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Solid Biofuel Production by Mechanical Pre-Treatment of Brewers' Spent Grain

Andreas Weger[a]*, Samir Binder[a], Matthias Franke[a], Andreas Hornung[a,b], Winfried Ruß[c], Wolfgang Mayer[d]

[a] Fraunhofer UMSICHT – Institute branch Sulzbach-Rosenberg, An der Maxhütte 1, 92237 Sulzbach-Rosenberg
[b] Director of the European Bioenergy Research Institute - EBRI, School of Engineering & Applied Science, Aston University, B4 7ET Birmingham, England, UK
[c] Hochschule Weihenstephan-Triesdorf, Weihenstephaner Berg 4, 85354 Freising
[d] Technische Universität München, Lehrstuhl für Rohstoff- und Energietechnologie, Petersgasse 18, 94315 Straubing
andreas.weger@umsicht.fraunhofer.de

The brewing industry produces large amounts of by-products and wastes like brewers' spent grain (BSG). In Germany, each year approximately 2.1 million tonnes of BSG are generated. During the last years conventional routes of BSG utilization face a remarkable change, such as the decline in the demand as animal feed. Due to its high content of organic matter energetic utilization may create an additional economic value for breweries. Furthermore, in the recent past breweries tend to shift their energy supply towards more sustainable concepts. Although, a decent number of research projects were carried out already, still no mature strategy is available. However, one possible solution can be the mechanical pre-treatment of BSG. This step allows optimized energy utilization by the fractionation of BSG. Due to the transfer of digestible components, such as protein, to the liquid phase, the solid phase will largely consist of combustible components. That represents an opportunity to produce a solid biofuel with lower fuel-nitrogen content compared to only thermal dried BSG. Therefore, two main purposes for the mechanical pre-treatment were determined, (1) to reduce the moisture content to at least 60 % (w/w) and (2) to diminish the protein content of the solid phase by 30 %. Moreover, the combustion trials should demonstrate whether stable processes and flue gas emissions within the legal limits in Germany are feasible. The results of the mechanical pre-treatment trials showed that a decrease of the moisture and protein content has been achieved. With regard to the combustion trials inconsistent outcomes were found. On the one hand a stable combustion was realized. On the other hand the legal emission levels of NO_x (500 mg·m^{-3}) and dust (50 mg·m^{-3}) could not be kept during all trials. The further research steps will focus on the optimization of the air/fuel ratio by reducing the primary and secondary air conditions.

1. Introduction

The brewing industry produces large amounts of by-products and wastes, such as BSG which represents with nearly 85 % the biggest part of the total by-products (Mussatto et al., 2006). Due to its high protein and fibre content BSG is predominantly used as animal feed (mainly for cattle) (Russ et al., 2005). However, due to its high humidity (> 70 % w/w) and fermentable sugar content (Santos et al., 2003) the biological stability and consequently the transport distances around breweries are restricted. Within three days (during summertime even shorter) BSG deteriorate because of microbial activity and cannot be used anymore as animal feed (Russ et al., 2005). Moreover, the number of cattle in Germany decreases for many years which finally led to a decreasing demand for BSG (Russ et al., 2005). According to German legislation the disposal of BSG without further treatment is no longer possible after 2005. To address this challenge a decent number of research projects were performed to identify innovative utilization strategies for BSG.

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Since BSG is available throughout the whole year at low or no costs directly at breweries site especially the energetic usage aroused the interest of breweries. The potential of BSG can be estimated by 20 kg fresh mass (FM) per 100 litre produced beer (Mussatto et al., 2006). In Germany the beer production is around 10.5 billion litre which is equivalent to approximately 2.1 million tonnes of BSG annually (Mussatto et al., 2006). Furthermore, breweries tend to shift their energy supply towards 100 % renewable resources for economical and ecological reasons. An example of these efforts is the “Green Brewery” concept which aims at energy efficiency increase and use of renewable energy sources in breweries (Muster-Slawitsch et al., 2010). Although, BSG covers just a maximum of up to 20 % of breweries energy demand, its energetic usage can be an incentive for breweries to cover their energy demand with up to 100 % biomass.

Therefore, several concepts for the energetic usage were investigated in the last 20 years but mostly limited either to digestion or combustion. However, both pathways are facing different problems which need to be considered. For instance, the high fibre content makes digestion without pre-treatment difficult. According to the literature, anaerobic digestion of BSG is only efficient if it is separated into a hydrolytic and a methanogenic step (Mussatto et al., 2006). In addition to digestion and combustion, alternative fermentation strategies were investigated as well (e.g. bioethanol production from BSG by acid pretreatment) (Caetano et al., 2013).

At breweries sites, crude BSG accumulate with 80 % moisture and a gross calorific value of 2 $MJ \cdot kg^{-1}$ FM, calculated with a gross calorific value of around 20 $MJ \cdot kg^{-1}$ total solid (TS). But for combustion a minimum of ≤ 55 % moisture is needed (Meyer-Pittroff, 1988). One option to decrease moisture to at least 50 % is thermal drying, but nearly 60 % of fresh mass must be vaporized. Regarding the vaporization enthalpy of water 2.45 $MJ \cdot kg^{-1}$, the energy demand for 1 kg BSG accounts for 1.47 MJ. Calculating energy losses due to exhaust gas heat and heating up BSG the total energy consumption is nearly 2 MJ. This example shows that thermal drying makes no sense from energetic points of view (Kepplinger, 2008). Beside the aforementioned problem, the protein and ash content of BSG are critical during combustion, because of arising NO_x and dust emissions (Meyer-Pittroff, 1988).

Despite the studies and results discussed above, no mature strategy is available to use BSG as renewable energy resource in breweries. In that context, the mechanical pre-treatment of BSG represents a further alternative and promising approach which offers the opportunity to produce a solid biofuel with lower fuel-nitrogen content compared to only thermal dried BSG. Although, mechanical pre-treatment processes are considered to be expensive steps with a high energy demand, a screw press represents an energy-efficient exception among mechanical pre-treatment options to dewater biomass (Yan and Modigell, 2012).

2. Process concept

The main element of the concept is a combination of mechanical, biological and thermal processes. In the first step, the mechanical pre-treatment has been realized by a screw press which splits the BSG into a liquid and solid phase to obtain a chemical fractionation. Components which are better suited for digestion, such as protein and fat are transferred mainly to the liquid phase. Cellulose, hemicellulose and lignin which are better suited for combustion remain mostly in the solid phase.

Given the proper prerequisites, the solid phase can be directly co-fired with wood chips without further thermal drying. One major advantage of this method is the simultaneous reduction of the protein content and thus the fuel nitrogen content in contrast to a simple thermal dried BSG. The chemical composition of BSG and the optimal energetic usage is shown by Figure 1.

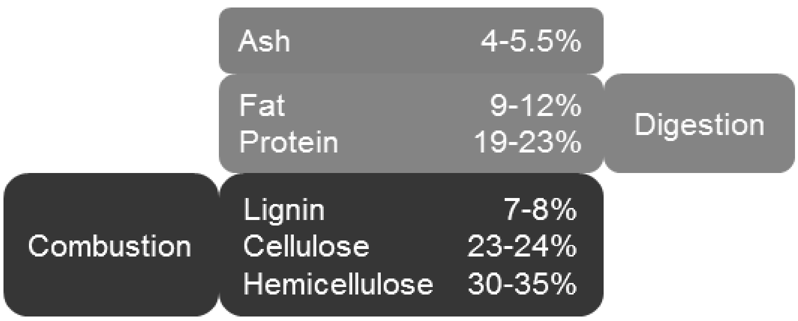

Figure 1: Chemical composition of BSG and optimal energetic usage (modified after Russ et al., 2005)

The overarching goal of the study was the optimization of the energetic use of BSG. Hence, the main purposes of the mechanical pre-treatment trials were (1) to reduce the moisture content from 80 % to at least 60 % (w/w) and (2) to diminish the protein content of the solid phase by 30 %. Furthermore, a throughput ≥ 40 $kg \cdot h^{-1}$ is required for cost effectiveness. In terms of the combustion trials stable conditions and the occurring flue gas emissions as well as the legal emission levels in Germany were the main aspects of interest.

3. Material and methods

3.1 Analysis

The crude BSG has always been analysed together with the solid and liquid phase as reference before the mechanical pre-treatment trials were conducted. TS content of all samples were continuously analysed according to relevant domestic industry standards (DIN EN 12880, 2001). The protein, fat and fibre content was analysed in a certified external laboratory according to state of the art methods.

The gross caloric value and the elementary composition of the solid phase was analysed at a certified external laboratory according to relevant domestic industry standards (DIN 51900-1, 2000; DIN EN 15104, 2011). The flue gas emissions (NO_x, CO, CO_2, etc.) were continuously measured during all combustion trials using a gas-analysing system which is accredited according to German emission control regulations. Dust particles were measured according to standard methods.

3.2 Experimental setup

The mechanical pre-treatment was performed with a screw press (Harburg-Freudenberger, TP 100) which original application was the oil extraction from oilseeds with a throughput of 150 $kg \cdot h^{-1}$. One key parameter to optimise and adapt it to BSG was the screw channel geometry. Therefore, several trial series with and without adding dewatering substances, such as enzymes, were carried out. The combustion trials were conducted by means of a furnace with ridge grate with an installed thermal power of 30 kilowatt (kW). The injection of the combustion air took place via the primary and secondary air. This enables an optimised setting of the air/fuel ratio during the trials.

4. Results

4.1 Mechanical pre-treatment trials

Several mechanical pre-treatment trials with different screw channel geometries were performed to meet the two main purposes mentioned above. Figure 2 shows the results of the trials with the optimized screw press configuration.

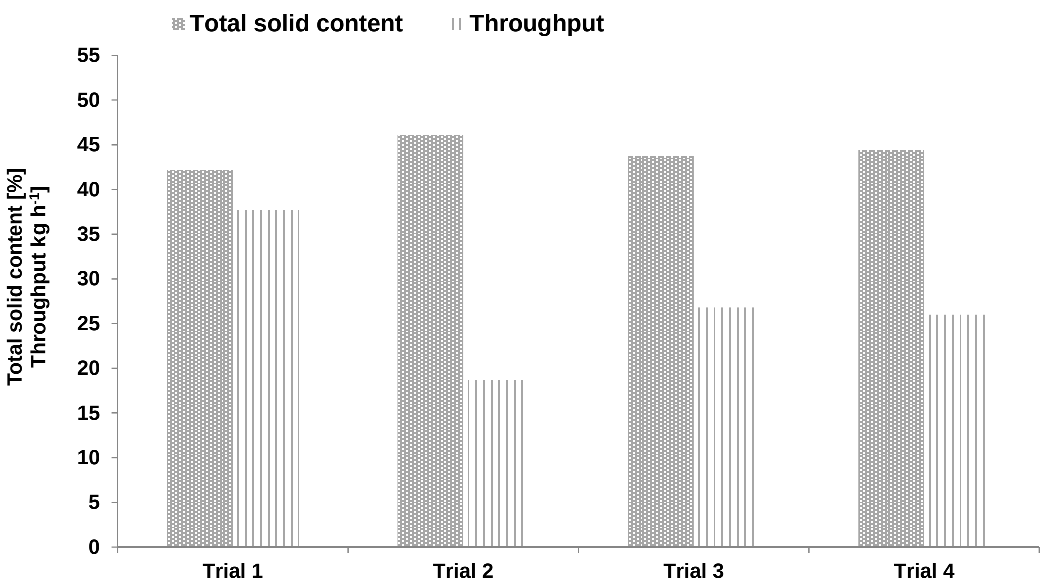

Figure 2: TS content and throughput of mechanical pre-treated BSG

During the mechanical pre-treatment trials, the TS content of the solid phases ranged between 42.2 and 46.1 %. The calculated standard deviation of 1.4 % showed almost stable conditions. The estimated benchmark to reduce the moisture content from 80 % to a minimum of at least 60 % (w/w) was achieved successfully.
However, the throughput benchmark of 40 $kg \cdot h^{-1}$ has not been obtained and values between just 18.7 and 37.7 $kg \cdot h^{-1}$ were generated. This was mainly caused by blockages inside the screw press. An evidence for this presumption was the relatively high electrical energy demand of 2.0 kW which was nearly 35 % higher than in similar trials. The second important goal, the reduction of the protein content of the solid phase by 30 % was accomplished, too. Analysis showed that around 55 % of the protein content was transferred to the liquid phase.
The configuration was additionally used to investigate the influence of two enzymes on the mechanical pre-treatment. The crude BSG was picked from a brewery, treated enzymatically and after an exposure time of two hours mechanically treated. Hence, to increase the practical relevance, a short exposure time was necessary to avoid storage capacities. However, fresh BSG from lauter tun still has high temperatures of about 60 °C, which may affect the efficiency of the enzymes.
To compare the different trials, a steady amount of 25 kg crude BSG was used in all trials. The dosed amount of enzyme corresponding to 1 % (high) and respectively 0.01 % (low) were calculated by the total solid mass of the crude BSG (4.5 kgTS). If the trial duration was less than one hour, the results were extrapolated up to one hour. Figure 3 shows the results of enzymatic and mechanical pre-treated BSG.

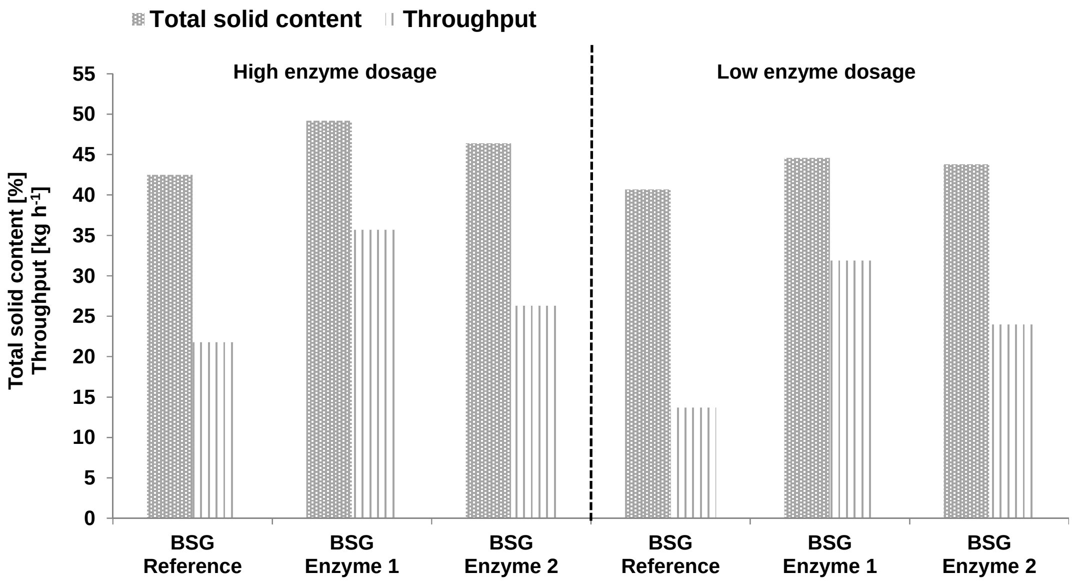

Figure 3: TS content and throughput of enzymatic and mechanical pre-treated BSG

The reference trial with enzymatic untreated BSG gave a TS content of 42.5 % with 21.8 $kg \cdot h^{-1}$ throughput. In contrast, a significant increase in the mechanical pre-treatment performance was obtained by the high enzyme dosage. The TS content increased up to 49.2 % with enzyme (1), the throughput nearly doubled up to 35.7 $kg \cdot h^{-1}$. At the same time, enzyme (2) showed a TS content increase up to 46.4 %, but not as significant as enzyme (1). The throughput of 26.3 $kg \cdot h^{-1}$ was lower compared to enzyme (1), but still higher than the reference value.
The trials were repeated with low enzyme dosage. Initially, enzymatic untreated BSG was mechanically pre-treated but compared to the previous reference trial, the throughput decreased to 13.7 $kg \cdot h^{-1}$. The results confirmed a high variance in the measured throughput performances. Nevertheless, the enzymatic treatment showed again a positive effect. With regard to the energy demand of the screw press, no significant difference was measured compared to the trials without enzymes.
Interestingly, the protein transfer to the liquid phase was similar to enzymatic untreated BSG. The values of the high and low dosage for both enzymes were around 50-60 %. One reason for the improved throughput may be that the lignocellulosic structure was affected by the enzymes leading to a higher transfer of bounded water by mechanical pre-treatment.

4.2 Combustion trials

In front of the combustion trials the solid phase was mixed with wood chips and stored one day to achieve a proper homogenisation and distribution of the humidity. The two main aspects were stable conditions during the combustion and to evaluate whether the emissions fulfil the regulatory frameworks in Germany. Firstly, an elementary and gross calorific value analysis of the solid phase was performed (Table 1).

Table 1: Result of the elementary analysis and gross calorific value analysis

Parameter	Gross Calorific Value [$MJ \cdot kg^{-1}TS$]	C [%TS]	H [%TS]	N [%TS]
Solid phase	19.6	50.4	6.51	2.45

The measured gross calorific value of 19.6 $MJ \cdot kg^{-1}TS$ corresponds exactly to the literature value of 19.9 $MJ \cdot kg^{-1}TS$ for BSG (Kepplinger, 2008). The TS content of the wood chips was 95 % with a gross calorific value of 19.0 $MJ \cdot kg^{-1}TS$. The defined mass ratio of solid phase and wood chips during all combustion trials was 50:50 mass.-%. Figure 4 shows the carbon monoxide (CO), nitrogen oxides (NO_x) and dust emissions of the combustion trials, all values were calculated according to standard conditions.

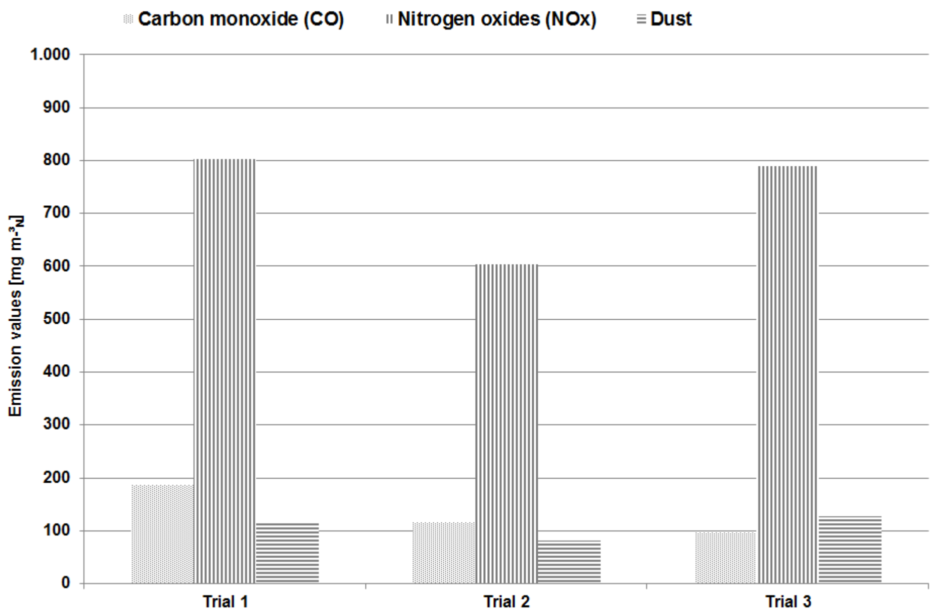

Figure 4: CO, NO_x and dust emissions of the combustion trials

All trials showed stable combustion conditions indicated by low carbon monoxide emissions which were always below the limit value of 250 milligrams per cubic metre ($mg \cdot m^{-3}$) according to German emission legislation. Nevertheless, the limit values of 500 $mg \cdot m^{-3}$ (NO_x) and 50 $mg \cdot m^{-3}$ (dust) could not be reached yet during all trials.

In general, the higher emission level of trial (1) primarily arises due to the different particle size of wood chips and the solid phase. This led to segregation inside the feeding press of the combustion plant. This resulted in concentration peaks due to unsteady feeding conditions. To avoid this, the wood chips were chopped up into smaller particles during trial (2) and (3). After this the number of concentration peaks reduced significantly. Moreover, both trials run more stable indicated by lower carbon monoxide amounts (97-116 $mg \cdot m^{-3}$). In terms of the NO_x emissions, a decrease of around 25% to 604 $mg \cdot m^{-3}$ was obtained in trial (2), but during trial (3) the NO_x emissions were again up to 789 $mg \cdot m^{-3}$. One explanation could be the lower protein transfer rate during the mechanical pre-treatment step and thus a higher fuel-nitrogen content of the co-fired solid phase.

Altogether, stable combustion conditions for the co-firing of the solid phase combined with wood chips was demonstrated. However, the amount of NO_x is still too high and needs reduced further efforts in reduction. This is important to avoid the installation of a flue gas cleaning system which increases costs. One next step to decrease the NO_x emissions will be to optimize the air/fuel ratio during combustion by reducing the primary and secondary air conditions.

5. Conclusions

To date, the heat supply of breweries mostly depends on fossil fuels. Introducing a mechanical pre-treatment of BSG could help to realize 100 % sustainable energy concepts for breweries. The advantage of this concept is the biochemical fractionation which offers the opportunity of an optimized energetic usage. By mechanical pre-treatment of BSG a liquid phase and solid phase is produced. The solid phase has lower fuel-nitrogen content due to the protein transfer to the liquid phase. Moreover, given the proper prerequisites, the solid phase can be directly incinerated with wood chips without further drying. The liquid phase could be fermented together with brewery waste water and create an additional economic value. It can be concluded, that the utilisation of BSG is efficient from an economic point of view if other renewable energy sources, such as wood chips are used. However, the utilisation of BSG can be seen as incentive to completely cover a breweries energy demand up to 100 % with biomass.

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