Economic Evaluation of Biofilters

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During studies on the optimization of biofilters for the reduction of odours from piggeries, two filter materials and different designs were tested parallel in a stall for fattening pigs. Measured mean odour reduction amounted to 70 to 80%. Odour concentration in the waste air constitutes the main influencing factor for odour reduction. Sufficient material moisture in the entire volume of the filter material is an essential prerequisite for odours to be reduced significantly and as continuously as possible. The use of coarsely structured materials such as biochips allows larger bulk heights and filter volume loads to be reached, which reduces the investment cost considerably. However, flow resistance and, hence, operating expenses for electricity, grow disproportionately. Therefore, these effects must be given special attention when designing a biofilter and calculating the resulting total cost.

Keywords
Biofilter, filter material, flow resistance, cost, odour reduction

Introduction

As shown already in previous long-term investigations with a bulk height of 0.5 m, the use of a new filter material (biochips - coarsely hacked coconut shells) allows the same odour reduction (ca. 81%) to be achieved as the mixture of coconut fiber - fiber peat often employed in practice. In contrast to coconut fiber - fiber peat, however, biochips distinguished themselves by significantly lower flow resistance, which leads to lower operating expenses (electricity cost) [1].
The present investigations pursued the goal of determining the odour reduction and the flow resistance of selected filter materials and different designs. The gained results were supposed to provide a recommendation for the construction and the design of biofilters (using exemplary designs of so-called “model biofilters”) for the reduction of odour emissions from agricultural animal housing. Another goal was the economic evaluation of the examined variants.

Material and Method

Five biofilters with a closed design (on a semi-commercial scale) were connected to an experimental stall for fattening pigs from July 8, 1999 until February 7, 2000 [2] (**figure 1**). The designs, bulk heights, and filter materials used for the individual biofilters (area: 2.19 m^2) are listed in **table 1**. As in the previous investigations carried out between February 19 and June 4, 1999 [1], biofilters number 1 and 2 continued to operate without any alteration with biochips (hacked coconut shells; test material from the company Roth GmbH, Oberteuringen) and coconut fiber - fiber peat (ratio of mixture 1:1) as filter materials. Due to the very low flow resistance of the biochips, biofilters number 3, 4, and 5 were altered such that a bulk height of 1 m could be tested for both the “downstream” and the “upstream” design.
The arrangement of the individual measuring points in the “downstream” and “upstream” design is shown in **figure 2**. According to the draft of the European standard “Air Quality Determination of Odour Concentration by Dynamic Olfactometry” [3], the odour samples taken in front of and behind each individual biofilter were analyzed with an olfactometer TO7 (type Mannebeck). For the control of the system along with a summarizing overview of the measuring instruments used, the reader is referred to a previous “Landtechnik” article [1].

Results

With regard to odour reduction, partly significant differences between the individual biofilters were determined. Especially during the first 8 weeks of the trial, lower odour reduction by biofilters num-

Figure 1: Experimental system during the investigation

Table 1: Experimental set-up

biofilter	filter material	bulk height	design
no. 1	biochips *	0.5 m	up-stream
no. 2	coconut-peat *	0.5 m	up-stream
no. 3	biochips	1.0 m	down-stream
no. 4	biochips	1.0 m	down-stream
no. 5	biochips	1.0 m	up-stream

* continuation of the experimental set-up of the first main trial phase

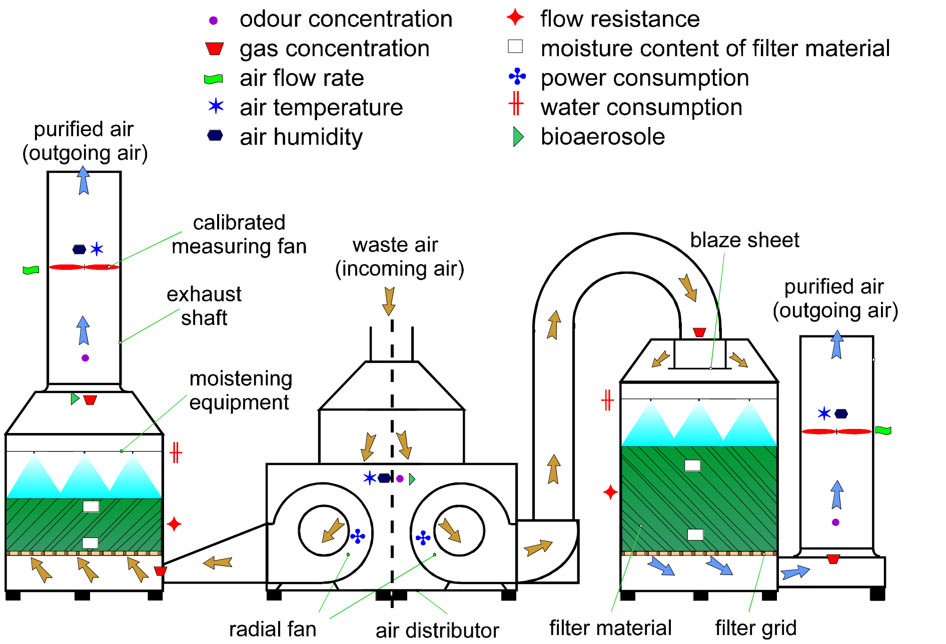

Figure 2: Arrangement of the measuring points

ber 3, 4, and 5 was observed (**figure 3**). This was probably caused by the population of microorganisms which had not yet sufficiently developed in the filter material of these biofilters during the starting time of the biofilters since the differences between the individual biofilters were considerably smaller in the further course of the experiment and since, in comparison, biofilters number 1 and 2, which had been taken over from the first main trial phase, exhibited greater odour reduction with smaller fluctuations during the entire investigation (figure 3). In the variants with a bulk height of 0.5 m, calculated mean odour reduction showed virtually no differences between biochips (69.6%) and coconut peat (70.1%). The "downstream" variants achieved the highest mean filtration efficiency of 73.3 and 75.5% (**table 2**). The lowest mean odour filtration efficiency (57.1%) was measured in filter number 5. If the negative reduction of –42.6%, which was likely caused by an evaluation error, remains unconsidered, the mean odour filtration efficiency of filter number 5 amounts to 61.5% (table 2). As compared with the other variants (number 1, 3, and 4), the mean odour reduction of filter number 5 was approximately 15 to 20% lower, which can be explained as a result of lower water consumption and a higher percentage of dry spots in the filter material in comparison with the other biofilters.

In all examined variants, the consideration of odour reduction as a function of the filter volume load did not allow a clear correlation between these two parameters to be determined. The straggling of odour reduction increased with growing filter volume load. However, no noticeable decrease in odour reduction could be determined.

All in all, the results showed that increasing odour concentration in the waster air caused improved odour reduction in all variants. If odour concentration in the waster air exceeded approximately 1,000 OU/m^3, all variants achieved an odour reduction of more than 50%. In biofilters number 1 and 2, the individual values straggled in a similar range as during the previous investigations [1]. These results speak against a possible influence of the operating time of the filter materials on the amount of odour reduction (**figure 4**).

In all variants, specific odour cleaning performance [OU·m^{-3}·s^{-1}] increased with a higher specific odour filter load [OU·m^{-3}·s^{-1}]. It was possible to describe this connection with the aid of a positive linear regression line (R^2 = 0.75 to 0.96). However, no clear differences between the individual variants were established. Odour concentration in the waster air thus constituted the main factor which influenced specific odour cleaning performance [4], [5].

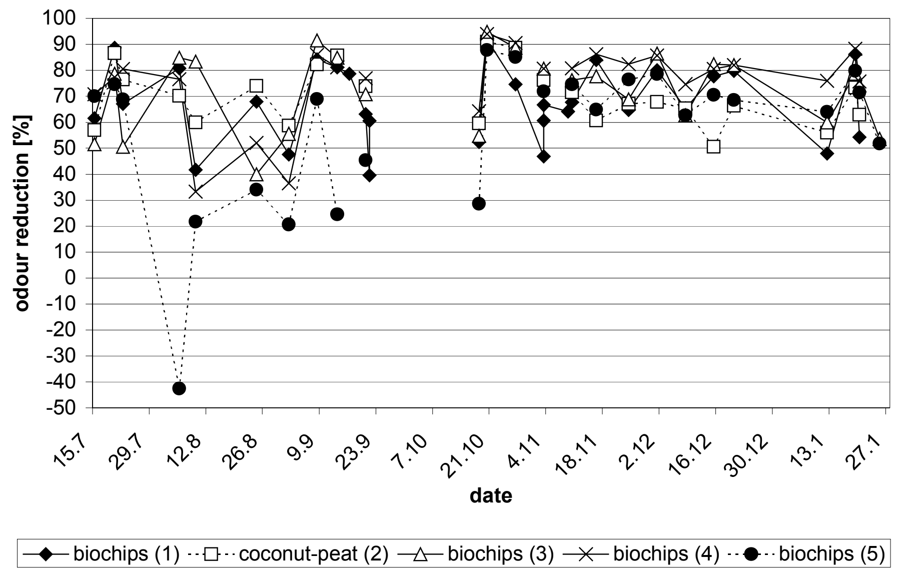

Figure 3: Course of relative odour reduction of different filter materials and designs examined (July 1999 until 2000)

Tabelle 2: Odour reduction of the examined filter material ad designs

biofilter (no.)	biochips (1)	coconut-peat (2)	biochips (3)	biochips (4)	biochips (5)
mean value [%]	69.6	70.1	73.3	75.5	(57.1) 61.5*
median [%]	67.8	69.0	78.2	80.6	(68.9) 68.9*
minimum [%]	41.7	50.6	40.0	33.3	(-42.6) 20.6*
maximum [%]	91.9	91.1	94.9	94.0	(87.9) 87.9*
standard deviation [%]	13.9	10.9	14.4	14.9	(28.9) 20.5*
error of the mean value [%]	2.8	2.2	2.9	3.0	(5.9) 4.3*
number of samples [n]	24	24	24	24	(24) 23*

* The values were calculated without the one-time value of -42.6% (measurement error)

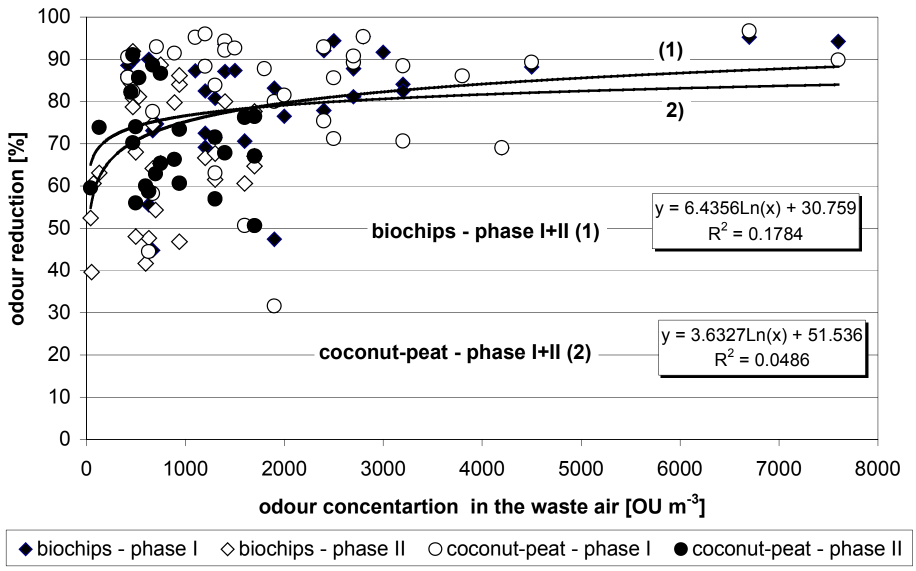

Figure 4: Connection between odour reduction and odour concentration in the waste air for the filter materials biochips and coconut fiber-fiber peat during all investigation phases

With regard to resulting flow resistance, significant differences between the individual filter materials and designs were established. Figure 4 shows the amount of flow resistance as a function of the filter volume load at the end of the trial period, i.e. after an operating time of one year (biofilters number 1 and 2) or 32 weeks (biofilters number 3 and 5). The flow resistance of biofilter number 4 could not be shown because a measurement signal was incorrect at that time. In coconut fiber - fiber peat, pronounced straggling of flow resistance was established. This was caused by the variable moisture content of the filter material, which, in contrast, did not show any influence in the case of the coarsely structured biochips. Thus, coconut fiber - fiber peat resulted in the same flow resistance of ca. 430 Pa, for example, at a filter volume load of ca. 500 $m^3 \cdot m^{-3} \cdot h^{-1}$ and a high moisture content of the filter material and at a filter volume load of ca. 900 $m^3 \cdot m^{-3} \cdot h^{-1}$ and a low moisture content of the filter material (**figure 5**).

With increasing operating time, the flow resistance of biofilters number 1 and 2 grew. At a filter volume load of 600 $m^3 \cdot m^{-3} \cdot h^{-1}$, an increase in the flow resistance of biochips from ca. 20 to ca. 45 Pa was observed, while the flow resistance of coconut fiber - fiber peat grew from ca. 50 to ca. 250 to 450 Pa. The increase in flow resistance can be attributed to the growing compression of the filter materials during the trial period due to the material´s own weight and the deposition of dust in the filter material. As shown by the reduction of the bulk height of the filter material, biochips distinguished themselves by better structural stability than the mixture of coconut fiber - fiber peat. At the end of the investigation, the reduction amounted to ca. 10% in all variants with biochips and to ca. 20% in the coconut fiber - fiber peat variant.

After the operating time of one year at a filter volume load of 600 $m^3 \cdot m^{-3} \cdot h^{-1}$, the power requirements of the radial fan used in the variant with biochips in biofilter number 1 (0.5 m) were ca. 40 to 55% lower than those of the ventilator used in the reference variant with coconut fiber - fiber peat in biofilter number 2 (0.5 m). The difference between the two filter materials thus increased by ca. 10 to 25% as compared with the relative difference in the electric power requirements of the two filter materials after an operating time of 15 weeks. This means that, with longer operating time, the flow resistance of the coconut fiber - fiber peat mixture increased significantly faster than the flow resistance of biochips and that therefore, in relation to coconut fiber - fiber peat, lower electricity expenses must always be expected when using biochips.

Model Design and Cost Estimation for a System on a Commercial Scale

With the aid of the results gained from the experimental biofilter system along with literature data, as well as information and empirical values from companies which work in the field of biological exhaust air cleaning, a model for a commercial system was designed, and the process cost was estimated.

Dimensioning

The investigations carried out by the authors using the experimental system showed that a biofilter may be dimensioned such that its filter volume load reaches 1,200 $m^3 \cdot m^{-3} \cdot h^{-1}$ without causing a negative alteration of odour reduction. Even at a filter load of 1,400 to 1,950 $m^3 \cdot m^{-3} \cdot h^{-1}$, HOPP [6] was able to measure an odour reduction of more than 80%. The results show that microbial degradation capacity was not yet reached and that therefore the amount of odour reduction depends on the absorption between the gas- and the liquid phase. For this reason, sufficient material moisture must be maintained in the entire volume of the filter material. With growing filter volume load, the moistening of the filter material must meet increasing requirements since significantly larger air quantities result in more moisture evaporating from the filter material during a given time period.

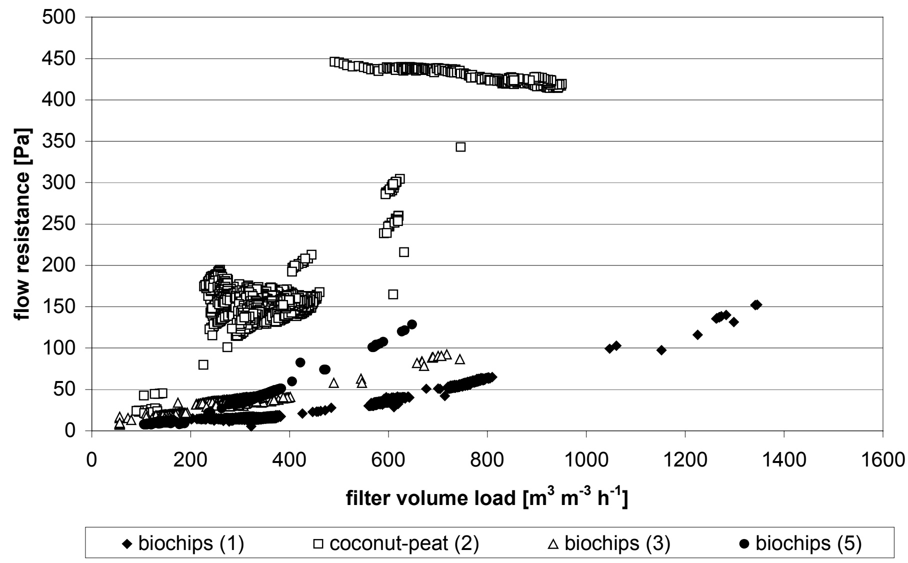

Figure 5: Exemplary course of the flow resistance of the examined filter materials and designs during the 32nd trial week (February 2 until February 7, 2000) as a function of the filter volume load

Design of the Biofilter

For the reduction of the odour emissions from agricultural animal housing systems, a model biofilter was developed which features a very simple design so that its operation causes minimum financial and personnel requirements. It can be connected to the central or the decentralized stall air exhaust system and consists of the components shown in **figure 6**.

One important prerequisite for the operation of a biofilter is the use of a suitable fan (generally a radial ventilator) in order to guarantee the supply of fresh air to the aminals and the discharge of the exhaust air with the simultaneous use of a biofilter (DIN 18910). In agricultural animal houses, axial ventilators are generally employed, which usually only have a pressure stability of up to approximately 120 Pa. However, as the authors´ results show, the flow resistance of an entire biofilter system with a biochip bulk height of 0.5 m or a similarly coarsely structured filter material and a maximum filter volume load of 600 $m^3 \cdot m^{-3} \cdot h^{-1}$ must already be expected to reach about 110 Pa (ca. 40 Pa filter material; ca. 70 Pa central exhaust system). An increase in the flow resistance of the filter material due to dust deposits or the use of finely structured filter materials and a higher filter volume load, for example, could therefore easily lead to the pressure stability of an axial ventilator being exceeded.

In biofilters with a larger filter area and a central exhaust air system for the individual stalls, a design with an air distribution channel seems sensible so that better air distribution over the entire filter area can be achieved. If the biofilter is connected to a stall with a decentralized exhaust system, the filter tub should be divided such that the exhaust systems of the individual stall compartments do not influence each other. In this case, the air distribution channel can be dispensed with, and the air can be conducted directly under the grid of the biofilter. Since the load on the individual filter segments must be expected to vary, the filter segments must be moistened separately.

The results gained by the authors also show that the removal of dust from the waster air becomes unnecessary if very coarsely structured filter materials with a similar or larger grain size than biochips (94% of the particles with a grain size between 8 and 20 mm) are used. This allows investment costs and part of the variable expenses to be saved. However, a long-term study would be required in order to examine whether possible alterations of odour reduction and flow resistance (increase by ca. 10 to 15 Pa in one year) occur during many years of operation.

For a biofilter used in agriculture, the classic open "upstream" design with superficial moistening of the filter material seems to be best suitable. The "downstream" version, i.e. the container filter design (frequent in industrial systems), is rather unsuitable due to the relatively high price of the container. The classic design of the biofilter as a concrete basin (floor- and wall thickness: 20 cm; concrete B25wu; ca. EUR 358/m^3) is approximately 25% cheaper than a container filter. If the filter areas exceed 100 m^2, the alternative design of the container as a film basin (company Fritz Paulmichel GmbH, Leutkirch) may be approximately 10 to 50% cheaper than a comparable container.

The filter grid can be manufactured from different materials or material combinations, which differ with regard to investment cost and service life. A filter grid out of fiberglass-reinforced plastic material distinguishes itself by very long service life. However, it causes high investment expenses (ca. EUR 215/m^2). Therefore, the substructure, which usually consists of bongossi wood, is combined with a lath grid (larch wood) and/or a galvanized wire grid (ca. EUR 84/m^2). As the authors´ investigations have shown, spruce wood (substructure and lath grid) in combination with a galvanized wire grid may also be used, which results in a further reduction of the investment cost (ca. EUR 41/m^2).

The filter material should be moistened by an automatic moistener combined with a moisture sensor specially calibrated for the individual filter material. Given the very high filter volume load, a manual moistening system [6], [4] cannot guarantee continuous, demand-oriented moistening of the filter material and would result in very high personnel requirements. An automatic moistener, e.g. MULTIRAIN UniWA (company Staudinger GmbH, Loiching-Kronwieden), however, allows for the simultaneous control of moisture in up to 10 biofilter segments with a corresponding number of moisture sensors.

A light roof (e.g. out of trapezoidal sheet) fitted above the biofilter enables the desiccation of the filter substrate due to solar radiation to be reduced. In addition, overwetting of the filter substrate and the collection of excess water in the substructure of the filter during heavy rain, as well as the possible sealing of the biofilter due to heavy snowfall can be prevented. The use of a roof, however, leads to an increase in investment expenses of approximately EUR 30,68 per m^2 of roof area.

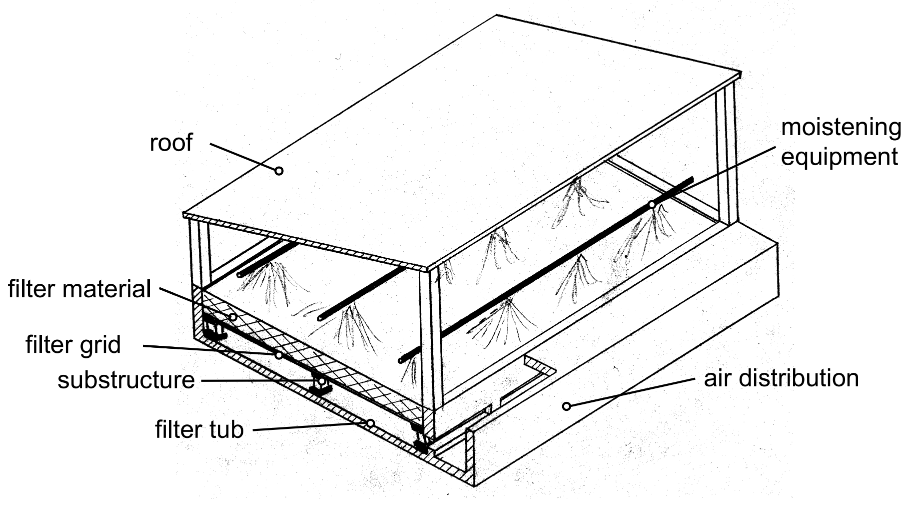

Figure 6: Diagram of a model biofilter for the reduction of odour from agricultural animal housing

Cost Estimation for Systems with Different Dimensioning/Designs

For the cost estimation of biofilters with different designs, a special Excel data sheet has been created into which the number of animals, the temperature zone (DIN 18910), the maximum filter volume load, the bulk height, the prices of the individual construction processes and -components, as well as electricity and water consumption/prices can be entered. These data enable the necessary filter area and -volume, as well as the resulting fixed cost to be calculated [4], [8]. When the electricity expenses caused by the operation of the individual model biofilter were calculated, a certain mean flow resistance of the filter material was attributed to the corresponding exhaust air volume flow or filter volume load using the data basis gained from the authors´ own investigations. The flow resistance of a central exhaust system estimated on the basis of empirical values was added to these figures. The electric power required by a fan for the generation of the exhaust air volume flow at the corresponding flow resistance of the entire system was determined using the software of a manufacturer of plastic fans (company Colasit AG, Spiez, Switzerland). For the calculation of the water cost, average water requirements of 2.3 $g \cdot m^{-3}$ of exhaust air were assumed. The individual constructional components can be taken out of the calculation of the investment expenses as required, or the expenses for the conditioning of the waster air (washer, dust filter) can be integrated.

The influence of the filter material and the specification of the individual model biofilter on the expenses to be expected is shown in **table 3**. The investment expenses for two different specification variants (standard and minimum) are listed for both filter materials (coconut fiber - fiber peat and biochips). The system with minimum specification does not feature an air distribution channel and a roof over the biofilter, and the filter grid was made of spruce wood. As compared with the standard specification, this allows approximately 39 or 35% of the investment cost to be saved. As compared with coconut fiber - fiber peat, the use of biochips requires approximately 9% higher investment expenses, which, given the fixed cost, is the equivalent of an additional amount of EUR 0.80 per fattening pig produced. However, the variable expenses caused by the use of biochips, which induce significantly lower flow resistance, allow savings of EUR 0.81 per fattening pig produced to be achieved. The total cost of the model biofilter with biochips will thus diminish by approximately EUR 0.02 or EUR 0.01 per fattening pig produced. As compared with data provided by the literature, the estimated total cost of the model biofilter (EUR 6.22 and EUR 8.36 per fattening pig produced) are within the range of the data of HARTUNG et al. (1997), who examined a biofilter designed for a filter volume load of 600 $m^3 \cdot m^{-3} \cdot h^{-1}$.

Biofilters in agricultural animal housing, however, can be designed for the two- to threefold filter volume load, i.e. 1,200 to 1,800 $m^3 \cdot m^{-3} \cdot h^{-1}$. In addition, coarse filter materials with a stable structure, such as biochips, allow a bulk height of 1 m to be realized.

Therefore, differently designed model biofilters filled with biochips (with standard specification) for an exemplary stall with 400 fattening pigs were compared with regard to their investment expenses (**figure 7**). By increasing the filter volume load from 600 to 1,600 $m^3 \cdot m^{-3} \cdot h^{-1}$ and the

Table 3: Influence of the filter material and the specification of a model biofilter on cost composition (stall with 400 fattening pigs, max. filter volume load 600 $m^3 \cdot m^{-3} \cdot h^{-1}$, bulk height 0.5 m, filter area: 112 m^2 / 6 x 18.7 m)

	coconut fibre – fibre peat		**biochips**	
	recommended specification	**minimum specification***	**recommended specification**	**minimum specification***
investment costs				
excavation [EUR]	1,812	1,812	1,812	1,812
base [EUR]	1,207	1,207	1,207	1,207
filter tub [EUR]	10,959	10,959	10,959	10,959
air distribution [EUR]	6,694	0	6,694	0
filter grid [EUR]	9,277	4,592	9,277	4,592
moistening [EUR]	1,861	1,861	1,861	1,861
roof [EUR]	3,922	0	3,922	0
fans [EUR]	2,556	2,556	2,556	2,556
filter material [EUR]	2,291	2,291	5,726	5,726
sum [EUR]	39,372	24,071	42,807	27,507
sum [EUR/m³ air handling capacity]	1.17	0.72	1.27	0.82
sum [EUR/fattening pig]	98.43	60.18	107.02	68.77
fixed costs				
sum [EUR]	6,135	3,840	6,994	4,699
sum [EUR/m³ air handling capacity]	0.18	0.11	0.21	0.14
sum [EUR/fattening pig]	5.68	3.55	6.48	4.35
variable costs				
electricity [EUR]	2,011	2,011	1,134	1,134
water [EUR]	696	696	696	696
maintenance [EUR]	184	184	184	184
sum [EUR]	2,891	2,891	2,014	2,014
sum [EUR/m³ air handling capacity]	0.09	0.09	0.06	0.06
sum [EUR/fattening pig]	2.68	2.68	1.87	1.87
total costs				
[EUR/year]	9,026	6,731	9,008	6,713
[EUR/m³ air handling capacity]	0.27	0.20	0.27	0.20
[EUR/fattening pig]	8.36	6.23	8.34	6.22

* without air distribution, substructure and lath grid out of spruce wood, without roof

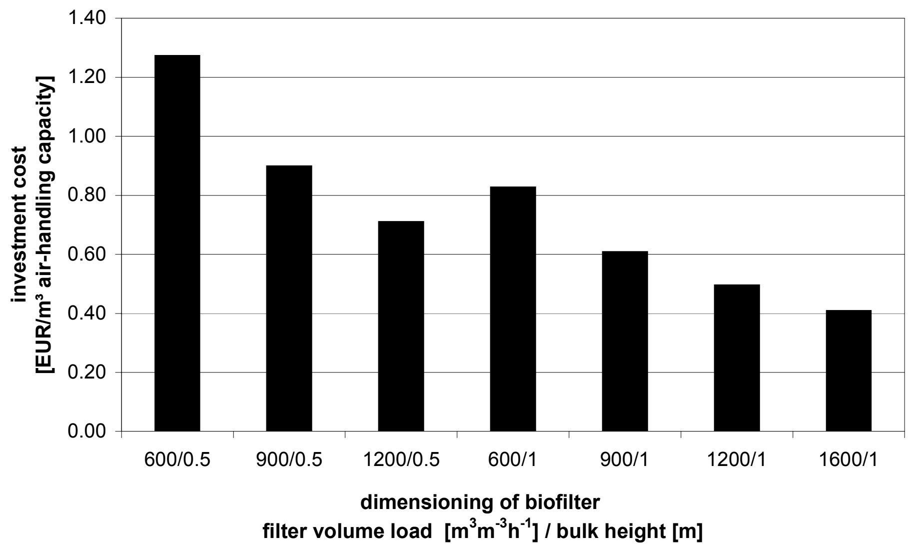

Figure 7: Investment cost of differently designed model biofilters (recommended specification), filled with biochips, for 400 fattening places

bulk height from 0.5 to 1 m, it was possible to reduce the area of the biofilter from 112 to 21 m^2. The investment expenses for a biofilter thus also diminished more than threefold (from 1.27 to 0.41 EUR/m^{-3} of installed air-handling capacity). The estimated investment expenses for the two highest load variants are below those determined by HARTUNG et al. [4] and HOPP [6]. If the filter were designed for a filter volume load of 600 $m^3 \cdot m^{-3} \cdot h^{-1}$ and a bulk height of 1 m, the investment expenses would increase as compared with the previous variant of 1,200 $m^3 \cdot m^{-3} \cdot h^{-1}$ and a height of 0.5 m because deeper excavation, higher filter tub walls, and twice the quantity of filter material would be required while the filter area would remain the same (56 m^2).

In addition to the investment expenses and the fixed cost, the variable expenses (in particular the electricity cost) are of interest (**figure 8**). An approximately 2.7-fold increase in the filter volume load allows the fixed cost to be reduced from about EUR 4.09 to EUR 2.05. Consequently, the flow resistance of the filter material grows as does, hence, the electricity cost, which is responsible for the increase in the variable expenses from about EUR 2 to EUR 3.6. The total cost diminishes with growing filter volume load. However, it reaches its minimum at approximately 1,100 to 1,200 $m^3 \cdot m^{-3} \cdot h^{-1}$ (about EUR 5.42). The given potential of the filter material, which is marked by high absorption and the microbial degradation rate and which would also allow for a higher filter volume load, cannot be fully exploited [4], [6].

If the design is optimal (filter volume load: 1,200 $m^3 \cdot m^{-3} \cdot h^{-1}$; bulk height: 1 m), only a small filter area of 28 m^2 (3 x 9.4 m) is required for the exhaust air from a stall with 400 fattening pigs. For this reason, the possibility of admitting the exhaust air to be cleaned on the smaller side of the filter directly below the filter grid and of dispensing with the air distribution channel exists. This allows the total expenses to be reduced to EUR 5.15 per fattening pig produced. If the model biofilter were operated with minimum specification, this would enable the total cost to be reduced by another EUR 0.16 or EUR 0.15 per fattening pig produced by cutting down on the expenses for the filter grid and the roof so that the total cost would amount to EUR 4.83 per fattening pig produced. This corresponds to investment expenses of EUR 12,963 or EUR 0.37/m^3 of installed air-handling capacity. The simple design of the model biofilter enables part of the work to be done by the farmer, which, according to calculations by HARTUNG et al. [4], would allow the investment cost to be reduced by approximately another 20%.

As expected, the investment expenses diminish with growing stall size and the number of fattening places from about EUR 0.66/m^3 of air-handling capacity (200 fattening places) to about EUR 0.38/m^3 of air-handling capacity (2,000 fattening places). However, the course of the function becomes ever flatter and is comparable with model calculations by SCOTFORD et al. [9].

Conclusions

With regard to odour reduction, it was possible to determine differences between the individual filter materials and designs in some cases. However, these differences must mainly be attributed to uneven moistening of the filter material. The use of a new filter material (biochips) allows the same odour reduction to be achieved as the coconut fiber - fiber peat mixture often used in practice. However, the filter material significantly influences the flow resistance of the biofilter and, hence, the variable cost (electricity expenses). When planning a biofilter, one must attach importance to an optimal relation of dimensioning and the total cost of the biofilter. Further investigations should examine what operating times can be reached by using biofilters with coarsely structured filter material such as biochips without significant deterioration of odour reduction.

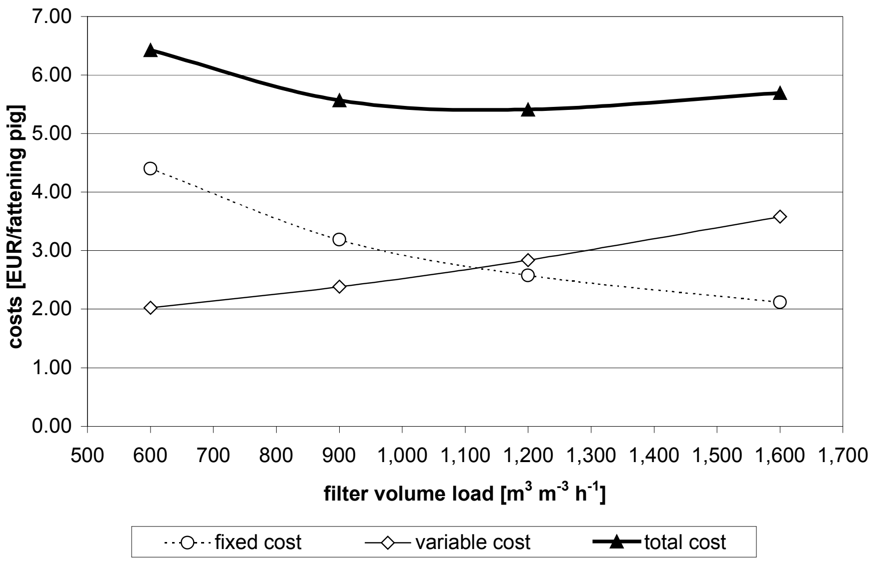

Figure 8: Cost development as a function of the filter volume load of a model biofilter with standard specification for 400 fattening places, filled with 1 m of biochips

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