Conversion of water plants to biomass fuel using torwash

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CONVERSION OF WATER PLANTS TO BIOMASS FUEL USING TORWASH

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ABSTRACT

Invasive water plants are harvested in The Netherlands in order to keep waterways open. It is expected that due to improved water quality the growth of these water plants will increase significantly. Waternet, the watercycle company of Amsterdam and surrounding areas, wishes to turn this material into useful products. One of the investigated options was TORWASH, a technology under development by ECN for converting wet, salt-containing biomass into clean solid biofuel suitable for energy production, e.g. by co-firing in power plants.

Elodea nuttalii and *Cabomba caroliniana* were harvested and directly processed. Samples were chopped into a slurry and then subjected to TORWASH conditions. The resulting product was filtered and pressed into disks. All inputs and outputs were weighed and analysed to make mass balances and to determine the fate of key elements like potassium, chlorine, nitrogen and phosphorus. The pressed disks were assessed for their suitability as solid biomass fuel.

Both water plants are suitable feedstock for the TORWASH process. Chopping turns these plants into a slurry with 90% water and reduces the volume by a factor of four. Chopping and milling when applied onsite will therefore result in substantial lower transport costs. The slurry has the right consistency to be introduced into the TORWASH reactor. No addition of water is needed. After wet torrefaction the slurry can be mechanically dewatered to a level of more than 70% dry matter. The dewatered solids are suitable for direct combustion in a fluidized bed system. Alkali and chlorine content are in the same order as fresh wood chips. For applications in co-firing in a pulverized fuel plant, additional drying and probably an extra washing of the product is needed to further remove alkaline and chloride.

It is recommended to investigate how sand and other inert ash-forming constituents can be removed. To make the fuel comparable to clean wood pellets, an extra washing to remove alkali and chloride may need to be included.

Keywords: cofiring, advanced fuel, solid biomass fuels, wet torrefaction, TORWASH, hydrothermal conversion, water plants

1 INTRODUCTION

Biomass is expected to play a major role in the transition to sustainable energy production worldwide. It is anticipated that in 2050 biomass could supply up to 30% of the total global energy consumption [1]. Most of the energy will be produced via thermal conversion processes (combustion, gasification). The biomass used will be a combination of biomass residues, various blends of low-grade biomass, waste and cultivated energy crops [2].

1.1 Waterplants and Waternet

Invasive water plants are harvested in The Netherlands in order to keep waterways open. Dutch Waterboards have been working on the reduction of eutrophication [3,4]. Water has become clearer, light can reach the bottom where plants are growing while nutrients in water and soil are still available. It is expected that the growth and nuisance of these water plants will therefore increase significantly [5].

Waternet, the water cycle company of Amsterdam and surrounding areas, is one of the Dutch water authorities confronted with the excessive growth of invasive water plants. Increasing growth of invasive water plants interferes with recreation, agriculture, water management and even commercial shipping [6]. It is also in conflict with the European Water Framework Directive [7] as dominance of invasive species is undesired. These water plants, mainly *Elodea nuttallii* (in English: water weed, in Dutch: waterpest) and *Cabomba caroliniana* (Eng. Fanwort), have been introduced in the late 19th century, but in recent years they show excessive growth Waternet wishes to turn harvested water plants into useful products to support the bio-based- and circular economy.

Several technologies for sustainable use of the harvested water plants are investigated by Waternet. A suitable technology should be able to cope with the intermittent availability of the water plants and preferably be mobile. Water plants are only harvested in summer and quantities vary significantly from year to year. Any installation should have the option to process other feedstock so that it can be used when fresh water plants are not available. One of the techno1ogies investigated that may meet these requirements was TORWASH.

1.2 TORWASH technology

ECN has developed TORWASH technology for the upgrading of unattractive, wet low-grade biomass feedstocks (e.g. grass) into high-grade solid fuel of quality suitable for co-firing [8]. TORWASH combines torrefaction of biomass with washing. Water plants are a new potential feedstock.. Other suitable feedstocks are grass, straw, agro-residues and other similar forms of biomass that cannot be used directly as a fuel. Practical problems when using these feedstocks include:

- High transportation costs due to low bulk density and high water content.

- Corrosion, slagging and fouling in the boiler or on heat exchanger tubes due to high salt concentration, in particular KCl.
- Low net energy production due to high moisture content.
- Biological degradation during storage.
- Seasonal harvest.
- Difficulties with milling and (pneumatic) feeding.

After TORWASH, there are two products. The primary product is solid biofuel, the secondary product is biogas. The solid fuel that is equivalent to clean torrefied wood pellets:
- High bulk density
- Low salt levels
- No biological degradation
- Easy milling and feeding

Salt removal of 98% or better has been demonstrated, turning feedstock with 1% chlorine into fuel with 200 mg/kg (d.b.) which is the requirement for ENplus A1 pellets. The fuel has a caloric value of 20-22 MJ/kg (High Heating Value = HHV, dry basis), which is between wood and dry torrefied wood. Mechanical dewatering of the product yields solids with only 30-40% moisture. Hard pellets can be made without addition of a binder. They are suitable for combustion in pulverized-fuel burners and the milling of the pellets shows relatively low energy consumption. [9,10].

Biogas, the secondary product, is made by digesting TORWASH effluent, produced at various stages in the mechanical dewatering (pre-wash, TORWASH or post-wash). The produced biogas can be used in a combined heat and power (CHP) plant. The waste heat from a CHP is enough to supply the heat needed for the thermal treatment [9]. The biogas may be also upgraded for use in the natural gas grid.

TORWASH is complementary to dry torrefaction since it aims at feedstock with high moisture and high salt content. In recent years, TORWASH has been successfully applied on lab-scale to:
- Grass, hay, straw and reeds
- Wet agro-residues, incl. wet by-products from food industry, digestate and fermentation residues

TORWASH has the potential to be the basis of a process to turn mowed grass into fuel pellets and biogas, both as a stand-alone installation and when integrated with waste-water treatment [9].

TORWASH is a hydrothermal treatment in which biomass is treated in liquid water at elevated pressure between 150 and 230°C. The heat treatment partly decomposes the biomass structure: hemicellulose is largely dissolved, cellulose is degraded to a small extent, just enough to make the fibres brittle. The overall effect is that the material becomes brittle, easy to mill and easy to dewater. At the same time, various mineral components are dislodged from the biomass structure and dissolve into the water. When the biomass is dewatered these dissolved components are removed as well. The result is demineralized and dewatered fuel of high quality that can be used in energy production.

The level of structural degradation and dissolution of minerals depends on the process temperature and the residence time. These conditions are critical: too low temperature or too short exposure means that the biomass is still tenacious and not so easy to dewater. Water (with minerals) is retained in the fibres. Too high temperature or too long exposure may cause too much decomposition of the structure and biomass becomes a viscous gel that is also not easy to dewater.

1.3 Other options under investigation by Waternet

Waternet is looking for sustainable solutions that contribute to an economy which is no longer based on fossil resources, the biobased economy. Furthermore Waternet focusses on solutions that move away from the linear economic model towards a circular economy, where finite resources are not depleted. With this in mind research is conducted to find the best way to harvest and process water plants.

An important aspect is reduction of required transport and storage of the harvested plants, as it is expected that considerable volumes can be produced. Currently the harvested water plant are left to decompose on the waterside or they are composted evoking considerable costs. Decomposition can result in methane emissions and washout of nutrients to soil and surface water. Furthermore composting is not considered the most sustainable form of reuse.

The options under investigation can be separated in pre-processing and processing steps. Pre-processing steps are chopping, on land drying, silage, pelleting and draining. Processing steps are composting, animal feed digestion, bio-composites, (on site) pyrolysis and TORWASH.

1.4 Objective of this study

The main objective of this study is to investigate whether the advantages of the TORWASH technology – as established for grass, etc. – can be obtained for water plants as well, in particular applied to water plants Elodea and Cabomba. The secondary objective is to compare TORWASH with other ways of processing water plants

Specific objectives are to investigate the effects of the thermal treatment on density, solids yield and the distribution of elements. The solids are investigated for their potential as biomass fuel based on water content, ash content, calorific value and chemical composition (salts).

Additionally, the effect of the treatment on the distribution of nutrients over the solid- and water phase (in particular N, P and K) is determined to assess the potential use of the liquid as fertilizer.

2 EXPERIMENTAL

Elodea and Cabomba were harvested on site and immediately transferred to ECN for processing. Samples were first chopped and extruded deploying standard household kitchen appliances in order to make a uniform and fluid slurry. **Error! Reference source not found.**s 1 and 2 demonstrate the physical change of this treatment.

The slurry was subjected to TORWASH in an autoclave in order to establish suitable temperature and exposure time. The autoclave used for testing was a Buchi Glasuster with heated and cooled vessels of variable size. In TORWASH tests, the vessels are filled for 80% and then closed. The contents are only stirred and heated to temperatures in the range of 150-250°C. The pressure is not controlled, but it is slightly above steam pressure. After the test, the contents are cooled down before the vessel is opened. A photograph of the 0.5 L autoclave vessel is presented in Figure 3. Initial tests showed that the best results were obtained when TORWASH was performed at 190°C for a duration of 30 minutes.

Figure 1: Fresh water plants

Figure 2: Chopped water plants

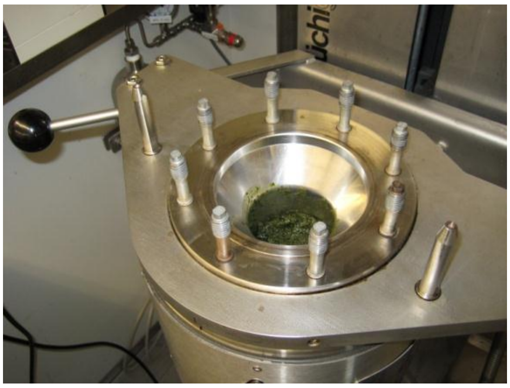

Figure 1: Autoclave vessel used for TORWASH

Larger TORWASH tests in the 20 L vessel of the autoclave were performed at the optimal conditions. After the heat treatment, the TORWASHed material was mechanically dewatered by pressing a volume of slurry into a disk. For these press tests, a Carver Die (2¼ inch) was used in a lab-scale unidirectional press at 150 bar mechanical pressure. Similar disks were pressed from fresh and chopped material in order to observe the effect of the heat treatment.

All inputs and outputs of the autoclave TORWASH operations were weighed to make overall mass balances and to determine yields. The dry matter content of all input and outputs is determined by overnight drying at 105°C. Samples of the original material, the input slurry, the output slurry, filtrate and pressed disks were analysed for fuel characteristics and elemental composition. The following analyses have been done:

- Density
- Dry matter content
- Mass yield
- Acidity of slurry
- Proximate and ultimate analyses
- Ash (elemental) analyses

The pressed disks were assessed for their suitability as solid biomass fuel. A comparison was made with wood chips and (subbituminous) coal. The fate of key elements like chlorine, potassium, nitrogen and phosphorus was determined as well.

3 TORWASH RESULTS

3.1 Mass yields in 0.5 L autoclave tests

The mass yield is defined as the amount of solids material recovered after TORWASH and pressing. It depends on the amount of material that has been dissolved and the efficiency of the mechanical dewatering. The influence of the TORWASH temperature on the mass yield is presented in Figure 4. With increasing temperature, the mass yield decreases since more material is dissolved.

The dissolution of solid matter involves both water soluble salts and organic matter that is formed as a result of the partial decomposition of the organic matrix. Elodea gives higher yields than Cabomba at all investigated temperatures. This is likely due to the amount of non-soluble ash-forming components, which is much higher in Elodea. It is less likely that the organic matrix is significantly more stable.

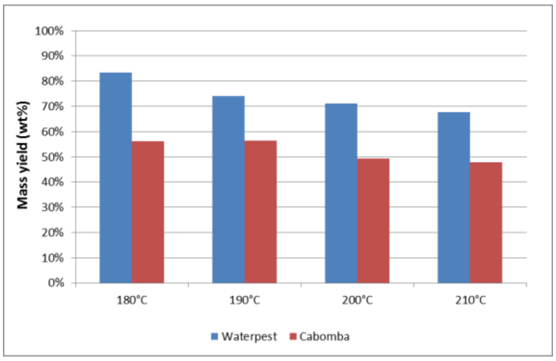

Figure 4: Mass yield after TORWASH at different temperatures in 0.5 L autoclave vessel

It is primarily hemicellulose that decomposes and dissolves during TORWASH. The products that are formed include carbon dioxide and organic acids, e.g. light carboxylic acids like acetic acid, that lower the pH of the solution. In the case of Cabomba the slurry that is formed during TORWASH has a pH of ~4.5. For Elodea, the pH is higher: 5.5 – 6.0. It is tempting to attribute the lower pH to the fact that less solids have been dissolved, but this cannot be the only explanation. It is assumed that the high Ca content of Elodea is buffering the solution and binding organic acids.

The yields of the small autoclave tests and the visual observations with respect to speed of filtering and dewatering (not reported) were used to select 190°C as the optimal TORWASH temperature to perform larger tests in a 20 L autoclave that gave larger samples and more reliable results. In the sections below all results relate to the 20 L autoclave tests using Elodea and Cabomba.

3.2 Dry matter content

The fresh water plants have a water content of about 90%, which means that after chopping, no additional water was needed to make it into a fluid slurry that can be used in a TORWASH reactor.

The heat treatment during TORWASH dissolves part of the solids and hence decreases the dry matter content from 10% to 5-8%, depending on time and temperature. Pressing after TORWASHing raises the dry matter content substantially. High dry matter contents of about 75% are obtained after pressing of the slurry.

In Figure 5, the measured dry matter contents are presented of fresh and chopped material as well as disks pressed from these materials and from TORWASHed material. It can be seen that pressing of fresh or TORWASHed material can result in higher solid matter contents. Also, it becomes clear that chopping does not improve the results of pressing. Elodea behaves somewhat different from Cabomba. In the case of Elodea the dry matter content is substantially higher after pressing the slurry before TORWASH. For Cabomba the increase in dry matter content is much smaller. This may be due to differences in the tenacity of the plants or it may be due to the presence of sand.

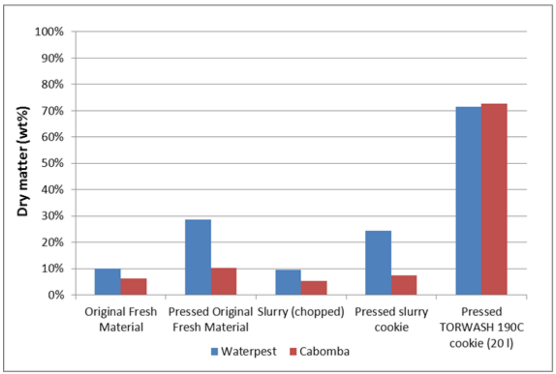

Figure 5: Dry matter content after different processing steps

During the TORWASH operation the structure of the biomass is degraded in such a way that it loses most of its elasticity, but still maintains enough structure to keep small channels open in the filter cake so that water can keep flowing. The nature of the components that clog the filter is unclear but they appear to be resulting from the TORWASH rather than original unconverted plant matter. As a result of these structural changes compression of the biomass is easier and faster compared to the untreated biomass slurry, which are very difficult to dewater mechanically as filters block almost immediately. TORWASH also changes the feedstock in such a way that it does not re-bounce after compression, once the pressure is released. The overall effect is that the dry matter content of the pressed TORWASHed disk is over 70%.

For Cabomba, TORWASH treatment means that 98.6% of the water that was present in the Cabomba slurry has been mechanically removed. From the Elodea slurry, 96.7% of water has been mechanically removed.

3.3 Density

Harvested water plants have a low density. The compression of the plants increases the density as it eliminates voids. This directly improves logistics of the harvested plants, since less volume is needed to transport certain amounts of biomass. The density of biomass after compression depends on the tenacity of the material, its particle size, the applied pressure and the duration of the pressing. In the TORWASH process the structure of the material is degraded so that the elasticity decreases. In this way it is much easier to maintain high density biomass after the compression.

The measured bulk densities, based on wet material, are presented in Figure 6. The fresh material has a density of about 0.2 kg/dm^3, which can be increased to about 0.8 kg/dm^3 by chopping only. Both have 90% moisture content or more. After TORWASHing and pressing, the bulk density slightly increases to about 0.9 kg/dm^3, but the material contains only 25% moisture.

The densification of Elodea, from fresh to TORWASHed is about 3.7 times; for Cabomba 4.5 times. Based on solid content, the increase is about 8 times more. This can be attributed to the chemical changes during the TORWASH operation, which enables water removal and decreases the elasticity of the material. When these results are combined with the solid matter contents, the density in terms of solid matter per volume are even higher; a combined densification of solids by a factor 25 in the case of Elodea and about a factor 40 for Cabomba.

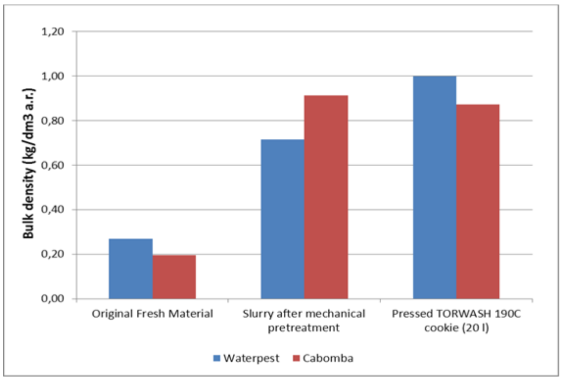

Figure 6: Bulk density of fresh, chopped and TORWASHed material

3.4 Assessment of fuel quality

Samples from the experiments with Elodea and Cabomba in the 20 L autoclave were used to perform proximate and ultimate analysis on the discs assessing their fuel quality. The parameters of the proximate analysis are moisture, volatile matter (VM), ash, and fixed carbon as well as the higher heating value (HHV). The elemental or ultimate analysis encompasses the quantitative determination of carbon, hydrogen, nitrogen, oxygen and sulphur within the fuel. The values for Elodea and Cabomba, both fresh and after TORWASH + compression are presented in Table 1 with the corresponding values for wood chips from thinning and subbituminous coals for comparison. All values are weight percentage on dry basis (w/w d.b., except moisture which is weight percentage as received (w/w a.r.).

It is clear that the fresh plant material is too wet to be used as a fuel directly. Pressed discs, after TORWASH, have a moisture content of ~25%. It can be used as a fuel in this condition, although lower moisture contents are obviously preferred.

The ash contents of the discs are quite high: 22% for Cabomba and as much as 47% for Elodea (measured at 550°C). The large difference between ash content measured at 550°C and 815°C for Elodea indicates a high amount of carbonates in the fuel ash, likely due to the highly calciferous ash matrix (*vide infra*). The calorific value (High Heating Value) of TORWASHed Cabomba is comparable to the HHV of wood chips. The HHV of TORWASHed Elodea is substantially lower, which is caused by the high ash content.

In both TORWASHed water plants, the nitrogen content is ~2%, which is slightly lower than in the fresh material. The levels are above the typical numbers of woody biomass fuel, but within the acceptable limits for coals. The sulphur contents are comparable to those of coals and well within acceptable limits. Volatile matter and the values for carbon, hydrogen and oxygen are as expected for high-ash biomass and still much higher than for the reference coal..

Table 1: Ultimate and Proximate analyses of water plants fresh and after being pressed into a disc following TORWASH, with values for Wood chips (thinning wood) and subbituminous coal for comparison

	moisture (105°C)	**ash (550°C)**	**ash (815°C)**	**volatile matter**	**HHV**	**C**	**H**	**N**	**O**	**S**
	% w/w a.r.	% w/w d.b.	% w/w d.b.	% w/w d.b.	MJ/kg	% w/w d.b.				
Cabomba, fresh	94	17	16	64.7	15.6	39.2	5.25	2.9	37.8	0.30
Cabomba, disc	29	22	21	59.6	17.7	42.6	4.85	2.2	29.3	0.30
Elodea, fresh	89	40	27	54.1	10.9	31.2	3.85	2.3	36.2	0.26
Elodea, disc	27	47	33	42.5	11.3	32.5	3.35	1.8	31.3	0.19
Thinning wood (chips)	8.2	2.6	2.1	79.0	19.2	48.2	6.5	0.5	43.7	0.04
Subbituminous coal	10	6.6	6.2	42.0	26.4	67.9	5.0	1.0	23.9	0.33

Table 2: Ash-forming elements (in mg/kg dry base) of water plants fresh and after pressed into a disc after TORWASH, with values for Wood chips (thinning wood) and subbituminous coal for comparison; < d.l. = below detection limit.

	Si	**Al**	**Ca**	**Mg**	**K**	**Na**	**P**	**Cl**
Cabomba, fresh	19766	2318	9536	2605	17877	31234	3013	16051
Cabomba, disc	60961	4974	22227	2016	2575	1738	261	545
Elodea, fresh	11417	1217	141776	2120	18438	7842	4199	6201
Elodea, disc	17329	2551	183875	1916	2255	921	6025	418
Thinning wood (chips)	840	267	4780	627	2479	179	520	295
Subbituminous coal	5744	4884	8737	1715	228	716	320	29

3.5 Inorganics and nutrients

In Table 2, the concentrations of various ash-forming elements in water plants (fresh and after TORWASH + pressing) are presented. It can be concluded that Ca dominates the ashes of Elodea and that the amounts do not decrease as a result of the TORWASH operation. When used as a fuel in a boiler, the high amounts of ash may pose a risk of deposition as dust. However, since the ashes after TORWASH are predominantly calcium-based with some silica, one can expect that the ashes will have a relatively high melting point and that the risk of slagging is small. Nonetheless the calciferous ash is highly reflective and hence may lead to the so-called whitening, leading to the loss of boiler efficiency due to decreased radiant heat uptake.

In Cabomba, silicon is the dominant element. It may be present as silica, either in the plant as the structural component of the outer plant wall or as soil/sand entrained in the sample during harvest. This has not been investigated further, but it might be an important aspect for the deployment of the fuel Whatever the speciation of this silica, the relatively low ratio between Ca and Si may lead to ashes with a low melting point that are sticky at combustion conditions. The result may be slagging on the water-walls and the superheaters in power plants. This problem can be diminished by separation of the sand from the biomass at the harvest, provided that the silica originates indeed from sand and not from within the plant.

Alkali metals (K and Na) are removed from the biomass with up to ~90% efficiency in TORWASH. The concentration of these volatile and reactive metals in the product is at the same level as chipped wood and may be acceptable for replacing this kind of woody fuels. However an additional washing step has been demonstrated (not part of this work) to lead to the removal of 99%, resulting in alkali levels as low as those of clean wood pellets.

The chlorine content in the original material is too high to be directly used as a fuel, but it is effectively removed by means of TORWASH. In Cabomba 97% of chlorine has been removed together with the water. In Elodea 93% of chlorine is removed. These numbers are comparable to the 98.5% and 96.7% removal of water. Chlorine removal is similar, but slightly lower than proportional to water removal. It can be concluded that after TORWASH chlorine is likely largely soluble in the liquid phase and removal is only a matter of washing.

For utilization as fuel, the original material has too high a chlorine content and can be expected to cause serious problems with corrosion. The TORWASHed material has chlorine contents similar to chipped wood, but it is still above the 300 mg/kg criterion for ENplus-A2 pellets. However, the S/Cl ratio of the TORWASHed material is relatively high (> 2.0), so it can be expected that it will not cause chlorine corrosion.

The nitrogen content in the solid after TORWASH is somewhat lower, indicating that nitrogen is preferentially dissolved, but not much. This applies to both water plants. Nonetheless, despite the increased fuel N levels, thanks to the still high volatility of the carbonaceous matrix, these should not lead to high NOx formation rates. However this issue should be investigated further in detail, in order to define whether additional NOx reduction measures like SCR deNOx need to be applied to comply with emission limits.

With respect to phosphorus, the behaviour of Cabomba and Elodea is completely different in TORWASH. Both start with a similar P-content in the plant, but in Elodea, phosphorus is fully retained, while in Cabomba 95% of the phosphorus originally present in the plant is removed. The latter is comparable to the overall water removal and chlorine removal, indicating nearly complete dissolution of phosphorus and leading to levels even lower than in plain wood chips.. Also, although phosphorous levels are very high in the final product from Elodea it is not likely to cause problems in the combustion environment. With this high a calcium content, this P is either already present in the form of apatite (plane calcium phosphate) or will be directly converted into this very thermally stable mineral early on in the conversion process. This “immobilisation” will likely eliminate the risk of SCR-deNOx catalyst poisoning, which is often an issue for high-P biomass fuels.

4 DISCUSSION

4.1 Water plants as a feedstock for TORWASH

TORWASH turns chopped water plants into a compressible material where the water can be easily mechanically removed. Both Elodea and Cabomba are considered to be a good feedstock for a TORWASH process. After chopping, the slurry has directly the right consistency for introduction into the pressure reactor.

In this study, 190°C was established as the optimal TORWASH temperature. At this temperature, the yield of solid material in the TORWASH process is about 55% for Cabomba and 75% for Elodea. When comparable conditions were used for TORWASHing grass and reed, yields of 52% and 65% were found, respectively [9]. At optimal conditions, soluble ions like K and Cl go into solution. This has been established since the bulk – more than 90% – of K and Cl is removed.

At the optimal conditions, the biomass structure is partly decomposed. It has a weakened cellulose structure that easily collapses when put under pressure. However, it is strong enough so that small channels remain between the broken fibres where water can flow out and mechanical dewatering can take place. For both water plants this goal has been accomplished, since the slurry that is recovered from the autoclave after wet torrefaction can be mechanically dewatered to a level of more than 70% dry matter. This means that 96-99% of the original water has been removed. It is the primary objectives of TORWASH to enable mechanical removal of liquid with dissolved salts. Mechanical dewatering is an efficient method to obtain dried material using much less energy than drying, which is of particular importance for moist materials like sludges and wet biomass. On the other hand, presses are relatively expensive machines. The degree of dewatering depends on the resistance of the material, particle size, pressure, duration and on clogging the filter.

The treatment also results in dissolution of organic components of the biomass, especially hemicellulose. These dissolved components (sugars and their decomposition products) are removed together with water and minerals. This is an unwanted effect when pursuing a solid fuel, but the dissolved organics can efficiently turned into biogas using anaerobic digestion [9].

4.2 Fuel quality

TORWASHed and dewatered water plants can be regarded as a fuel, which may be dried further and/or compressed into pellets/briquettes. The heating value is good, comparable to wood. The water content is acceptable (30 wt%), but the ash content (mostly Ca and Si) rather high (20-30 wt%). The latter is partly due to sand being lodged in the harvested roots of the plants. The ash contents of the TORWASHed materials are somewhat increased compared to the fresh material which indicates presence of both soluble (e.g. K and Cl) and non-soluble ash-components, e.g. silica. The reference numbers for ash content of wood and coal are well below 10%. Since the ash contents of the water plants (TORWASHed and fresh) exceed this number they are not attractive fuels. In fluidized-bed systems, where sand is added as bed material, water plants can be an acceptable fuel.

Alkali and chlorine content have dropped dramatically, but are still relatively high, though in the same order as wood chips. These elements are present as dissolved ions in the remaining water of the pressed cake. It is expected that by partly dewatering of the TORWASHed slurry and controlled washing the concentrations of alkali an chlorine can be lowered further. The viability of this post-washing remains to be investigated.

The nitrogen content is higher than for wood and similar to that of coal. Depending on the overall N-content of the fuel blend removal of nitrogen oxides may be needed to clean the flue gas, e.g. installing an SCR-unit (Selective Catalytic Reduction).

The high phosphorus content of TORWASHed Elodea may limit its use due to the potential poisoning of SCR catalysts. It should be noted though that it is likely that the chemical speciation of this phosphorus is highly immobile in typical combustion environment, due to the high levels of calcium in the ash matrix.

The fuel is suitable for combustion in a fluidized bed systems and replace a fuel like wood chips. For applications in co-firing in a pulverized fuel plant, the quality needs further improvement. In any case additional drying, but also extra washing of the product is needed to remove alkaline and chloride. The high ash content is more difficult to improve, but it should be worth to avoid taking in sand at the harvest.

4.3 Logistics

Harvested water plants are voluminous (low density) and consist mostly of water. Independent of TORWASH size reduction and water removal at the harvest site are desirable to reduce transport movements and resulting costs. Up to ten tons (dry weight) of water plants can be produced per hectare [11]. Such a size reduction can be opbtained by chopping these plants. This directly reduces the volume by a factor of four and results in a pumpable slurry with >90% water.

Removal of water is desirable. Some kind of treatment is needed before water can be removed. It was shown that TORWASH is one of those techniques..

4.4 Comparison between techniques

Initial experiments to dry water plants on land have shown that within two days the dry matter content increased from 10 to over 70% (under dry and sunny conditions). However, for drying land should be available, the area required will be further investigated. Dried water plants can also be baled (dry or wet) to make silage. Both techniques are efficient from a practical, financial and energetic point of view. They can be done on site, reducing transport movements and the material can be stored for further processing.

Water plants are currently not suitable as animal feed due to low protein content and high calcium levels, further research is required to see whether calcium (and other elements) are removed by drying on land. It was observed that calcium precipitates mainly on the leaves which break of the stems during drying process.

Whether the plants can be used to make bio-composite materials is currently investigated, this would be a preferable route, because this form of utilization has a higher added value than fuel pellets.

In parallel research Biogas yields per ton of dried plant material were found to be relatively high (unpublished results), even after storage for several months. When drying on land is possible, digestion may be an economically feasible solution for energy production from water plants. In this case smaller reactor volumes and less transport are required. However, a disadvantage of anaerobic digestion is the production of digestate which needs a disposal route (e.g. composting or incineration).

Pyrolysis and TORWASH are comparable in the sense that these techniques are more 'high tech' and not available on a practical scale yet. Pyrolysis of water plants should still be tested by Waternet. When drying of water plant on land (to >70% dry matter) and pelleting are possible, pyrolysis could have an advantage over TORWASH. Because pyrolysis in comparison to TORWASH or digestion does not produce a water stream or digestate that has to be further treated. Pyrolysis produces four products oil, syngas, wood vinegar (pyroligeneous acid) and biochar. Both techniques can potentially be mobile making onsite treatment possible, this is preferable from a logistic point of view. The water produced by the TORWASH process can be digested to produce biogas, this means extra technological treatment step. Nutrients K, sometimes all P and a portion of N are removed by the TORWASH process, these nutrients will remain in the water after digestion. Reintroducing of the nutrient rich effluent to surface waters is not an option because of the risk of eutrophication. Further research to investigate whether this water can be used as a fertilizer or may have ecotoxic effects is under way [12]. Finally, the economic feasibility of TORWASH and pyrolysis should be assessed.

5. CONCLUSIONS

TORWASH can be successfully applied to Cabomba and Elodea, resulting in production of solid biomass fuels. The primary goals of mechanical dewatering and substantial salt removal have been reached. However, the alkali and chloride are still higher than for clean wood pellets. As produced, i.e. without further washing, the fuel quality is comparable to chipped wood in most aspect, notably with respect to moisture content, calorific value and salts. The high ash content, in particular for Elodea, is preventing a favourable assessment as fuel. They should only be used in applications, where high ash contents are not a problem, such as fluidized beds. They might be used in co-firing in pulverized coal plants, but only at a low rate.

A large increase in the density of water plants is already obtained by chopping, which can be done on site during harvest. For a high degree of dewatering, TORWASH can be used. To avoid lengthy transportation and degradation of chopped water plants, it is desirable to have a mobile TORWASH unit that directly processes chopped water plants during the harvest.

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