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# Energy and carbon footprints of different technologies for energy recovery from wastewater of the Vietnamese seafood processing industry

## *So sánh lượng năng lượng và dấu chân carbon từ các công nghệ thu hồi năng lượng từ nước thải chế biến thủy sản tại Việt Nam*

Research article

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The treatment of industrial wastewater with high organic loads has a large potential for energy recovery and the reduction of greenhouse gas emissions. In this work, the energy and carbon footprints of different process technologies for the treatment of fat rich wastewater from the Vietnamese seafood industry have been examined. Three options have been compared: the current low-tech solution in which the fat is used as an input for biodiesel production, the anaerobic treatment of the fat with power generation from the biogas and a combined option in which the fat is converted into biodiesel and the effluent is pre-treated anaerobically. Energy consumption and recovery as well as other emission sources have been analysed during the construction and operation phase of the plants, while the demolition phase has been neglected. All analysed options have a positive net energy output which sums up to 4.17; 4.44 and 9.82 kWh per treated $m^3$ of wastewater for variants 1, 2 and 3 respectively. The corresponding carbon footprints are -0.90. -0.69 and -2.24 $KgCO_2$ /$m^3$. Hence, anaerobic digestion of the fat can slightly improve the net energy output but performs even worse on the carbon footprint of the treatment plant, whereas the combination of biodiesel production and anaerobic pre-treatment reduces energy consumption during the operational phase and recovers more than twice as much energy as the other options. Furthermore, all variants have a negative carbon footprint and thus save $CO_2$-emissions, since the carbon in the wastewater is biogenic and the recovered energy can replace fossil fuels.

*Việc xử lý nước thải công nghiệp với hàm lượng hữu cơ cao có tiềm năng rất lớn trong việc thu hồi năng lượng và làm giảm phát thải khí nhà kính. Trong nghiên cứu này, lượng năng lượng và khí thải gây ô nhiễm môi trường (dấu chân Carbon) từ các công nghệ xử lý nước thải giàu chất béo ngành công nghiệp chế biến thủy sản tại Việt Nam đã được nghiên cứu. 3 phương pháp đã được so sánh: giải pháp hiện tại sử dụng chất béo làm nguyên liệu sản xuất diesel sinh học; phương pháp xử lý kỵ khí chất béo có sản sinh năng lượng và phương pháp kết hợp trong đó chất béo được chuyển thành diesel sinh học và nước thải đầu ra được xử lý kỵ khí. Lượng năng lượng tiêu thụ và thu hồi cũng như các nguồn phát thải khác đều đã được phân tích trong suốt quá trình xây dựng và vận hành nhà máy. Các phương pháp phân tích đều cho kết quả tích cực về mặt năng lượng, chẳng hạn như* $1m^3$ *nước thải tạo ra lần lượt 5,24; 4,56 và 11,16 kWh tương ứng với các phương pháp 1, 2, 3. Lượng* $CO_2$ *lần lượt là 0,90; 0,69 và 2,24 Kg* $CO_2$ /$m^3$*. Do đó, xử lý kỵ khí chất béo không thể cải thiện lượng năng lượng đầu ra hoặc dấu chân carbon của nhà máy xử lý, trong khi việc kết hợp sản xuất diesel sinh học và tiền xử lý kỵ khí làm giảm lượng năng lượng tiêu thụ trong quá trình vận hành và thu hồi lượng năng lượng nhiều gấp 2 lần các phương pháp khác. Ngoài ra, các phương pháp đều tạo ra giá trị dấu chân carbon âm, tức là làm giảm lượng phát thải* $CO_2$*, vì carbon trong nước thải là carbon sinh học và năng lượng thu hồi có thể thay thế nhiên liệu hóa thạch.*

**Keywords:** wastewater, carbon footprint, greenhouse gas, energy, seafood industry

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# 1. Introduction

Due to the public discussion about climate change, the carbon and energy balances of products and services have come into focus. Wastewater treatment facilities generally have high energy consumption and therefore high indirect $CO_2$-emissions, since in most countries the electricity is mainly produced by fossil resources. Technologies for energy recovery from carbon rich wastewaters such as anaerobic treatment with biogas production have been introduced in the literature (Cakir & Stenstrom, 2005; Shahabadi et al., 2009) and are able to gain a net energy output as well as overall net $CO_2$-savings treating wastewater with high organic loads. Animal fat can also be converted into biodiesel (Jayasinghe and Hawboldt, 2012) which is a more flexible energy source compared to biogas, due to its good transportability.

The wastewater of most seafood processing companies in the Mekong Delta contains high loads of carbon in the form of fish fat and is conventionally treated aerobically (Trautmann et al., 2011). This results in high energy demands and high amounts of excess sludge that may not always be treated adequately. The fish fat is extracted, transported to China and converted to biodiesel. With an annual production of 566 million liters in 2012 and much higher capacities, biodiesel technology has long been applied on a large scale in China (Meador, 2012). Anaerobic treatment would have the advantage that electricity could be produced on site with a cogeneration unit, which would make the companies less dependent on the often instable national grid. In the present work, the energy and carbon footprints of the conventional treatment method have been compared to those of two different variants. One of them implies the anaerobic digestion of the fat and conversion of the resulting biogas to electricity and heat, the other one is a combination of biodiesel production of the fat and anaerobic pretreatment of the remaining wastewater.

# 2. Plant design and calculation methodology

## 2.1 Plant description

The assumptions for the modeling of the three wastewater treatment variants are based on on-site collected data of wastewater parameters of the fish processing industry in southern Vietnam. Typical wastewater parameters at a fish processing site have been assumed as shown in Table 1. The plants have been designed for a cleaning capacity of 1,000 $m^3$ per day that ensures to comply with the regional Vietnamese regulations at the point of wastewater discharge. Those were calculated to be 55 mg/l COD and 33 mg/l nitrogen according to the Vietnamese Ministry of Natural Resources and Environment (VEA, 2008).

Regarding the operation of the plant, it has been assumed that a constant wastewater inflow of 100 l/h is occurring for 10 hours on weekdays. Furthermore, an average temperature of 25°C has been assumed. Fluctuations in wastewater inflow as well as temperature have been neglected.

**Table 1. Typical wastewater parameters of a Vietnamese fish processing factory**

| Parameter | Unit | Value |
|---|---|---|
| COD | [mg/l] | 4,200 |
| Total Nitrogen | [mg/l] | 140 |
| Solids (fat) | [% Vol.] | 4 |
| N content fat | [mg/Kg] | 40 |

A simplified flowchart of the different variants is given in Figure 1. Variant 1 shows the typical low technology option currently used for wastewater treatment in the Vietnamese fish industry. A large part of the sediments is extracted from the inflow with a simple grease trap, the remaining wastewater is treated aerobically to meet the effluent standards. The fat is transported to China where it is converted into biodiesel while possible leftovers of this process are neglected. The excess sludge is lead to sludge disposal.

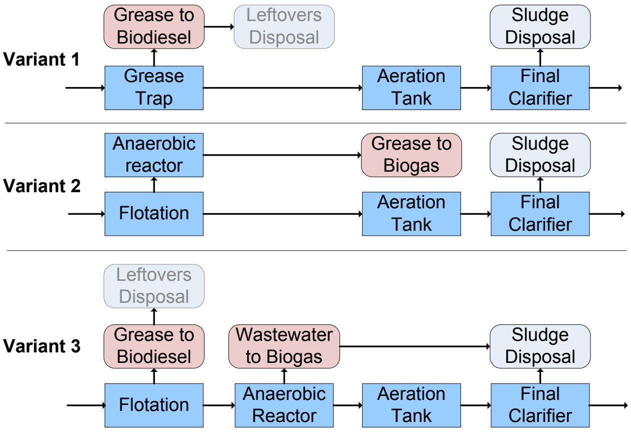

**Figure 1. Overview process variants**

Variant 2 operates with a precipitation-supported flotation to achieve a more effective extraction of the fat, which then is converted into biogas in a two-step anaerobic reactor. A biogas powered cogeneration unit provides the factory with electricity while the excess heat is used as input energy for absorption chillers. Despite the more effective fat extraction, remaining wastewater has to be post-treated aerobically to meet the effluent standards.

Variant 3 represents a combination of both of the previous variants. The fat is extracted by flotation and sent to biodiesel production while the remaining wastewater with sufficiently high COD loadings is pre-treated anaerobically and post-treated aerobically. Since the anaerobic pretreatment extracts only small part of the nitrogen load, this variant requires an additional denitrification unit to meet the effluent standards.

Excess sludge disposal is carried out in dry beets without previous dewatering in all variants.

## 2.2 System boundaries

In the calculation of $CO_2$ emissions, construction and operation of the plants were considered. There is a consensus within the literature that the demolition phase of wastewater treatment plants is irrelevant for the carbon footprint (Larsen et al., 2007) and, moreover, shut down

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plants are not necessarily deconstructed and recycling rates as well as emission factors can hardly be estimated over a predicted lifespan of 15 years. Hence, the demolition phase of the plant is neglected in the calculation. Figure 2 shows an overview on the system boundaries.

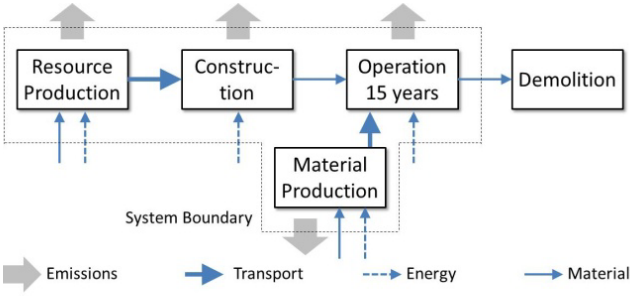

**Figure 2. System boundaries and life cycle**

### 2.3. Calculation of energy demand and $CO_2$-emissions

Since there hasn't been a generally admitted norm for the calculation of carbon footprints yet, this work's calculation is based on the PAS manual (PAS2050, 2011) published by the British Standards Institution BSI, which has proven to be practical. Energy demand and emissions resulting from construction and operation of the plant have completely been taken from literature and manufacturers data. Direct emissions only result from dissolved methane in the discharge of anaerobic reactors, which have been calculated using Henry's law. Direct emissions from the aerobic treatment are considered biogenic and therefore, referring to IPCC, do not contribute to the carbon footprint (Doorn et al., 2006).

For the embodied emissions of resources, emission factors from Gemis (Öko Institut e.V., 2010) and Idemat (TU Delft, 2010) databases were applied. The necessary quantities of construction materials were taken from contract documents of existing plants that resemble the ones analyzed in this paper. The quantities were up- or downscaled to the designed size. The energy demand was determined using literature data from Zhang and Wilson (2000), who used a factor for energy demand per $m^2$ of required surface area for the plant. It was assumed that the energy used for construction consists of 90% diesel and 10% electricity taken from the national grid, as transport and most of the construction machinery is powered by diesel fuel.

The transport of construction material, chemicals and excess sludge was assumed to be realized by truck over a distance of 50, 20 and 10 km respectively. Since biodiesel production usually is carried out in China, the fat is transported 2,000 km by train. For the estimation of the energy consumption during plant operation, electrical installations, including electric power and hours of operation, have been designed referring to literature and manufacturers data. An overview of operation parameters and electrical power consumers with the corresponding sources is given in Table 2.

### 2.4. Allocation of emissions

The processes analyzed in this paper produce as by-product either biogas, biodiesel or both. Those by-products were assumed to be biogenic and therefore lead to a saving of $CO_2$-emissions when replacing fossil fuels. Since fossil diesel can directly be replaced by biodiesel, 1 kg of biodiesel produced accounts for a saving of 3,71 $kg_{CO2}$ less the amount of emissions resulting from the conversion process of the fat (Jensen et al., 2007; López et al., 2010) and from the transport to China.

Biogas is usually converted to electricity in cogeneration units, so that the emission savings depend on the application of electricity and heat. It was assumed that the electricity could completely be used in the factories on site, so that it substitutes electricity from the national grid. The heat is used as input energy for absorption chillers that cool the storage rooms. Since the cooling is conventionally done by electrical compression chillers, there is also a saving of grid electricity to be calculated. The latest Vietnamese grid emission factor available is 0.57 $kg_{CO2}/kWh_{el}$ (Quách, 2009).

Assumptions concerning the recycling of the used resources would have a high uncertainty due to the long lifespan of 15 years. However, the applied databases provide a typical market mix for most resources used in the designed plants, which is composed of a certain share of new and recycled material. Apart from that, recycling of resources has been neglected.

## 3. Results and discussion

### 3.1. Energy footprint

A comparison of the energy consumption of the different variants is given in Figure 3. All three variants recover more energy than the treatment demands, so that they produce a net energy output. Regarding the high rates of energy recovery, energy consumption for construction and operation phase is almost insignificant. The demand for construction includes transport of materials, resource production and energy demand on site. It sums up to 0.10, 0.21 and 0.18 $kWh/m^3_{ww}$ for variants 1, 2 and 3 respectively, and thus can be neglected. In the operation phase, aeration is by far the largest consumer. Pumps, flotation, stirring, clarifier and transport of excess sludge and chemicals can also be neglected. The total energy consumption in the operation phase sums up to 1.44, 1.36 and 0.84 $kWh/m^3_{ww}$ for the three variants.

Anaerobic conversion of the fat with an effective fat extraction by flotation in variant 2 shows a lower energy demand for aeration compared to variant 1, whereas there is additional demand for pumps, flotation and stirring. The energy recovery of 6.02 $kWh/m^3_{ww}$ as well as the net energy output of 4.44 $kWh/m^3_{ww}$ result to be slightly higher compared to variant 1 with a recovery of 5.72 at a net energy output of 4.17 $kWh/m^3_{ww}$. The transport of the fat and energy demand of the conversion process have been subtracted from the total amount of energy recovered by biodiesel.

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In variant 3, a total energy recovery of 10.84 kWh/m$^3_{ww}$ can be achieved of which biogas accounts for 3.72 kWh/m$^3_{ww}$ and biodiesel for 7.12 kWh/m$^3_{ww}$. In contrast to variant 1, the more effective flotation extracts a higher amount of fat so that more biodiesel can be produced. Furthermore, variant 3 shows the lowest energy demand of all variants. While pumps, flotation and stirring require more energy than in the other variants, aeration energy is reduced to a minimum as most of the COD loading is extracted anaerobically in the pretreatment. In total, a net energy output of 9.82 kWh/m$^3_{ww}$ can be achieved, which is more than twice as much as in the previous variants.

**Table 2. Overview process parameters and energy demand** (values in parenthesis for variant 3, when differing)

| Parameter | Value | Source |
|---|---|---|
| ***Wastewater*** | | |
| Flow rate | 100 m$^3_{WW}$/h | |
| Operating times on weekdays | 10 h | |
| COD | 4,200 mg/l | |
| Total nitrogen | 140 mg/l | |
| Temperature | 25 °C | |
| ***Aeration Tank*** | | |
| Retention time | 1 (0.5) d | Assumption |
| Standard Aeration Efficiency | 1,30 Kg $O_2$/kWh | (Rosso et al., 2008) |
| Aerobic yield | 0.67 kg COD/Kg COD$_{eli}$ | (Henze et al., 2000) |
| N-fixing | 0.045 Kg N/ KgCOD$_{eli}$ | (Gujer, 2007) |
| Oxygen saturation | 2 mg/l | (Gori et al., 2011) |
| Mean cell residence time | 3 d | Assumption |
| Recirculation rate denitrification | (5) d | Assumption |
| ***Flotation*** | | |
| Efficiency | 4 %Vol., 56 % COD | (Steinke and Barjenbruch, 2010) |
| Power consumption | 0.1 kWh/m$^3_{WW}$ | (Trautmann et al., 2011) |
| Ferric chloride dosing | 0.5 g $FeCL_2$/Kg COD$_{eli}$ | Own experiments |
| ***Pre-acidification*** | | |
| Power consumption | 0.24 kWh/(m$^3_{Vol}$*d) | (Urban, 2008) |
| ***Anaerobic reactor*** | | |
| Process technology | CSTR (with sec. sedimentation) | |
| Retention time | 20 (1) d | |
| Anaerobic yield | 0.05 | (Trautmann, 2007) |
| Metabolic rate | 80 (70) % | |
| Methane production | 0.32 m$^3$/Kg COD$_{eli}$ | |
| Power consumption | 0.18 (0.12) kWh/(m$^3_{Vol}$*d) | (Urban, 2008) |
| pH-adjustement | 0.01 Kg NaOH/m$^3_{WW}$ | Own experiments |
| ***Final clarifier*** | | |
| Surface area | 35 (25) m$^2$ | |
| Power consumption | 1.8 Wh/m$^3_{WW}$ | (Müller et al., 1999) |
| Return sludge ratio | 1 | |
| Return sludge density | 7 Kg/m$^3$ | (Gujer, 2007) |
| ***Pumps*** | | |
| Power cons. centrifugal pump | 54.4 Wh/m$^3$ at 50m$^3$/h | (Gülich, 2010) |
| Power cons. eccentric screw pump | 0.53 kWh/m$^3$ at 4m$^3$/h | (Seepex, 2012) |
| ***Energy recovery*** | | |
| Electrical eff. cogen. unit | 40% | (FNR, 2010) |
| Thermal eff. cogen. unit | 43% | (FNR, 2010) |
| Performance ratio AC* | 0.75 kWh$_{cold}$ /kWh$_{th\ input}$ | (Ziegler 1998) |
| Performance ratio CC | 3 kWh$_{cold}$/kWh$_{el\ input}$ | |
| $CO_{2eq}$ electricity Vietnam | 0.57 Kg $CO_2$/kWh$_{el}$ | (Quách, 2009) |
| $CO_{2eq}$ natural gas | 0.29 Kg $CO_2$/kWh | (Öko Institut e.V., 2010) |
| $CO_{2eq}$ diesel | 3.71 Kg $CO_2$/kg | (TU Delft, 2010) |

* The performance ratio indicates the quotient of cooling energy (output heat) and electrical (compression chiller, CC) or thermal (absorption chiller, AC) input energy. In contrast to an efficiency factor, this figure can reach a value > 1.

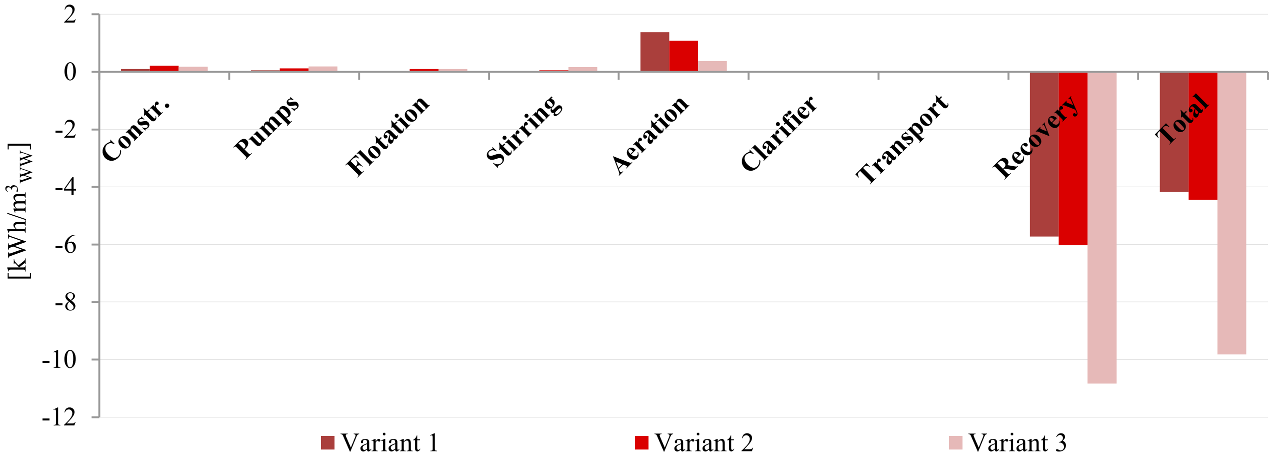

**Figure 3. Energy demand and recovery of different process variants**

### 3.2. Carbon footprint

The resulting greenhouse gas (GHG) emissions are shown in Figure 4. The emissions strong dependency on the energy consumption causes similar proportions between the different variants. The sum of emissions is also negative in all variants. Construction phase has a lot more impact on the final result, however, since the embodied emissions in the construction materials are considered additionally. Variant 2 has the highest construction complexity and consequently the highest emissions in this category. In total, the emissions in the construction phase add up to 0.12, 0.27 and 0.24 kg $CO_2/m^3_{ww}$ for variants 1, 2 and 3 respectively.

In the operation phase, variants 2 and 3 save electricity and therefore emissions for aeration compared to variant 1, but have a higher demand for additional power consumers such as pumps and stirring. Clarifier and transport of chemicals and excess sludge can be neglected in all variants. The emissions of dissolved methane in the outflow of the anaerobic reactors are almost negligible for variant 2, since the flow rate of the extracted fat is relatively small. In variant 3, however, dissolved methane is the major source with emissions of 0.34 kg $CO_2/m^3_{ww}$. The total GHG emissions of the operation phase sum up to a total of 0.82, 0.78 and 0.82 kg $CO_2/m^3_{ww}$ for the three variants.

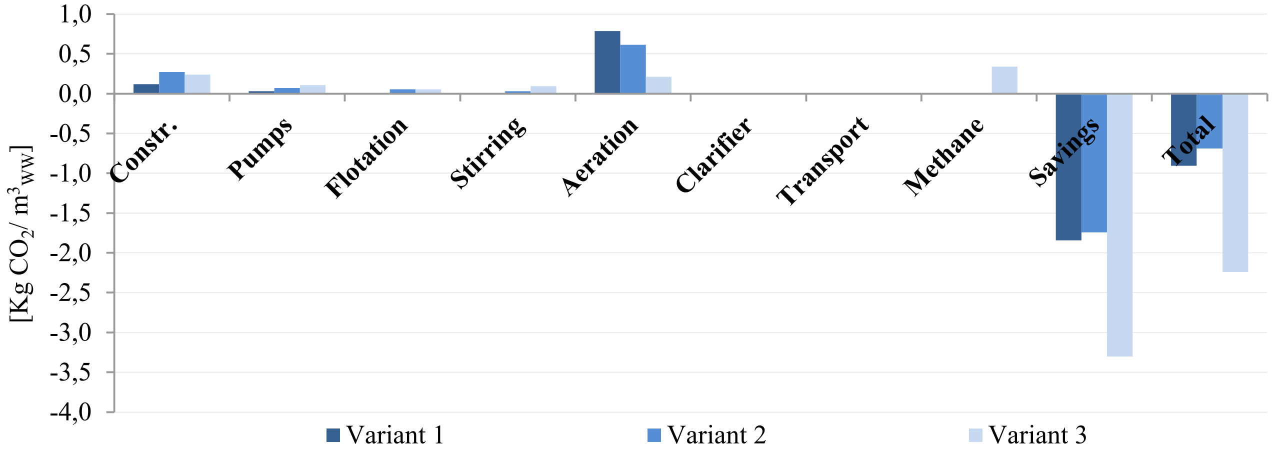

**Figure 4. GHG emissions and savings of different process variants**

The emission savings depend on both the amount of recovered energy and the method of calculation mentioned in section 2.4. Despite the higher energy recovery, variant 2 performs worse than variant 1 regarding the savings, so the direct substitution of diesel by biodiesel even with a long transport considered turns out to be a more effective way to save emissions compared to the biogas production and conversion in cogeneration units. As compression chillers work quite efficiently, the emission savings by replacing the cooling energy have shown to be low. Because of the higher construction complexity of variant 2, the difference even grows bigger in the overall performance. Variant 3, however, achieves savings almost twice as high as the other variants. The final carbon footprint of the three variants is -0.90, -0.69 and -2.24 kg $CO_2/m^3_{ww}$.

## 4. Conclusions

In this work, energy and carbon footprints over the whole lifespan of three technology variants for wastewater treatment and energy recovery of Vietnamese seafood processing wastewater have been compared. It has been shown that the current technology option has a high net energy output as well as a high negative carbon footprint. The conversion of the fish fat to biogas in variant 2 combined with a modern process technology results in a better energy footprint but due to less effective substitution of fossil fuels and a higher complexity in construction, the carbon footprint is worse.

Variant 3, in which the fat is converted to biodiesel and the remaining wastewater is pretreated anaerobically, shows a considerable potential for further energy recovery and emissions saving. In total, a net energy output of 9.82 kWh/$m^3_{ww}$ and a net emissions saving of 2.24 kg $CO_2$/$m^3_{ww}$ has been shown to be possible. It has also been proven that the construction phase has a very low impact on both energy and carbon footprints of wastewater treatment plants.

## 5. Acknowledgement

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