luis	90					
a.		1	Ø=15m;h=1.3	220	3	-
b.		1	54x26x1.5m	2100	30	+
				2320	33	
3. La Gloria	70	3	Ø=16m;h=1.5	300	6	-
			Ø=32m;h=1.0	800	15	-
			Ø=40m;h=2.5	3125	58	-
				4225	78	
4. La Ponderosa	9	1	Ø=11m;h=1.0	100	14	±
5. La Cuesta	60					
a.		1	Ø=16m;h=0.5	100	2	+
b.		3	Ø=24m;h=1.5	675	15	-
				775	17	
6. Los Alpes	160					
a[1].		1	Ø=27m;h=1.3	700	20	+
b[2].		3	17x27x0.4m	184	2	+
			24x16x1.8	670	8	+
			15x10x0.5	75	1	-
				1630	13	
7. La Chiripa	18	1	10x5x0.7m	38	3	-
8. San Pablo	5	1	Ø=7.5m;h=1.0	45	12	-
9. Cueva del Tigre	14	1	Ø=24m;h=1.3	575	53	±
10. Quinta Praga	10	1	Ø=11m;h=2m	200	26	±

* Min. retention time = retention time in harvest peak, based on data of fig. 12

1) treating pulpwater only

2) treating fermentation water only

fig. 39: Coffee farms and their stabilization lagoons

General observations that were made with respect to design of the lagoons are:

1. The lagoons lack any design whatsoever.
   Although the national institution of Environmental Protection (IRENA) recommended a detailed design for oxydation ponds to treat the coffee wastewaters (59), in practice these recommendations were ignored. Lagoons were situated in the locations where the natural situation offered an opportunity to make a construction that could contain a consideable amount of (waste-)water.
   In practice, the lagoons are "holes in the field" without any designed form or preconsidered depth (depth in general does not exceed 1.5m, which is very little for an anaerobic lagoon).
2. As a consequence some lagoons were situated in places where wind had no access to the water surface. In this way, vertical mixing may have been avoided and stratification might have occurred. In treatment of coffee wastewaters this phenomenos may lead to a sort of "phase separation" in the anaerobic treatment process: In the liquid bulk fermentation will take place, due to the presence of hydrolizing exo-enzymes and fermenting bacteria. pH will drop in this lagoon zone. At moments of nocturnal turnover, the methanogenic bottom sludge will be contacted with the acid bulk, with inhibition as a consequence. From acidification experiments, performed in laboratory, can be concluded that acidification of the upper 10%-layers of the lagoon during 18 hours can lead to a pH-drop of the total lagoon to pH = 5.6-6.0 at nocturnal inversion, causing severe inhibiting shocks to the methanogenic population.
3. In not one of the lagoons, proper in-and outlet structures are constructed: In general the water is led into the surface of the lagoon via an open canal, and on the other side an overflow functions as an outlet structure.
   In many cases considerable short-circuiting was observed (fresh coffee wastewater (brown) has a different color than acidified (green); In this way, a brownish line in the green background could be observed from in- to outlet).
   Especially in combination with the stratification phenomena the effect of poor horizontal mixing will lead to a very poor use of the available lagoon volumes.
4. In some cases the lagoon was located at a spot of inappropiate pedological structure: High infiltration-rates were observed, in some cases up to the hydraulic load ("La Gloria"), so that the lagoon never filled up.

4.3.2 Process control

For control of the micro-biological processes that occur in oxydation ponds, the process perfromances and the possible risks of re-use of pond effluent regular process monitoring is unavoidable. This monitoring should exist of:

* Control of the hydraulic and organic loads, to prevent overloading of the lagoon;
* pH-control;

* Control of the concentrations of the effluent quality (bacteria, BOD-COD), to prevent re-use of unsuitable water for irrigation of consumption ends.

Because of the absence of knowledge of the process no such monitoring took place. It should be remarked, however, that also in the (better designed) facultative lagoons of INAA, that treat domestic wastewaters, no such regular monitoring programs exist. In Nicaragua it is no custom to check these wastewater treatment processes, not even in situations where the needed knowledge does exist.

Reasons for this situation could be:

a. The lack of laboratories and equipment for the realization of such programs;
b. The lack of educated personnel;
c. The lack of material means to transform the results of such monitoring to consequential action, in the form of extension of infrastructure or more expensive processing, or to charge overloaded government institutions with more activities;
d. The lack of priority that wastewater treatment has for some decision makers.

4.3.3 Maintenance

With maintenance, the case was rather the same as with design and process-control: In most oxydation lagoons, no maintenance was applied, with as a consequence:

- much vegetation at the lagoon-border, giving rise to insect breeding problems;
- declining capacity of the lagoons, due to the sedimentation of sludge in the lagoons. In most ponds, depth was between 1-2 meters, which is rather poor for anaerobic ponds.

As causes for the poor maintenance should be mentioned:

a. Ignorance of the problems brought about by lack of maintenance;
b. Lack of manpower to perform maintenance activities;
c. Neglect of the necessity, especially in those cases where insect breeding and/or bad smells did not offend directly at the farm, i.e. where the lagoon was situated far from the housings of owners or labourers of the farms.

Organisations like IRENA, INAA and MIDINRA did emphasize the importance of maintenance in their (mostly internal) reports , but in many cases those reports were not received by the direct responsibles of the coffee farms.

4.3.4 Process performance: Results and discussion

During the coffee harvest the UPE "Los Alpes" uses two lagoon systems for the treatment of its wastewater (see fig. 39). The one consists of one single lagoon of 700 m^3 of volume, in which mainly pulping waters are treated. This one is in a reasonable condition. The second system consists of a series of 2 grass filters and 3 lagoons, which are in a poor condition (see fig. 40).

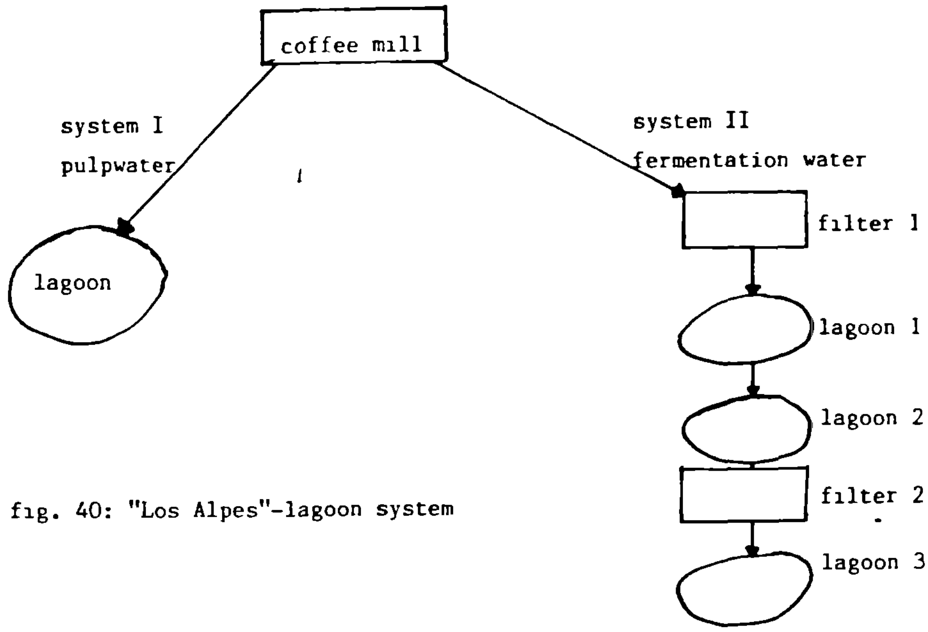


fig. 40: "Los Alpes"-lagoon system

In fig. 41 the results are shown for system I, in fig. 42 for system II.

date	load (kgCOD/m³.d)	pH	C_{in} (kgCOD/m³)	C_{out} (kgCOD/m³)	eff_{COD} (%)
17.12.'85	0.6	5.6	4.2	3.4	19
24.01.'86	0.4	5.5	6.5	4.7	28
25.02.'86	0.3	6.0	5.2	1.9	64

fig. 41: Performance of Los Alpes' system I, R_{min}=20days, V=700m³

element	load (kgCOD/m³.d)	pH	C_{in} (kgCOD/m³)	C_{out} (kgCOD/m³)	eff_{COD} (%)
date: 24.1.'86					
filter 1		5.8		2.4	
pond 1	1.5	nd	2.4	1.7	29
pond 2	0.26	nd	1.7	1.6	6
filter 2			1.6	1.5	
pond 3	2.2	nd	1.5	1.5	0
date: 25.2.'86					
filter 1		6.7		2.5	
pond 1	0.60	6.7	2.5	0.9	64
pond 2	0.061	7.5	0.9	0.6	33
filter 2		7.5	0.6	0.6	0
pond 3	0.36	7.9	0.6	0.7	0

fig. 42: Performance of Los Alpes'system II, R_{min}=11days, V=930m³

These results indicate, that:

* Process efficiency is rather poor, although the load of the system was not very high (≤ 0.6 kg COD/m^3.d).
  A possible explanation is that, due to the favorable conditions for the acidifying population in the wastewater and the sludge, considerable overloading of the methanogenic fase took place, with the acidification of the process as a result;
* It is clear that literature values of maximal permissable loading rates (in these circumstances: ±0.6 kg COD/m^{-3}.d) can not be applied to anaerobic lagoons just like that; More factors than only temperature seem to play a role in the design of the lagoons. At least the maximum applicable sludge load, sludge contents and sludge development play an important role;
* During the coffee season, some sludge development has taken place. In february, the total methanogenic capacity of the sludge present in system I was determined at approximately 100-120 kg CH_4-COD/d (with a pH of the sludge of 6.8), while ±210 kg COD/d were being loaded. This indicates, that it still was overloaded (by 35%), although since november, when the system was taken into operation, sludge development had taken place.
  As a result of this sludge development, process pH rose, and better COD-efficiencies were reached.
* Process start-up took too much time. Even at the end of the season, sludge had insufficiently developed to treat all wastewater.

Experiments that tested the performance of other lagoons systems, such as listed in fig. 39, were done irregularly. Results indicated, however, similar ("La Hamonia") or poorer results ("La Cuesta") than the "Los Alpes"-system. It appeared that poor treatment restults of the letter were not unique, and that similar problems of small sludge quantities, with little methanogenic activity and structural organic overload took place.

Although the results are based on very little data, it is my personal impression that more data would not have changed the major conclusions of the investigation.

In the next paragraph the design of anaerobic lagoons will be (re-)considered: A model is developed to predict sludge development and process stability in the system and to identify (minimal) process parameters.
As a result of the evaluation of existing ponds, this model will have to consider the following aspects:

1. Pond dimensions:
2. Process stability: Sludge should be maintained in the lagoon, and process pH should be kept within acceptable limits.
3. Start-up procedure:
4. Influence of seasonal use: The consequences of the seasonal use for treatment of coffee wastewaters should be determined.

From these aspects a statement must be done on the feasibility of anaerobic ponds as a treatment system for coffee wastewaters.

4.4 Design of anaerobic lagoons II: Reconsideration

4.4.1 Qualitative description

4.4.1.1 Mixing aspects

In high strength wastewaters in which the main part of the contamination is in a dissolved form (like coffee wastewaters) relations as for domestic wastewaters (4.2) hardly can be applied: Now sedimentation of suspended matter hardly is of substantial importance, and processes that remove dissolved matter should be promoted. The major difference with fermentation of suspended matter is that the substrate is dispersed in the liquid bulk over the sludge layer: Mass transfer from the bulk to the sludge layer may become a limiting factor in substrate removal.
This mass transport takes place through:

1. Diffusion of organic molecules to the surface of sludge particles and/or dispersed bacteria;
2. Mixing of sludge and bulk, through fluid flow, gasproduction and/or mechanical mixing.

Diffusion processes alone do not offer sufficient transport of substrate to biomass, when biomass is present in a concentrated form. For that reason, mixing of sludge and bulk forms a principal aspect of biological treatment processes in which the breakdown of dissolved matter is important.

In anaerobic reactor techniques, fluid flow in combination with gasproduction form the major motor of mixing. In anaerobic lagoons, however,

* fluid flow is small (hydraulic loading rates are about 10 times smaller than in reactor techniques);
* fluid flow, in general, does not lead through a sludge layer, as it does in most reactor and biological filter techniques;
* gas production per unit of volume (or area) is much smaller than in reactor technique, because of the lower organic load applied to the system.

Optimal use can be made of these processes, when deep lagoons are applied with, as a consequence, a smaller surface.
They will be favourable for vertical mixing since, in case of the same gas production, more turbulence will be caused by the bubbles and the vertical fluid velocity is increased.

In the anaerobic contact processes, as well as the (aerobic) active sludge process, mechanical mixing perform the needed contact between liquid and sludge. Also in dung digestors, mechanical mixing is introduced to homogenize reactor contents (60,61). However, mixing the contents of an anaerobic lagoon does not appear a very attractive solution: Lagoons have a big volume, which causes that mixing will cost substantial investment while is washed out of the system. This would act against the objective of a low degree of technification that should be put in farm-level application in developing countries.

4.4.1.2 Sludge development

Sludge development depends on a number of factors, such as:
1. bacterial population and growth;
2. biomass development (the development of flocs, pellets or attached biomass films);
3. flow characteristics, that may cause bacteria to wash out of the system.

ad 1: bacterial population and growth
The nature of bacterial population and its growth characteristics again depend on a number of circumstances, such as:
a. Process conditions (temperature, pH, toxic or inhibiting substances);
b. Inoculum characteristics (different methanogenic species have different growth characteristics, and the dominant species is, to a certain extent, determined by the inoculum).

ad 2: biomass development
Biomass development also depends on various process conditions, among which the most important are (62):
a. Substrate concentration: With high substrate concentrations more densely packed sludge is likely to develop;
b. Flow characteristics: In a turbulent system, attached and flocculated biomass can persist, whereas cells in suspension are lost with the effluent; Shear forces from turbulent flow cause surface cells of bacerial flocs, films or pellets to detach;
c. Substrate characteristics: It appears that polysaccharides are needed for surface attachment; Also in pellet and floc-formation the availability of certain wastewater compounds seems of essential importance, such as organic polymers, polyelectrolytes, a.o;
d. The availability of inert materials for film-reactors and filters, such as filter material, sand or other inert particles, for biomass attachment.

ad 3: flow characteristics
Flow characteristics are of importance for:
* biomass development
* wash out of dispersed bacterial cells
* mixing phenomena, thus, the mass transfer of substrate to the surface of sludge particles.

They are influenced by
* devision of influent
* hydraulic loading rates
* gas production
* stratification phenomena, that may prevent vertical mixing due to a density gradient over the lagoon.

It is clear that detailed incorporation of all those factors into a model goes beyond the scope of this report: In many cases, a precise description of the occurring phenomena is not even possible.

This does not mean, however, that they are not important: Especially in the case of anaerobic lagoons, where low loading rates cause low gasproductions and poor flow conditions it will not be enough to consider bacterial growth only.

Still, to give an indication of minimum requirements that have to be put on anaerobic lagoons, some assumptions will be done to come to a -preliminate and incomplete- model for a better description of lagoon development for the treatment of medium strong wastewaters.

4.4.2 The design model

4.4.2.1 Introduction

In the former paragraph it was concluded that incorporation of as well bacterial growth as sludge development, mixing aspects and flow phenomena in one model goes beyond the scope of this report. An indication of **minimum** requirements for anaerobic lagoons, however, can be obtained if the bacterial growth aspects of anaerobic processes are considered, and simplifying assumptions on the other aspects are made.

To describe anaerobic digestion knowledge is required of reaction kinetics under different conditions.
Since in treatment of easily biodegradable substrates the methanogenic phase forms the rate limiting step, only this final step in the digestion process will be considered.

In general, microbial growth can be described by:

$$(dX/dt)_{growth} = u \cdot X \tag{1}$$

with:
- X = biomass concentration (kg BM/m^3)
- u = growth factor (1/d)

furthermore, a constant yield on the substrate is assumed, resulting in:

$$dX = -Y \cdot dS, \text{ or} \tag{2a}$$

$$dS/dt = -1/Y * dX/dt \tag{2b}$$

with:
- S = substrate concentration (kg/m^3)
- Y = yield factor (kg BM/kg substrate)

Many expressions for the growth factor have been proposed (66), of which the most famous is the relation given by Monod (67), giving an expression for bacterial growth and substrate limitation:

$$u = u_{max} * S/(K_s + S) - k_d \tag{3}$$

with:
- u_{max} = maximum growth rate (d^{-1})
- K_s = value of S for which $u = 0.5 * u_{max}$
- k_d = decay coefficient (d^{-1})

For the methanogenic population volatile fatty acids and higher fatty acids are potential inhibitors (68): At high substrate concentrations the methanogenic process is inhibited by the accumulation of undissociated acids (of which propionic acid is more toxic than acetate) and hydrogen (that is an intermediate in the fermentation process for 30% of the formed methane).

The precise mechanism still is subject to discussion (27,28,29,69).
At the moment it is the dominating opinion that accumulation of intermediates (H_2, propionate) leads to thermodynamically unfavourable conditions for other VFA-conversion reactions (26).

Andrews proposed an inhibition variant on the Monod kinetics to describe this phenomenon for the methanogenic process step quantitatively (70):

$$u = u_{max} * S/(K_s + S + S^2/K_i) - k_d \qquad (4)$$

where the Monod-relation has been modified by introduction of the inhibition constant K_i. This equation is known as the "Haldane-equation".

The Haldane equation can be derived from the velocity equation for an enzymatic reaction that is inhibited in a non-competive way, assuming a concentration of the inhibiting component that is proportional to the substrate concentration (73).

This function is able to fit experimental data (65,71) but, according to Henze and Harremoës, this can not be regarded as conclusive because the number of constants in the equation is rather high (31).

In practice, the Haldane equation is applied to describe anaerobic processes treating medium and highly concentrated industrial wastewater (> 3 KgCOD/m^3) (63,65,71,72).

A simple and useful approximation of the methanogenic phase in the anaerobic digestion process was presented by Van den Heuvel and Zoetemeyer (63), who applied Haldane kinetics on a methane reactor with proportional cell-recycle (see fig. 44) to determine the influence of the various process parameters on the performance and stability of the methanogenic step.

In this model it is assumed that the sludge retention time in the reactor can be expressed with an external settler with efficiency (1-p), retention = 0, and complete seperation of the liquid fraction. This is a model for the simulation of internal settling devices, such as sludge seals and settlers in UASB-reactors.

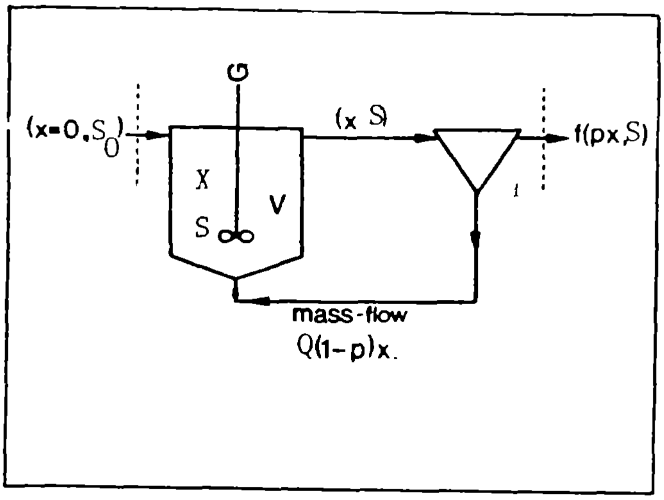


fig. 44: Model of methane reactor with proportional cell recycle

Application of Haldane kinetics on the CFSTR (Continuous Flow Stirred Reactor) with proportional cell-recycle gives the following mass balances:

Biomass:

$$V.(dX/dt) = -Q.p.X + u_{M,max}.[S/(K_s + S + S^2/K_i)]*X*V \quad (5)$$

Substrate:

$$V.(dS/dt) = Q(S_o - S) - u_{M,max}.[S/(K_s + S + S^2/K_i)]*X*V/Y_m \quad (6)$$

with: V = reactor volume (m^3)
- S = substrate-concentration ($kg.m^{-3}$)
- t = time (d)
- Q = flow (m^3/d)
- X = substrate-concentration ($kg.m^{-3}$)
- $u_{M,max}$ = max. growth rate of the methanogenic phase (1/d)
- K_s = substrate-limitation constante (kg/m^3)
- K_i = substrate inhibition constante (kg/m^3)
- Y_M = yield factor of the methanogenic phase
- p = sluice fraction = (1- sludge recycle fraction)

The same model is applied in this paragraph to obtain indications on the design and operation of anaerobic lagoons. This is justified since the model only treats on microbial kinetics. Flow phenomena and mixing are not considered.

Objective is to obtain indications on the process stability in the anaerobic lagoon under various conditions.

Furthermore, the influence of temperature on lagoon performance and process variables is estimated, as well as the sensitivity of the model to the value of some parameters in the Haldane equation. Consequences of the model for the design of lagoons for coffee wastewater treatment were also considered.

4.4.2.2 Model description, limitations and boundaries

The equations (5) and (6) were transformed into a dimensionless form, applying following definitions:

$x = X/K_m.Y_M$ $y = S_l/K_m$ $T = t.u_{M,max}$
$v = u/u_{M,max}$ $y_o = S_o/K_m$ $m = u_{M,max} * V/Q$
$k = K_m/K_i$ $(0 \le k \le 1)$

The following dimensionless equations are now derived:

$$dx/dT = -p.x/m + x.y/(1+y+ky^2) \qquad (7)$$

$$dy/dT = (y_o - y)/m - x.y/(1+y+ky^2) \qquad (8)$$

which describe the time dependent behaviour of the system.

The model implies the application of ideal mixing in the lagoon. However, it is the question whether this high mixing rate can be reached despite high hydraulic retention times (several days).

In 4.4.1 the impact of mixing phenomena on lagoon performance were already mentioned; It appeared, that mixing in anaerobic lagoons and, with it, the mass transport from the liquid-bulk to the sludge particles, will be a limiting factor.

To get an indication of their conduction, let us assume complete mixing as a compromise between the plug-flow model (that will lead to better conversion rates and more optimistic results) and reality, in which high fractions of dead-space and short-circuiting occur.

Another assumption of the model is good temperature and pH control of the reactor. Inhibition of the methanogenic process step because of a fall of pH is not accounted for, since substrate inhibition refers to inhibition of the methanogenic population for high acetate-concentrations in a neutralized form (see 4.4.2.1).

Conditions for stable lagoon operation in the local situation in Nicaragua are:
1. A stable steady state should be reached in such a way that enough sludge is maintained in the lagoon;
2. Since professional lagoon operation is unlikely to occur, no neutralization of the influent should be necessary. For that reason it is necessary that the methanogenic capacity of the lagoon (kg CH_4-COD/m^3) is sufficient to convert the formed VFA to methane.

4.4.2.3 Stability criteria

4.4.2.3.1 Process stability and sludge retention time

Under steady-state conditions, by putting d/dT=0, we obtain from equations (7) and (8):

$$x_s = (y_o - y)/p \qquad (9)$$

$$y_{1,2\,s} = [(m/p - 1) \pm ((m/p - 1)^2 - 4k)^{0.5}]/2k \qquad (10)$$

with m/p = sludge retention time (SRT)

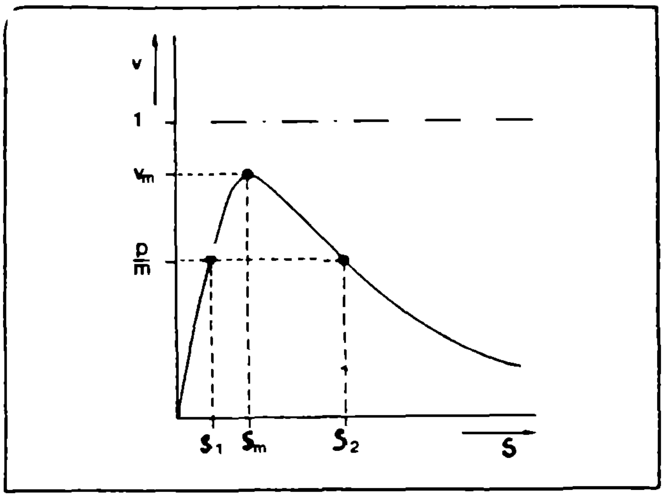


fig. 45: Solutions for
Haldane equation

The two solutions for the substrate concentration y_s are indicated in fig. 45. The difference solution of equation (10) corresponds to a high conversion state y_{s1} while the sum y_{s2} corresponds to a low conversion state; the latter was shown to be unstable (63).
It is clear that a general sludge wash-out is to be expected when the discriminant in eq. (6) <0,

or when:

$$(m/p - 1)^2 < 4k, \text{ or } m/p < 1 + 2*k^{0.5} \qquad (A)$$

and that two steady states with $y_s < y_o$ exist, when

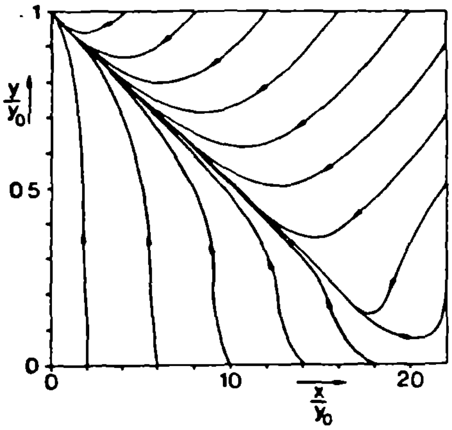
$$(m/p - 1) + [(m/p-1)^2 - 4k]^{0.5} < y_o \qquad (B), \text{ or}$$

which approximates:

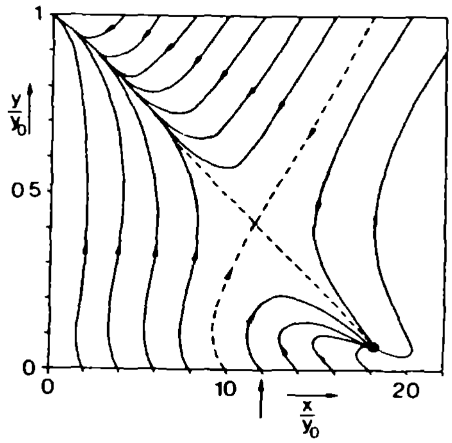
$$m/p < 1 + 2.k.y_o, \text{ for } (m/p - 1) >> k.$$

If $m/p > 1 + 2ky_o$ (C), stable steady-state operation in the end always can be expected.

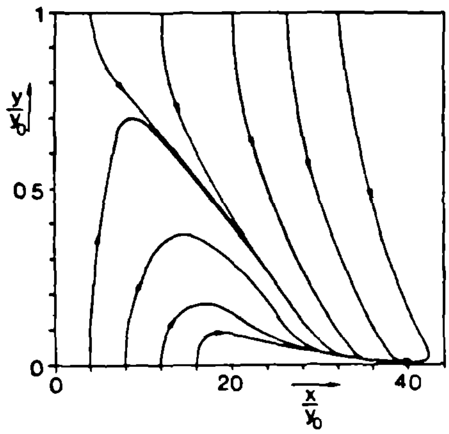
The 3 cases A,B,and C are shown in fig. 46.



High strength wastewater, wash-out state only.



High strength wastewater, multiple steady state region.



High strength wastewater, non-zero steady state only.

fig 46: Steady state solution for Haldane equations

4.4.2.3.2 pH-stability condition

If the methanogenic population of the lagoon is able to transform all produced volatile fatty acids to methane, the process can be called pH-stable: In that case, no accumulation of VFA will take place, and process pH will remain within acceptable limits.
In that case:

$$V_M * X_M = S/ t = Y_A * S_0/R \qquad (11), \text{ with}$$

V_M = specific methanogenic substrate utilization rate (d^{-1}) (kg VFA-COD/kgBM.d);
X_M = specific methanogenic sludge concentration (kg BM/m^3)
Y_A = fraction of substrate that is conversed to VFA
= $(1 - y_a)$, with y_a = yield factor for the acidifying phase.
R = hydraulic retention time (d)

Since the specific methanogenic sludge concentration is hard to determine, the maximum specific methanogenic activity of the sludge can be used to determine this concentration:

since:

$$A_M = (1 - Y_M) * V_M \qquad (12)$$

and $V_M = u_M/Y_M$ (13), with

A_M = specific methanogenic activity ($kgCH_4$-COD/kgBM.d)
Y_M = yield factor of the methanogenic phase (kgBM/kgVFA-COD.d), so that $(1 - Y_M)$=(Kg CH_4-COD/kgVFA-COD)
u_M = growth factor (1/d), of the methanogenic phase (kgBM/kgBM.d).

can be stated that the maximum methanogenic activity of the sludge:

$$A_{M,max} = V_{M,max} * (1 - Y_M) \qquad (12A)$$
$$= [(1-Y_M)/Y_M]* u_{M,max} \qquad (13A)$$

The needed sludge concentration to transform all VFA produced to biomass and methane can be derived:

with $V_M = u_M/Y_M = [S/(K_s + S + S^2/K_i)]/Y_M$ (14)

and with (11) can be derived that

$$X_{M,s} = S_O.Y_A/R * Y_M * (K_s + S + S^2/K_i)/S \qquad (15), \text{ or}$$

$$x_{m,s} = y_O/m * (1 + y + ky^2)/y \qquad (15A)$$

$x_{m,s}$ = dimensionless sludge concentration for 100% substrate conversion.

In practice this condition hardly ever will be met, since not all VFA will be converted, because of substrate limitation. For that reason, as a pH-stability criterium should be agreed that a certain fraction of this sludge concentration $x_{m,s}$ should be present in the lagoon.

In literature it is mentioned that, during UASB reactor start-up, at least 80% of VFA should be converted to methane (19).

Since the pH-criterium is stronger than the process stability criterium (i.e. to maintain enough sludge in the reactor) the former is in some cases used as the only stability criterium to be evaluated.
Computer simulations have been executed to determine the influence of process parameters on process performance and pH-stability in anaerobic lagoons, treating coffee wastewaters. In these simulations the dimensionless Haldane-equations (7) and (8), as well as the pH-stability condition (15A) have been used.

In the simulations that are performed, $x/x_{m,s}$ (the actual sludge concentration devided by the needed sludge concentration for 100% VFA-conversion) is plotted.
It is supposed that to the stability criterium will be fulfilled if $x/x_{m,s} >= 0.8$.

The amount of needed inoculum can be determined now: If x_B is the lowest initial sludge concentration for which the stability equation is fulfilled, the needed amount of seeding sludge is:

$$X_S = x_B * K_s * Y_M,$$

with a needed initial <u>methanogenic capacity</u> C_B of:

$$\begin{aligned} C_B &= A_B * X_B \\ &= [1-Y_M]/Y_M * X_B * u_{M,max} \\ &= x_B * u_{M,max} * K_s * (1 - Y_M) \quad \text{kg } CH_4\text{-COD/m}^3\text{.d.} \qquad (16) \end{aligned}$$

4.4.2.4: Application of the model in treatment of coffee waste-water

For the seasonal use of lagoons (as is the case with coffee waste treatment) there are two problems that will have influence on treatment performance:

1. The season has a start-up period.
   If it is to treat all wastewater produced, the treatment system has to have enough capacity throughout the campaign. Because of the loading some capacity development of the system will take place, that can be used for the treatment of later produced wastewaters;
2. During the period that the system is not used, the bacteria-population will, to a certain extent, die off. This will influence next-years performance (see fig. 47).

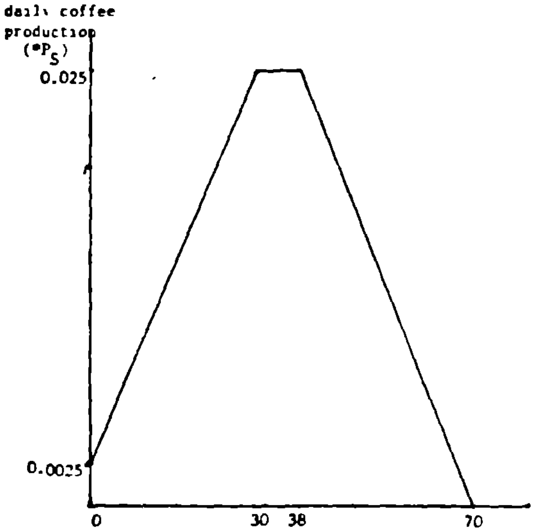


fig. 47: Assumed daily coffee production during the campaign.

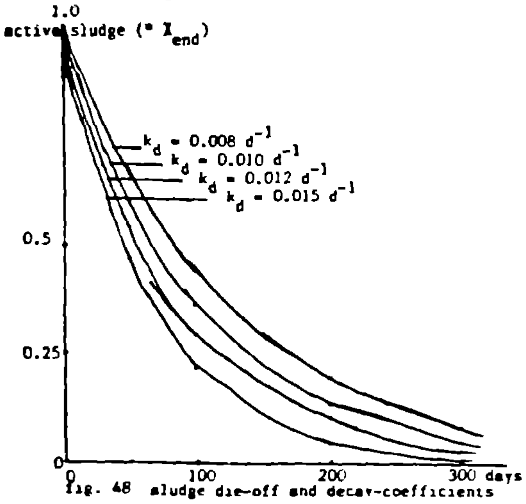


fig. 48 sludge die-off and decay-coefficients

For coffee harvest the following campaign is assumed (see fig. 48):

* During the first period the harvest is to start up from 0.25% of the total seasonal production P_s, to 0.025 P_s in 30 days;
* During the second period, or peak of the coffee harvest, 0.025 P_s is produced daily. This period is to long for 7 days.
* During the third period, coffee harvest already diminishes, reaching its minimum of 0.0025 P_s at day nr. 70.

The lagoon is assumed to be loaded with a continuous flow of wastewater with constant composition, and seasonal influence only stretches to the amount of wastewater produced, so to daily inflow and to the hydraulic retention times.
This assumption is justified since, in general, the hydraulic retention time of the lagoon exceeds the period of one day (the process repetition period) by far. No shock loadings are applied, so that no pH-shocks are to be expected. pH is assumed to remain within acceptable limits (6.7 - 7.2).

4.4.3: Process parameters and pond design: Results and discussion

4 parameters have been varied in the simulations:

1. The hydraulic retention time:
   The simulations are executed using different values for the HRT. The dimensionless parameter m (= $u_{M,max}$ * R) is varied form 1.2 to 2.4. This implies HRT's of 2-6 days, at 35 °C;
2. The amount of seeding sludge:
   This parameter is varied with constant settler efficiency and HRT.
3. The efficiency of the settler:
   In the other simulations there is no settler supposed (cell-recycle = 0), so that the sludge retention time equals the hydraulic retention time. This, to avoid over-optimistic estimations.
   Still, the influence of better settler efficiencies (SRT > HRT) is examined.
4. The temperature:
   The influence of this parameter can be estimated by corrections on the values of parameters in the Haldane equations for temperature.

Lin a.o (64) reports in a recent study on the temperature dependence of various kinetic constants (see fig. 49).

Temp. (°C)	$u_{M,max}$ (d^{-1})	K_s (gAc/l)	Y_M (g/g)	k_d (d^{-1})
20	0.166	0.419	0.031	0.015
25	0.170	0.233	0.022	0.008
30	0.201	0.214	0.026	0.012
35	0.414	0.166	0.030	0.010

fig. 49: kinetic constants at different temperatures. Source: (64)

In 4.4.3.1 to 4.4.3.3, in which the influence of the hydraulic retention time, the amount of inoculum and sludge retention are examined, simulations are executed for a temperature of 35 °C, with subsequent kinetic constants.
In 4.4.3.4, estimating the influence of temperature, simulations are executed for 23 °C (the mean temperature in Matagalpa).

4.4.3.1: The influence of the hydraulic retention time.

Supposing that in an anaerobic lagoon there are no devices to prevent sludge to wash out (p=1, or HRT = SRT), increase of HRT will lead to longer sludge retention times, and thus to more reactor stability.
This is shown in Appendix 4.1, figs a,b,c.

At 35 °C a hydraulic retention time of 3 days ($m = HRT*u_{M,max}$= 1.2) with p=1, will unavoidably lead to a fatal sludge wash-out (see fig. a), since the sludge stability criterium A of 4.4.2.3 is not fulfilled for during the coffee peak:

$$(m/p - 1) = 0.2 < 2*k^{0.5} = 0.45$$

If the HRT is increased to 3.5 days (m=1.4) the pH-stability criterium is almost fulfilled: $x/x_{M,m}$ decreases, at the peak of the coffee season, to 0.75, which can be reached throughout the season with an inoculum concentration of x_m = 2.5 (or an initial methanogenic capacity of 0.162 kg CH_4-COD.m^{-3}.d^{-1}) (fig. b), although during the coffee peak the sludge stability criterium still is not fulfilled:

$$(m/p - 1) = 0.4 < 2*k^{0.5} = 0.45$$

If the HRT is further increased to 4 days (m=1.6) the sludge- and pH-stability criteria are fulfilled for x_m=2.3 (C_B = 0.149 kg CH_4-COD.m^{-3}.d^{-1}). In this case the end methanogenic sludge concentration will be 20.4 (≙ 1.32 kg CH_4-COD.m^{-3}.d^{-1}), and treatment efficiency y/y_o>0.9 throughout the season.

Increasing the HRT further to 5 days (m=2.0), x_B will be 1.8, and treatment efficiency y/y_o>0.93.
The absolute needed amount of seeding sludge will not decline, in comparison to the former case, since total lagoon volume increases.

It can be concluded that for m=1.6 and x_B = 2.3 is fulfilled to the pH-stability criteria. At this residence time of 4 days, an acceptable treatment efficiency of more than 90% of VFA can be expected, and no problematical sludge wash-out will take place, since the sludge-stability criteria are fulfilled.
If HRT is increased further, some better treatment efficiency can be reached, without having to increase the amount of seeding sludge.

4.4.3.2: The influence of the amount of inoculum

As can be seen from Appendix 4.2, figs a and b, increasing the amount of inoculum much higher than the minimal needed initial quantity x_B will hardly result in better treatment performance. Only during the first 3-4 weeks of the season, better treatment results are reached, but during the peak of the coffee harvest the treatment efficiency will fall to the same level, independent of the inoculum amount.

A larger amount of inoculum neither will lead to more sludge at the end of the campaign: The over-loaded will be washed out and the sludge amount will grow to a steady state amount, almost independent of seeding quantities.

4.4.3.3: The influence of sludge retention.

Up to now, no extra settling device to prevent sludge to wash out from the lagoon was assumed. However, it is probable that the sludge, for its settling characteristics, does have a longer retention time than the liquid, in which case reactor stability will be improved. From Appendix 4.3, figs a to c, the effect of increasing sludge retention times can be seen. The lagoons are operated at m=0.8 (in this case: HRT = 2 days), and SRT = 1, 1.67 and 2.0 * HRT, resp.

Figures show that a steady state cannot be reached for the case that SRT = HRT (or 1-p = 0): Wash-out during the peak of the coffee season cannot be compensated for, not even in cases of high inoculum amounts.

In case that (1-p)=0.4 (or SRT = 3.33 days) stability almost can be reached, although still considerable sludge wash-out takes place at tha peak of the coffee harvest; At this peak, m/p = 0.8/0.6 = 1.33 < $(1+2k^{0.5})$, so a non-zero steady state still cannot be reached.

In case that (1-p) = 0.5 (or SRT = 4 days) stability can be reached, with x_0 = 4.3, or an initial methanogenic capacity of 0.278 kg CH_4-COD.m^{-3}.d^{-1}, reaching a final sludge amount of x_e = 40.4 , or 2.6 kg CH_4-COD.m^{-3}.d^{-1}.

It can be concluded that the introduction of "devices" to prevent sludge to wash out of the lagoon, such as proper in- and outlet devices, and scum-seperators (to prevent the wash-out of floating sludge layers) will improve operation stability to a large extent. However, it should be born in mind that such devices should not prevent optimal mixing in the lagoon!

4.4.3.4: The influence of temperature

Changing temperature has its influence on the kinetic constants of the Monod- and Haldane equation. Lin a.o (64) report on the temperature dependance of various kinetic constants of the methanogenic process step in anaerobic digestion (see fig. 50). Henze and Harremoës (31) present a more general relation for methane production rates:

$$r_{x,T1}/r_{x,T2} = \exp(c.(T1-T2)) \quad (13)$$

The temperature constant from 10-30 °C can be estimated to c=0.1 $°C^{-1}$.

Treatment of coffee wastewaters will take place at environmental temperatures. In Matagalpa, this temperature over the year lies between 20-25 °C, with a mean of 23 °C.
In Appendix 4.4, figs. a and b and in fig. 50, data from fig. 49 were used to estimate process pH-stability at various hydraulic retention times, with p=1 (SRT=HRT), at T=23°C.

m	HRT (d)	x_B	A_B*	$(y/y_o)_{max}$	x_s	A_s*
1.4	8.2	25	1.35	0.18	10.5	0.57
1.6	9.4	10	0.54	0.17	10.3	0.56
2.0	11.8	3	0.16	0.15	10.7	0.58
2.4	14.1	1.6	0.086	0.13	10.4	0.56
2.8	16.5	1.3	0.070	0.12	9.8	0.53
3.2	18.8	1.1	0.059	0.11	9.5	0.51

* (kg CH_4-COD.m^{-3}.d^{-1})

Assumptions: T = 23 °C $u_{M,max}$ = 0.17 d^{-1}

K_s = 0.326 g/l Y_M = 0.026 gBM/gVFA

fig. 50: Results of simulations for T = 23 °C

Most striking differences with processing at 35 °C, as was applied in 4.4.3.1 - 3, are:

1. During the coffee harvest, processes do not reach a steady state situation;
2. For that reason, higher dimensionless retention times m are needed to come to stable operation;
3. Higher inoculum amounts now do lead to better treatment performances;
4. The amount of sludge present at the end of the harvest season, is rather small. Because of bacterial die-off during storage, it is very likely that the process needs fresh inoculum during next years season. To prevent this, condition is that K_d<0.002, which is not very likely (see fig. 49)

Most important conclusions from these estimations are:

1. Anaerobic lagoons in this situation can be operated over a wide range of hydraulic retention times;
2. Small hydraulic retention times can be compensated for with more seeding sludge;
3. A minimal amount of seeding sludge is used when m=2.4; At larger HRT the total quantity of inoculum to be applied increases because of increasing volume of the ponds.

4.4.3.5: Sensitivity to $u_{M,max}$ and k-values

In Appendix 4.5 the sensitivity of process pH-stability to the actual values of $u_{M,max}$ and k, respectively, is shown. Since there is some discussion in literature on the values of these parameters, sensitivity analysis can provide information on the usefulness of the model.

In fig. a the process is operated with m=2.0, and x_{start} = 6.0, for various $u_{M,max}$-values.
The discrepancy between literature data on temperature-dependence of the anaerobic digestion process can be shown now: According to equation (13), at 23 °C $u_{M,max}$=0.12. From fig. a appears that for this value x_B=6.0. According to Lin, however, at this temperature a value of $u_{M,max}$=0.17 should be used, which results in a minimal initial sludge concentration of x_B=3.0!
It is clear now, that literature values cannot be applied just like that, and that these simulation results should be treated very carefully now.
Simulation results for a wide range of $u_{M,max}$-values are shown in fig. 51

$u_{M,max}$ (d^{-1})	x_B	x_e	$(y/y_o)_{max}$
0.08	9.0	10.3	0.10
0.12	6.0	10.1	0.13
0.17	3.0	10.7	0.15
0.22	1.5	10.3	0.14
0.30	1.15	10.4	0.12

fig. 51: $u_{M,max}$ and process pH-stability: Needed amount of inoculum decreases considerably with increasing $u_{M,max}$

Fig. b shows that sensitivity to the substrate inhibition constant is less dramatic: increasing the value of k with 100% hardly influences the pH-stability estimations. In case of neglecting substrate inhibition (k=0) (and thus applying Monod-kinetics) the eventual result will hardly be influenced.

K_s (d^{-1})	x_B	x_e	$x_e.K_s$ (d^{-1})	$(y/y_o)_{max}$
0.10	4.5	33.15	3.3	0.062
0.20	2.9	16.57	3.3	0.11
0.326	3.0	10.2	3.3	0.15
0.40	5.0	8.4	3.4	0.14
0.50	6.5	6.75	3.4	0.15
0.70	9.0	4.93	3.5	0.16

fig. 52: K_B-sensitivity

The influence of different values of K_s is shown in fig. 52.
The amount of needed seeding sludge appears to depend strongly on the actual value of K_s, on which value little agreement exists in literature.

4.4.4: Model implications for design of lagoons for treatment of coffee wastewaters

In this paragraph the results of the former will be used to design an anaerobic lagoon for coffee wastewater treatment at the "Los Alpes" coffee processing complex.

In fig. 39 is shown that this coffee processing unit produces about 160 metric tonnes of green coffee per year. This means, that following parameters should be assumed for the design of a wastewater treatment system (see fig. 12):

P_B = 160 mtonnes/yr
Q_{peak} = 123 m^3/day
S_o = 4.25 kg COD/m^3

Since the mean temperature in "Los Alpes" is not very high (20-25 °C), the values of fig. 50 are taken as a starting point for pond design.

Cow dung is used as inoculum, since no other material is available to a sufficient extent. Inoculum characteristics appear from fig. 34:

methanogenic activity = 0.015 kg CH_4-COD.kgVSS^{-1}.d^{-1}
volatile solids = 125 kg VSS.m^{-3}

So that the methanogenic activity of the cow dung is estimated at

$125 * 0.015 = 1.875$ kg CH_4-COD.m^{-3}.d^{-1}, or with density ≈ 1,
1.875 kg CH_4-COD.tonne^{-1}.d^{-1}

For various retention times, pond design is shown in fig. 53:

m	lagoon lay-out HRT$_{min}$ (d)	V (m^3)	A_s*	quantity of seeding sludge Quant. (tonnes)	re-start** (tonnes)
1.4	8.2	1010	1.35	727	698
1.6	9.4	1160	0.54	334	302
2.0	11.8	1450	0.16	125	83
2.4	14.1	1734	0.086	80	31
2.8	16.5	2030	0.070	76	22
3.2	18.8	2310	0.059	73	13

* (kg CH_4-COD.m^{-3}.d^{-1})
** Assumption: k_d = 0.008 . d^{-1}

fig. 53: Pond design and needed ~~inoculum~~ amounts

It appears that for m=2.4 an suitable pond lay-out is found: Almost minimal amount of needed seeding material, in combination with acceptable pond volumes.
For the "Los Alpes" case this would signify that existing pond facilities easily can be adopted to the new design: If the first pond of the second treatment system (see figs. 39 and 40) is excavated to a depth of 4 meters, sufficient pond capacity would be obtained.

Since the theoretical treatment efficiency of this system is 87% (i.e. 87% of the anaerobic biodegradable matter in the wastewater will be removed, and the waste is practically 100% anaerobic biodegradable (see par. 2.2)), treatment efficiency of an after-treatment system would only have to be ± 40%, so that a simple after-treatment method would offer enough COD-removal to meet the discharge standards as apposed in paragraph 2.4 (see page 19).

The amount of needed inoculum could cause problems: 80 metric tonnes represents the annual mean dung-production of 22 cows, or the monthly production of 263 animals, which has to be transported to the coffee mill, that is situated in the mountains around Matagalpa. Since "Los Alpes" only treats 23% of the coffee produced in the problem area, this amount would have to be multiplied with a factor 4.5 to satisfy the need of the entire problem area!
The practical problems of the collection of 360 metric tonnes of fresh cow dung will be gigantic.

Another problem will be the bacterial die-off during the period between the coffee campaigns. During these 290 days the sludge will be stored at environmental temperatures.
Even the optimistic estimation of Lin (see fig. 61) of a decay-coefficient of 0.008 d^{-1} would lead to a die-off of 90% of the formed sludge during this period.
This means, that at the start of the next coffee harvest, again 36% of the initial amount of needed inoculum must be a considerable extent;

* In cases where the use of biogas, produced in anaerobic reactor techniques is economically not area!

Imagine the logistic problems of the annual cow-dung collection and -transport campaign, when 22 6-tonnen trucks full of the (valuable) organic fertilizer have to be filled in the region!

4.5 Discussion and conclusions

At first sight anaerobic ponds offer important advantages over other aerobic and anaerobic pre-treatment methods:

* They can reduce the land area needed for (facultative) lagoon treatment to a considerable extent;
* In cases where the use of biogas, produced in anaerobic reactor techniques is economically not feasible, anaerobic ponds may offer an attractive alternative: Compared to this reactor technique, the ponds are cheap and they are simple to construct, operate and maintain. They will be able to treat wastewater problems in developing countries from agricultural and domestic origin.

From the experience in Matagalpa, and the theoretic opproach of 4.4.3 it appeared, that anaerobic ponds need good design and operation:

* To prevent sludge losses, the sludge growth must compensate for wash-out. Therefore, minimal sludge retention times are required. This minimal required sludge retention time is influenced by:
  - hydraulic phenomena: The sedimentability and the presence of devices to prevent sludge wash out determine the relation between sludge- and hydraulic retention times;
  - temperature: Since microbiological kinetics are strongly temperature dependent, operation at lower temperatures will require (much) longer hydraulic retention times.
* To prevent process-pH to fall, a microbiological equilibrium between fermenting and methanogenic bacteria must be maintained. This implies that, before loading the lagoon, a minimal amount of seeding sludge should be introduced. This conclusion is confirmed by the observations made in the evaluation of existing ponds (see 4.3).
* The collection of this inoculum will cause severe logistic problems in the region, for its gigantic amounts.
* During the coffee campaign, overloading the lagoon should be avoided.
* Depending on the endogenic decay coefficient of the methanogenic bacteria it is probable that also in next coffee seasons a certain amount of seeding sludge will be needed to re-start the process: During storage between two harvests, the methanogenic population will die-off to a considerable extent.

The model that was used, has its limitations: A number of factors were not considered, such as mixing phenomena and process inhibition through pH-shocks. A question that remains unanswered is whether fluid flow and gas production will provide enough mixing to assure the mass transport from the liquid bulk to the sludge, and to prevent unwished flow phenomena that can result in local accumulation of VFA, causing process inhibition.

Furthermore, the model is based on rather general literature data, and could not be compared to existing ponds. In general it can be stated that the model gives some minimal requirements to be put to the application of anaerobic ponds, such as minimal hydraulic retention time and minimal amount of seeding sludge.

In the local situation a hydraulic retetion time of 14-20 days (see fig. 53) will not give too many problems.
The minimal amount of seeding sludge neither, if the lagoon is operated continuously.

However, for treatment of a seasonal waste like coffee waste-water, the problem of inoculum will come back annually, and application should be considered as not feasible, unless devices are introduced into the lagoon to prevent the sludge to wash out of the system.

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Annex 1: Pectins

Pectins (or proto-pectins) are poly-galacturonics, existing of knotted chains of -1, 4D-galacturonic acid, partially esterfied with methanol.
These polymers, if saturated for more than +_10% with methanol, in the presence of high concentrations of sugars and organic acids, can form covalently bound hydro-gels, as is the case in coffee mucilage.

Protopectinase enzyms are able to transform these knotted polymeric chains to the single pectins. These pectins are dispersable in water, forming a viscous hydro-sol, in the case that more than 10% of the carboxylic groups are saturated with methanol.

De-esterfication can take place in two ways:

1. In strong alkaline conditions (pH>=8.5) de-methoxylation can take place through (chemical) hydrolysis;
2. Enzymatic de-methoxylation can be performed by action of pectases (pectin-methylesterases) which also can cause hydrolysis.

The resulting pectic acid, the polymeric form of galacturonic acid, is hardly soluble in water, unless in alkaline conditions.

Unlike the case of pectin, the carboxylic groups of pectic acids can be titrated with an alkalic compound, with dissociation constants between K_z = 2.7 - 4.

A second enzym, pectinase, is able to split the remaining pectic acids to their single D-galacturonic acid molecules:

```
          polymerisation            methanol          polym.
D-galac-================> pectic==========>pectin ========>proto
turonic <================ acids <==========        <========pectin
acids        pectinase              pectinase,      proto-
                                      OH-           pectinase
```

Bacteria and fungi, able to perform these processes, are present in coffee pulp and mucilage (1,3,4). During the fermentation process, the hydrogel is digested to pectic acids to an extent that all mucilage is dispersable in water (2).

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Annex 2: Determination of Chemical Oxygen Demand (COD)

Oxygen demand is an important parameter for the determination of the effect of organic pollutants on receiving waters. As micro-organisms in the environment consume these substances, oxygen is depleted from the water.
There are three main methods of measuring oxygen demand: Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and indirectly by Total Organic Carbon (TOC).

For reasons of simplicity in application, and the need of especialized technical equipment, in this investigation was choosen for the application of the COD to characterize organic contamination of the wastewater.

The COD-test has a specific and universal definition: The oxygen equivalent to the amount of organic mateer oxydizable by potassium dichromate in a 50% sulphuric acid solution. A silver compound often is added as a catalyst, while a mercuric compound may be added to reduce interference from the oxydation of chloride ions by the dichromate.

The end products are carbon dioxide, water and various states of the chromate ion.

After the oxydation step is completed the amount of dichromate consumed is determined either by titration or colorimetrically.

In fig. a, the amounts of reagents used in standard COD-digestion are given.

Range:	Standard Methods (1) 50-800 mg COD/l	Micro method (2) 50-1500 mg COD/l	0-150 mg/l
Sample(ml)	20	2	2
H_2SO_4	30	2.5	2.5
$K_2Cr_2O_7$ (g)	0.1226	0.0245	0.00245
$AgSO_4$ (g)	0.30	0.03	0.03
$HgSO_4$ (g)	0.40	0.03	0.03

fig. a: Quantities of reagents used in various COD-methods

In order to save scrace reagents (in Nicaragua) and to simplify the determination method, the micro-COD-digestion method, as developed by the Hach Chemical Company (2) was applied.

In this method, 90% savings of reagents is obtained (see fig. a), digesting samples in ready prepared reagent mixtures in special digestion vials. The oxidizing process is performed in a special heater block, or in a laboratory oven, at 150 ± 1°C.

Chromate concentrations may be determined by titration, or colorimetrically. The latter method is easier, and quicker to run.

The appearance of the Chromate (III)-ion (green color) is measured at 620 nm wavelength. Calibration curves of the absorbance concentration relation can be obtained with Potassium Acid Phtalate (KHP), the standard material most often used in calibrating the colorimetric measurement of COD for its availability in hig purity, its stability and its lack of moisture pick-up.
Each mg of KHP requires 1.175 mg of oxygen for complete oxydation.

Applying the micro-COD method in this investigation, two major modifications have been carried through:

1. Mercuric sulphate, usually added to reduce interference from the oxydation of chloride ions by dichromate, was not used for lack or reagent, and for environmental reasons; Performing the determination, no sediment in the reagent mixture was observed, indicating the absence or negligible concentrations of chloride ions (1);
2. The oxydation of the reagent mixture was performed in the laboratory oven, at temperatures varying between 120-140 °C, for lack of more precise equipment, avoiding over-heating of the vessels.
   Influence of these conditions to final results probably is negligible: No significant difference was found performing the digestion at 110 or 140°C. A reason for this phenomenon could be, that coffee wastewater hardly contains hard-to-digest compounds.

<u>literature</u>

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Annex 3: Determination of the specific methanogenic activity

The specific activity of anaerobic sludge, expressed as kg CH_4-COD. $kgVSS^{-1}.d^{-1}$, is an important parameter in several respects:

- It determines, together with the total amount of sludge present, the permissible organic loading rate;
- It provides information about the development of the sludge and changes in sludge activity, which may indicate inhibition, or the accumulation of non or slowly degradable organic matter originating from the wastewater.

A sludge activity test is commonly performed as a batch experiment in which a fixed amount of substrate is fed to a predetermined amount of sludge solids.
The specific sludge activity is calculated from the methane production rate or the substrate depletion rate and the amount of sludge present.
During the experiment, sludge growth should be negligible in comparison to the total amount of viable biomass present.

In these experiments a standardised batch sludge activity test has been used, in which activity is measured as the methane production rate per unit of sludge VSS, using acetate as substrate.

Most tests were performed in 0.5 l erlenmeyer-flasks, occasionly stirred (1-2 times daily), at environment temperature (due to lack of a thermostated bath).
The reactor was connected to a liquid desplacement system (serum bottle) for gas production measurement. CO_2 was removed from the gas stream by using an alkaline solution (2% NaOH) or by a alkaline tube (KOH-pellets), placed before the liquid desplacement system (see fig. a).

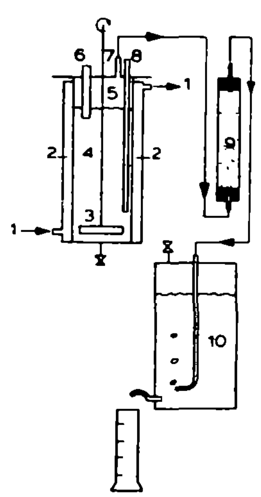

FIGURE a.
Batch reactor used for sludge activity tests.
1: warm water flow,
2: water jacket (30 °C),
3: stirring device,
4: sludge mixed liquor,
5: headspace,
6: inlet point for pH electrode,
7: gas outlet,
8: sampling port,
9. granular soda lime for CO_2 removal,
10: liquid displacement system for gas measurement.

A sludge concentration of 2.5 $kgVSS.m^{-3}$ was aimed at. The actual concentration ranges from 1.5 to 2.5 $kgVSS.m^{-3}$.
The sludge mixed liquor was diluted with deoxygenated (=boiled) tap water.

The substrate used was a solution of acetic acid (0.56 kg VFA-COD.m^{-3}), supplied as its sodium ~~salt in~~ order to obtain a pH of 7.0-7.2.
$(NH_4)_2SO_4$ and K_2HPO_4 were added, to obtain a nutrient with COD:N:P = 350:5:1.

In fig. b a typical curve, obtained from this method, is shown. Maximum specific methanogenic activity was determined from the maximum inclination found in the curve.

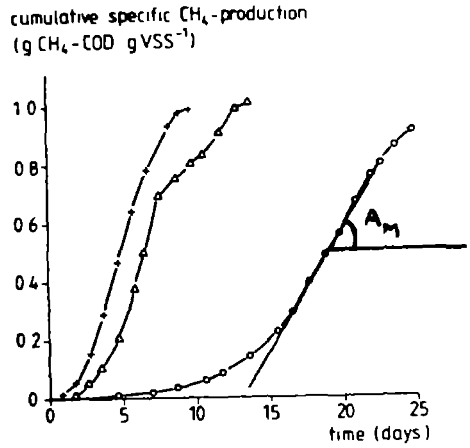

FIGURE b
Cumulative specific methane production in standardised batch activity tests with 3 different digested sewage sludge types.

literature:
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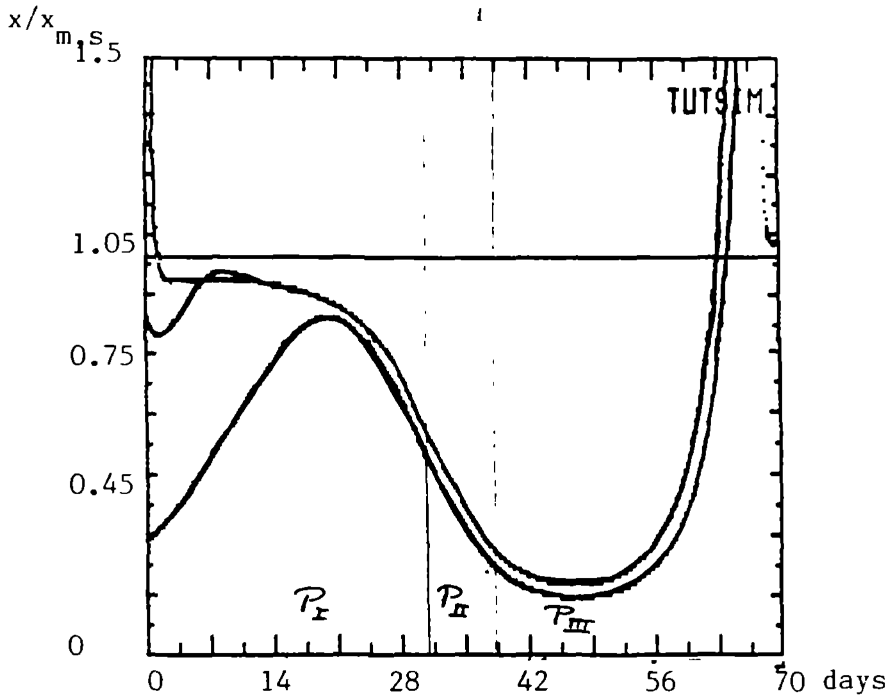
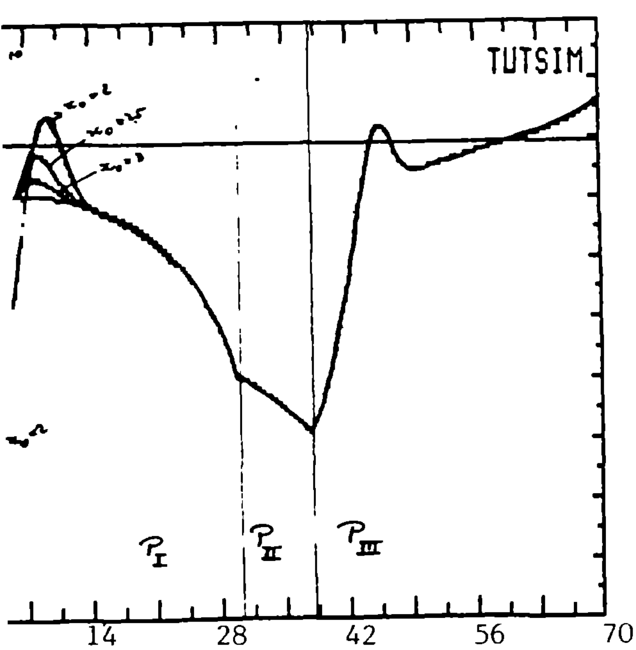
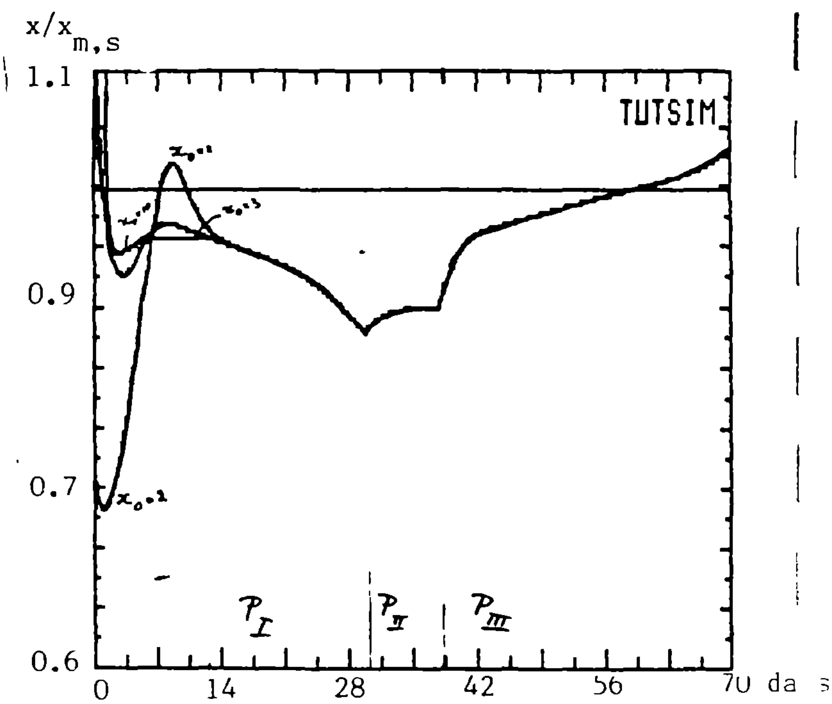
Annex 4: Simulation results

4.1 The influence of the hydraulic retention time



m = 1.2





1.4

m = 1.6

4.2 The influene of the amount of inoculum

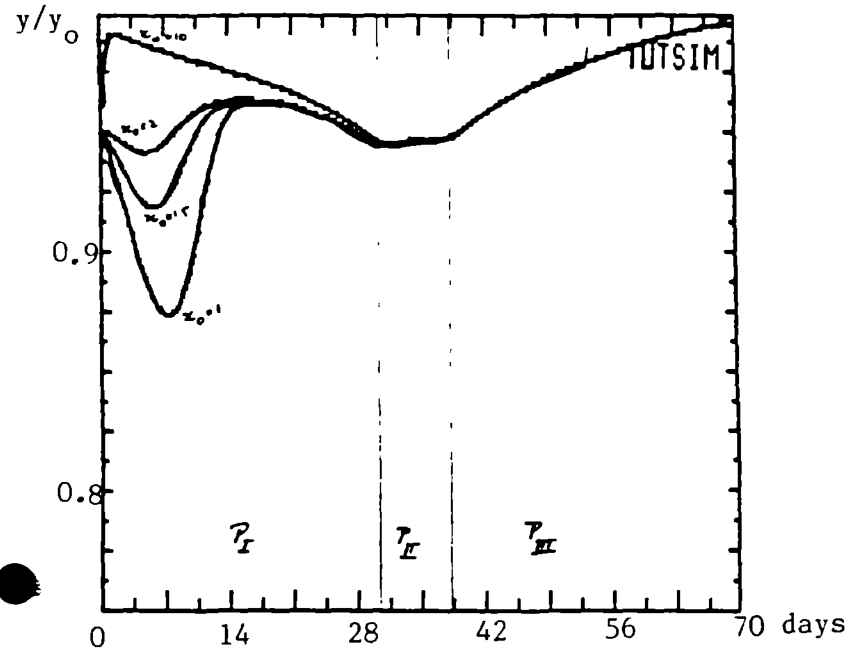


fig a:
m = 1.6, process performance

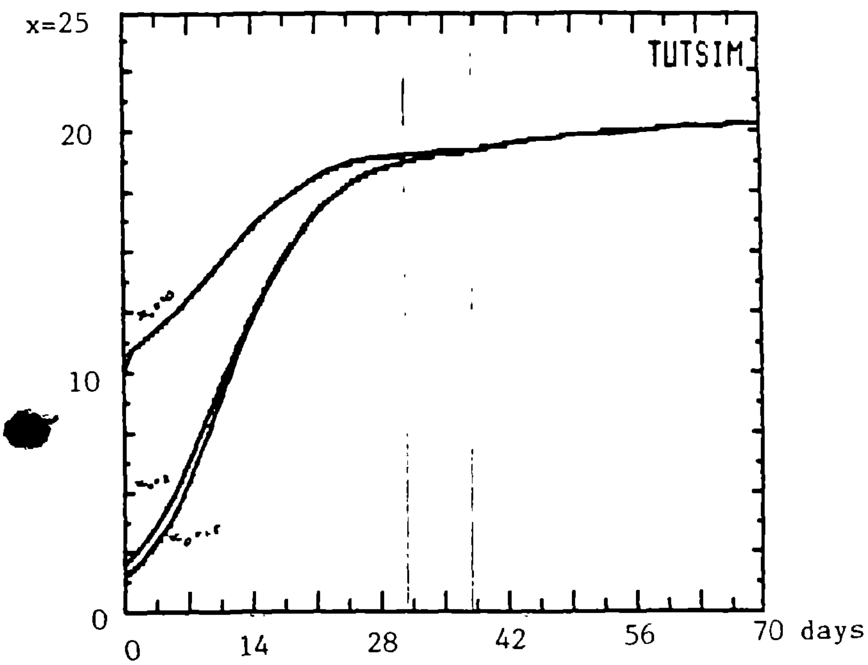
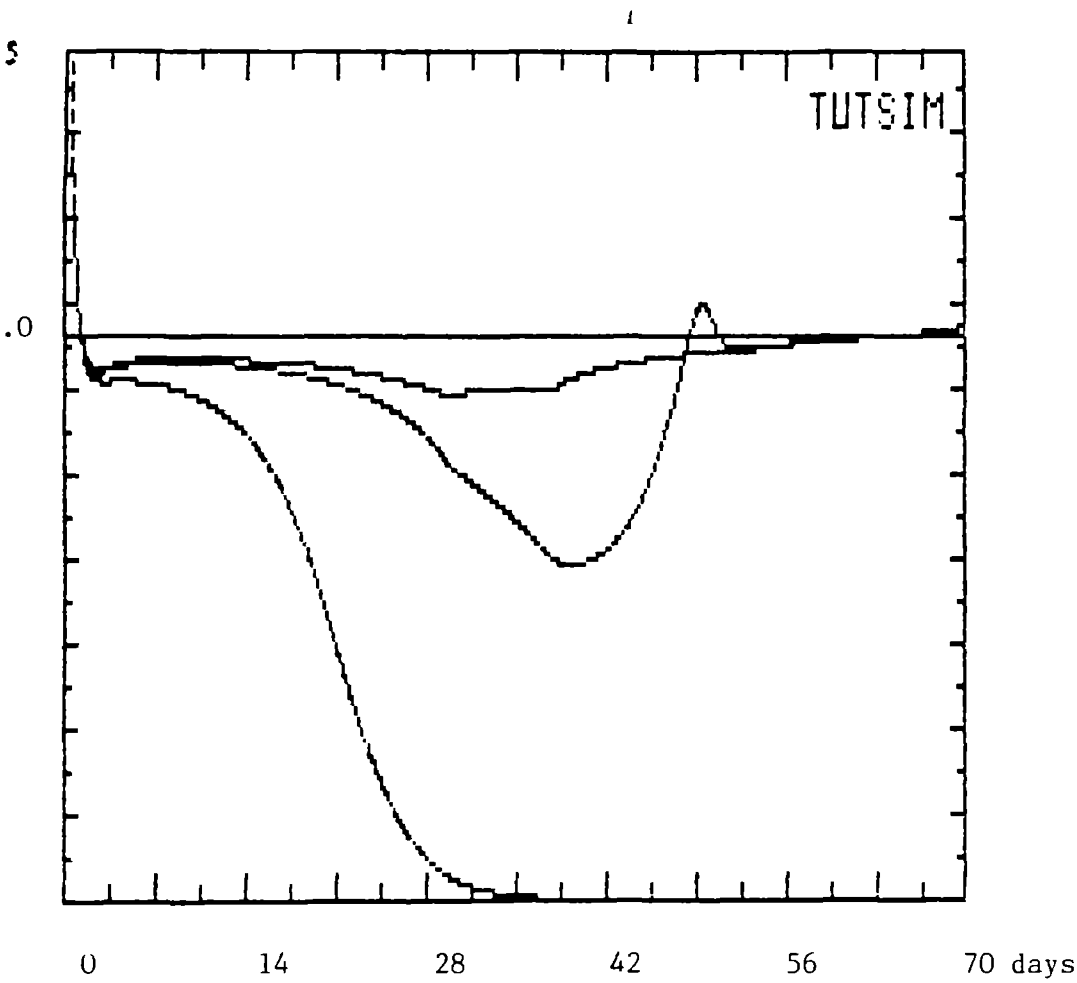


fig. b:
m = 1.6, sludge development

4.3 The influence of sludge retention



4.4 The influence of temperature

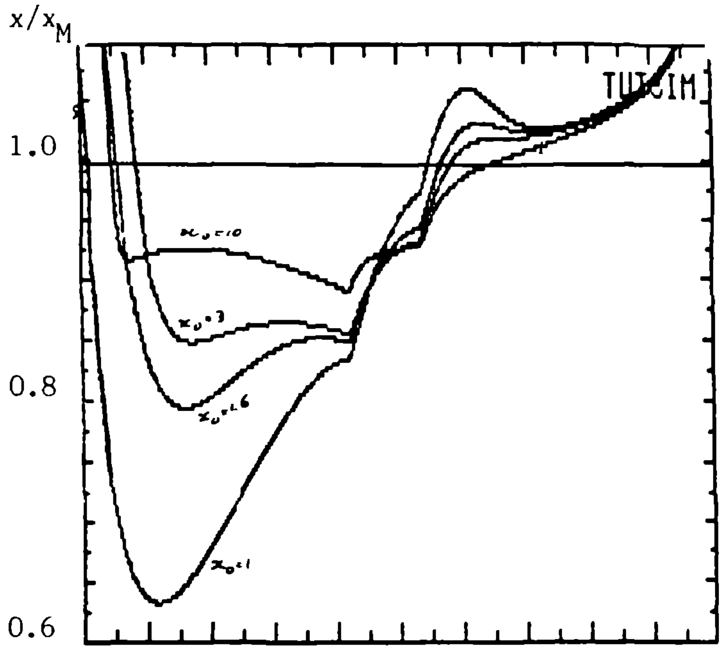


fig. a: T = 23 °C, x_0 = 10
3
1.6
1.0

pH-stability

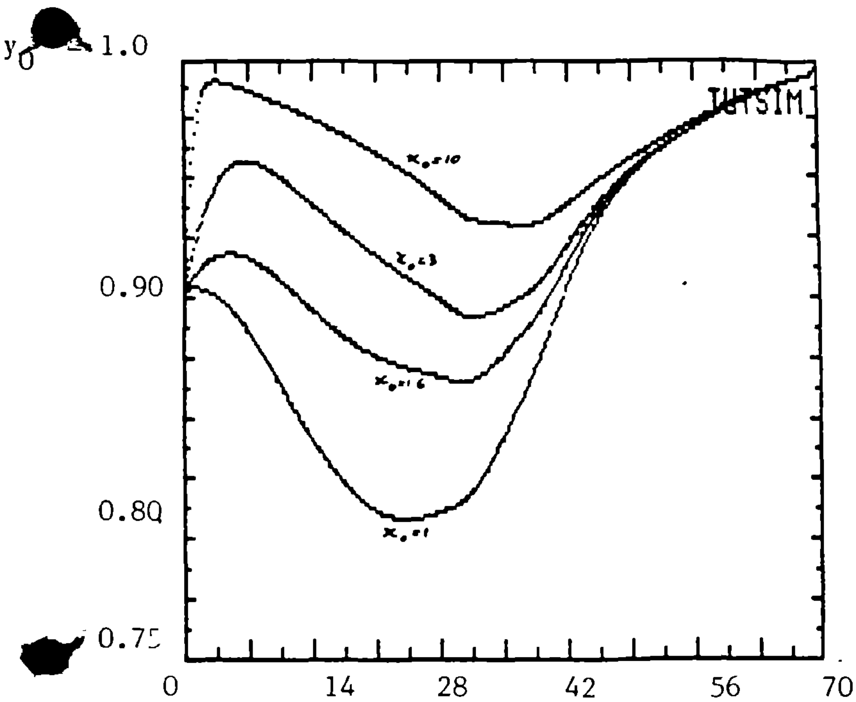


fig. b: process performance,
idem a.

4.5 The influence of $u_{M,max}$ and k-values

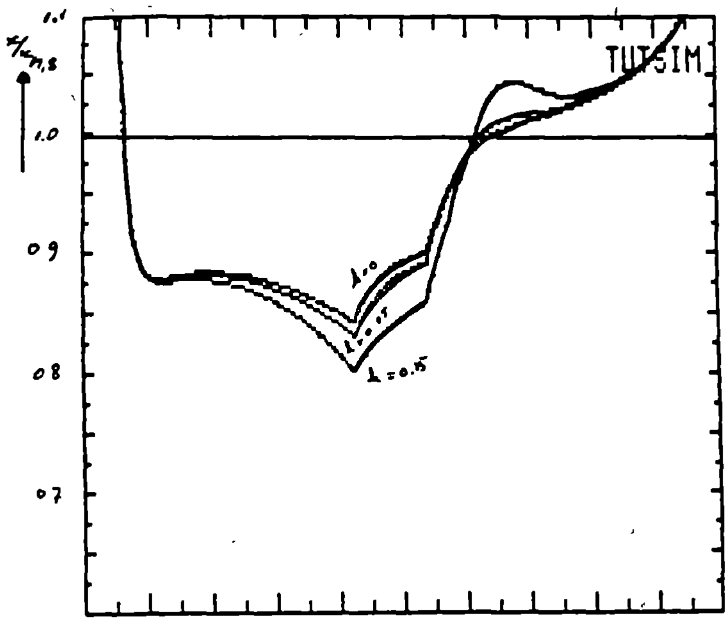


fig. a: Influence of k-value on pH-stability

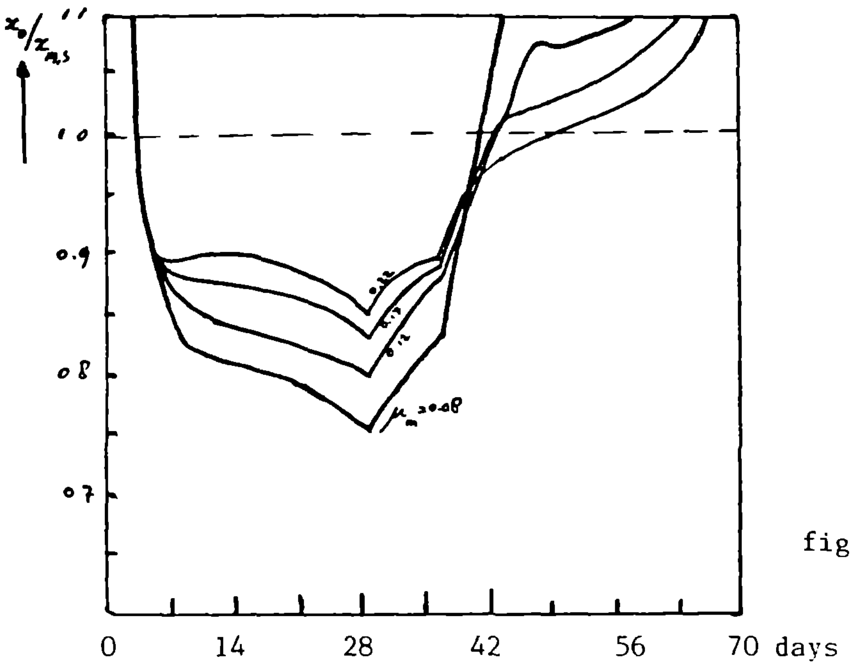


fig. b: Influence of $u_{M,max}$ - value on pH-stability