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Use of HTC hydrochar for water treatment in less developed countries.

Bachelor Thesis

by

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Abstract

Safe drinking water supply, safe sanitation, and hygiene (WASH) are recognised as human rights by the UN and anchored as goal number 6 in the SDGs. Nevertheless, there is still a lot of potential for improvement. Deficiencies in these systems often cause diarrhoeal diseases, which too often end in death. Sustainable and innovative technologies are supposed to counteract this difficulty. Ideally, such technologies are multifunctional and can be integrated into local cycles. After all, many people still see waste as filthy and an end product, yet it contains valuable resources and is wasteful to discard. For example, through hydrothermal carbonisation, the residues from on-site sanitation (OSS) can be sanitised and upgraded for several usages. The hydrothermal process converts organic material into hydrochar, process water and gas. Hydrochar, like other types of coal, has diverse applications. This work used a low-cost bench-scale reactor (BLR) to produce hydrochar from human manure mixed with other organic household wastes. Thereby, the methodical parameters of the reactor were tested. The resulting hydrochar was analysed and added to a sand filter in a further step. The aim was to check whether the charcoal is suitable as a filter medium for the removal of *Escherichia coli (E. coli)* and which parameters are responsible for a high removal rate.

Carbonisation with the BLR worked satisfactorily if the starting material was blended beforehand. In the case of a touch & down experiment, which employed a very short reaction time, it was required to heat up to 200 °C, whereas a temperature of 180 °C was sufficient with an extended reaction time of at least 30 minutes. After analysing the hydrochar, hydrothermal treatment at temperatures of 180 °C for 30 minutes was found more suitable for the intended application. The removal efficiency of the hydrochar turned out mixed. Collected data indicate that not one particular characteristic of the hydrochar is accountable for the removal of *E. coli*, but rather an interplay of various parameters leads to the best outcome. Hydrochar, which is obtained from a mixture of faeces and kitchen waste, or faeces and coffee grounds, holds the greatest potential. With 77% efficiency, the result with hydrochar from faeces and kitchen waste was the best. The downside is that the composition of household waste varies greatly depending on the region or diet and therefore is not representative of all situations. In addition, the inorganic content may include unknown constituents in complex mixtures and might influence the water quality. The second-best result, with a 36 % removal rate, was achieved by hydrochar from faeces and coffee grounds. Green waste and faeces, as well as faeces without additives, did not yield any added value compared to the sand filter without carbon additives.

Zusammenfassung

Obwohl eine sichere Trinkwasserversorgung, sichere Sanitäre Systeme und Hygiene (WASH) als Menschenrechte von den UN anerkannt werden und sie als Ziel in den SDGs verankert sind, gibt es noch viel Verbesserungspotential. Mängel an diesen Systemen sind oft Ursachen von Durchfallerkrankungen, die zu oft tödlich enden. Mit nachhaltigen und innovativen Technologien soll dieser Problematik entgegengewirkt werden. Im besten Falle sind solche Technologien multifunktional und können in lokale Kreisläufe eingebunden werden. Denn was viele immer noch als Abfall und dreckig beurteilen, enthält wertvolle Ressourcen. Beispielsweise mit der hydrothermalen Karbonisierung können Residuen von Trockentoiletten hygienisiert und aufgewertet werden. Durch den Prozess wird organisches Material in Hydrokohle, Prozesswasser und Gas umgewandelt. Die Hydrokohle hat, wie andere Kohletypen, diverse Anwendungszwecke. In dieser Arbeit wurde mit einem kostengünstig produzierten, kleinskalierten Reaktor (BLR) Hydrokohle aus Fäkalien und beigemischten organischen Abfällen in Haushalten hergestellt. Dabei wurde dessen methodischen Parameter getestet. Die erhaltene Kohle wurde untersucht und in einem nächsten Schritt als zusätzliches Filtermedium einem Sandfilter beigefügt. Dabei wurde getestet, ob sich die Kohle als Filter für *Escherichia coli* (*E. coli)* eignet und welche Parameter für eine hohe Entfernungsrate verantwortlich sind.

Die Karbonisierung mit dem BLR hat gut funktioniert, wenn das Ausgangsmaterial vorher vermischt wurde. Im Falle eines touch & down Experimentes (kurze Reaktionszeit) musste auf 200 °C geheizt werden. Bei einer verlängerten Reaktionsdauer von mind. 30 Minuten waren 180 °C ausreichend. Nach der Charakterisierung der Hydrokohle wurde ein hydrothermaler Prozess bei 180 °C für 30 Minuten als passender für diesen Nutzen eingestuft. Die erhobenen Daten weisen darauf hin, dass nicht ein einzelner Charakterzug der Kohle die Entfernung von *E. coli* verantwortet, sondern, dass ein Zusammenspiel verschiedener Parameter zum besten Ergebnis führen. Die Filterleistung der Kohlen hat sich als durchmischt herausgestellt. Am meisten Potential hat Kohle aus einer Fäkalien-Küchenabfall und einer Fäkalien-Kaffeesatz Mischung. Mit 77°% Entfernung war das Ergebnis mit Kohle aus Fäkalien und Küchenabfällen das Beste. Nachteilig ist, dass die Zusammensetzung von Haushaltabfällen stark variiert je nach Region oder Ernährungsweise. Darüber hinaus könnte der anorganische Anteil unbekannte Bestandteile in komplexen Mischungen enthalten, die sich auf die Wasserqualität auswirken könnten. Das zweitbeste Resultat mit 36 % wurde von einer Kohle aus Fäkalien und Kaffeesatz erreicht. Grüngut und Fäkalien sowie Fäkalien ohne Zusatz ergaben keinen Mehrwert gegenüber dem Sandfilter ohne Kohlezusatz.

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Abbreviations

Abbreviation	Explanation
BET	Brunauer–Emmett–Teller / specific surface area analysis
BLR	Bench-scale low-cost reactor
C	Carbon (Element)
CFU	Colony Forming Unit
CG	Coffee Grounds
Co-HTC	Hydrothermal Carbonisation with more than one kind of source material
CTT	Chloride Tracer Test
E. coli	*Escherichia coli*
GNI	Gross national income
GW	Green Waste / organic garden waste
H	Hydrogen (Element)
HC	Hydrochar
HTC	Hydrothermal Carbonisation
KW	Kitchen Waste
N	Nitrogen (Element)
O	Oxygen (Element)
OSS	On-site Sanitation
PW	Process Water
RSF	Rapid Sand Filtration
S	Sulfur (Element)
SDGs	Sustainable Development Goals
SSF	Slow Sand Filtration
TW	Toilet Waste also referred to as manure
UN	United Nations
WASH	Water, Sanitation and Hygiene
WHO	World Health Organisation
ZHAW	Zürich University of applied Science

1 Introduction

Environmental pollution is just as dangerous for nature and the planet as it is for humanity. Each day, man-made toxic substances are not properly handled and released into the surrounding ecosystem. For example, in 2020, about 45 % of the wastewater generated in global households was discharged without proper treatment (WHO, 2022b). This is particularly problematic when people simultaneously rely on such contaminated land or water for subsistence. In consequence, only 74 % of the world's population have access to secure drinking water in the year 2020 (WHO, 2022a). However, hazardous pollutants are not limited to industrial products like plastics and chemicals. Only 54 % of the global population has access to safely managed sanitation services, and still, 29 % of them practice open defecation. Naturally occurring waste products such as faeces are linked to the transmission of diarrheal diseases and intestinal worm infections. In up to 96 % of the cases in countries with low per capita income (GNI), diarrheal diseases can be attributed to unsafe water supply, sanitation and handwashing (Hamadeh et al., 2022; IHME, 2019). Simultaneously, the disease is responsible for about 6.77 % of fatalities in these countries every year. Especially for children under five years old, diarrheal diseases often end in death (WHO, 2017). For comparison, in Switzerland, diarrhoea accounts for 0.36 % of all deaths every year (IHME, 2019).

Access to water, sanitation, and hygiene (collectively referred to as WASH) is considered a human right (United Nations, n.d.). Consequently, the topic is anchored in the Sustainable Development Goals (SDGs) within goal 6 (United Nations, 2015). They are important components for significant enhancement in the quality of life among communities and have fundamental roles in public health. Improvements are not limited to the living conditions associated to WASH, but also include wider socio-economic factors. Proper sanitation systems boost dignity and safety, particularly for females. Furthermore, a positive relationship was found between sanitary facilities in schools and the attendance of female students (United Nations, 2019; WHO, 2022b). The global situation has already improved considerably in recent years. Nevertheless, there is still a need for action, especially in the countries of the lowest income and those in vulnerable situations (United Nations, 2015; World Bank Group, 2022).

Sustainable and innovative solutions are sought to combat the concerns mentioned above. These technologies should contribute beyond preventing further pollution of the environment, and in particular of water bodies, moreover ensure clean and reliable water supplies.

Safe sanitation faces various challenges yet many opportunities depending on the world region and regional conditions. There are two types of sanitation management systems: sewage systems and on-site sanitation (OSS). A sewerage system requires huge financial resources

and is cost-effective only in densely populated regions with stable water supply. Therefore, an OSS is often the superior approach (Hashimoto, 2021). Unfortunately, the management and treatment of the OSS and produced faecal sludge are insufficient in both developed and developing countries. Reasons can be managing problems like poor construction quality and periodic monitoring of functioning or unregulated and unsafe disposal of faecal sludge (Hashimoto, 2021; Shukla et al., 2022). Therefore, a safe sanitation system which can protect human health and the environment must be effectively managed (Shukla et al., 2022). As this waste is rich in water, energy and organic compounds, circular solutions to recover valuable resources are an opportunity to reduce pressure or dependency on alternative sources (Amery & Haddad, 2015; Flores, 2010). OSS represents a great opportunity for resource-oriented sanitation, where revenues from resource-recovery even could offset operation costs (Andriessen et al., 2019). However, the most suitable option has to be determined individually considering several factors such as remoteness, culture, ethics, existing infrastructure, funding, and know-how (Amery & Haddad, 2015; Tilley et al., 2014).

Hydrothermal carbonisation (HTC) is an energy-efficient technology that converts organic matter into hydrochar (HC) and process water (PW). One of the potential applications of the technology is the treatment of human waste in less developed countries (Chung et al., 2021). Simultaneously, faecal matter can be sanitized by the carbonisation process, while the resulting products can be reused in an upgraded manner (Andriessen et al., 2019). Already studied areas of application for faecal carbon include soil amendment and energy usage (Andriessen et al., 2019; Bleuler et al., 2021). Alternatively, for WASH application, it can be considered an adsorbent in water treatment. Although it has not yet been tried with faeces, studies with other feedstocks like peanut hull, pine needles or sewage sludge have proved promising (Chung et al., 2017; Fang et al., 2018).

This project is divided into two sections. In the first step, four different mixtures of organic wastes have been processed with hydrothermal carbonisation: i) faecal waste only, ii) faecal waste with coffee grounds, iii) faecal waste with green wastes, and iv) faecal waste with kitchen residues. The resulting hydrochar was used in the second part of the study, where it was investigated whether it can act as an adsorbent to remove *E. coli*. The HC was used as an additive in a small sand filter column and tested in terms of removal efficiency.

The resulting research questions are summarised as follows:

- What methodological parameters should be specifically considered for the co-HTC practice with a low-cost reactor system?
- What is the mechanism of adsorptive removal for *E. coli* in sand-hydrochar filtration?
- Is it possible to use hydrochar from the co-HTC process of human waste supplemented with common organic wastes for water treatment and if so, which mix is suited best?

2 Literature Review

This chapter addresses topics whose theoretical and technical foundations are relevant to the study. The background information is aimed to support the understanding of the experimental findings and the subsequent discussion. This work involved literature and internet research. Primarily, research was conducted on the search portals "google scholar", “ResearchGate” and other scientifical platforms. In addition, information was taken from the homepage of Unicef, WHO, and the World Bank.

2.1 Hydrothermal Carbonisation (HTC)

Hydrothermal reactions are natural geological phenomena responsible for the conversion of dead organic material such as leaves into gas, coal, and petrol deep within the earth. These processes, which require millions of years in nature, have been imitated by humans (Sharma et al., 2020).

The first documented experiments regarding hydrothermal carbonisation were conducted by Bergius in 1913, where he described the conversion of cellulose into coal-like materials using the process later to produce biofuels (Ramke et al., 2009). Until the 1930s, the process was studied in various aspects (Berl & Schmidt, 1932). After that, the topic gained momentum again in the 1990s and following the turn of the millennium (Hu et al., 2010). Nowadays, research focuses on carbonising organic waste and hydrochar utilisation. (Bardhan et al., 2021; Ramke et al., 2009). The expression co-HTC is used when the feedstock consists of more than one component (Bardhan et al., 2021).

2.1.1 Hydrothermal Carbonisation Process

In HTC at lower temperatures (180-250 °C), organic materials and water undergo chemical transformation. The process takes place at an increased pressure of 4-25 bar and can have a reaction time of only a few minutes to several hours, depending on the feedstock. The organic material is converted into solid hydrochar (HC), process water (PW) and gaseous products (Andreas et al., 2021; Fang et al., 2018; Ramke et al., 2009). The water content is crucial to the process, as it acts both as a catalyst and as a reagent. Because HTC can treat wet feedstocks at a relatively low temperature, it has advantages over conventional pyrolysis technologies, which require higher reaction temperatures and energy-intensive drying of the feedstock before or during the treatment (Sharma et al., 2020). The composition and quality of the final products depend on the source material (type of feedstock), reaction temperature and duration, as well as the pressure during the process. In general, an increase in temperature results in a lower amount of HC and a more porous structure, as gasification starts at around 215 °C. The gas ensures more dehydration and decomposition (Sharma et al., 2020). Similar effects are

seen with the reaction time. The longer the reaction, the higher the gasification reactivity. Hence, HC with lower densities (higher pore volume) can be obtained from those conditions (Qadi et al., 2019). Although catalysts are not required, they can have an impact on the reaction time and quality of the end product (Sharma et al., 2020).

The process is characterised by reaction mechanisms such as hydrolysis, dehydration, decarboxylation, aromatisation and recondensation (Fang et al., 2018). Organic molecules are split, recombined and eventually further polymerized, aromatised and recondensed to form HC (Fang et al., 2018; Sharma et al., 2020). Different organic structures, such as cellulose, hemicellulose or lignin, produce different intermediate products (Olszewski et al., 2019, as cited in Sharma et al., 2020).

2.1.2 Hydrochar Characteristic

The solid product of HTC, the hydrochar, has a hydrophobic nature, which facilitates the separation from the liquid phase. Various functional groups are present on the surface of HC. Much of them contain oxygen (Sharma et al., 2020). Compared with raw biomass, the HC displays higher carbon (C) and lower oxygen (O) proportions. In addition, dehydration and decarboxylation promote aromatic C bonds, which are more often found in HC than in raw biomass (Fang et al., 2018). Furthermore, HC has a lower ash content as well as lower sulfur (S) and nitrogen (N) content not only in comparison with raw biomass but also compared to other thermal processed biochar like pyrochar from pyrolysis. This is due to the inorganic elements, which dissolve in the PW during the process (Fang et al., 2015, as cited in Fang et al., 2018). The lower ash percentage also causes the HC to be more acidic (Parshetti et al., 2014, as cited in Fang et al., 2018). Pyrochar has a higher surface area and larger pore volume. During the process, pyrolysis has higher temperatures, which enhance gasification and thus disintegration. On the other hand, the surface of hydrochar features various functional groups causing pore blockage. (Fang et al., 2018).

2.1.3 Potential Usage Of Hydrochar

Hydrochar is applicable in various areas. Because each application requires specific characteristics of HC, different source materials and hydrothermal treatments are used (Fang et al., 2018). An overview of the most common usages is given in Figure 1.

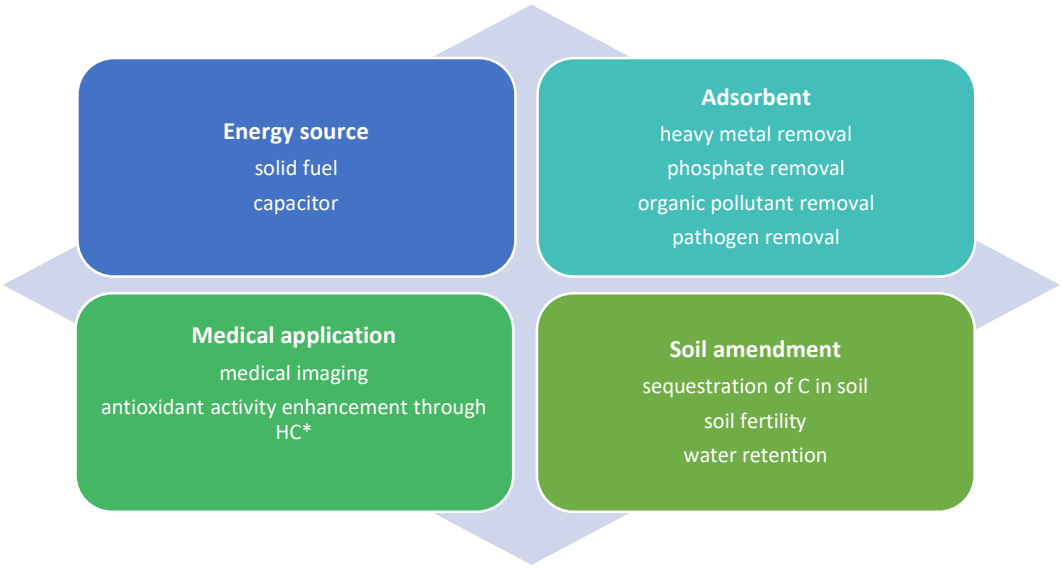


*Figure 1: Usage of hydrochar (Fang et al., 2018) *demonstrated in watermelons (Kim et al., 2014, as cited in Fang et al., 2018).*

In this study, the functionality as an adsorbent for *E. coli* bacteria was tested by combining HC produced by a Benchscale low-cost Reactor (BLR) with a sand filtration system.

2.2 Water Purification Methods

Various technologies are being implemented to obtain clean and safe water. Boiling, disinfection (chemical or solar), distillation, filtration and reverse osmosis are the most common physical and chemical mechanisms (Pomelo, 2022). Though boiling is one of the most certain disinfection methods, the treated water needs to be filtered to remove dead microorganisms and suspended impurities. The same applies to other methods like disinfection (Pomelo, 2022). There are various technologies such as membrane or sand filters with varying features and demands. However, the principles are the same. Through colloid deposition, blocking effects, adsorption and desorption and inactivation, the filtration process can successfully eliminate both large and small components (Foppen & Schijven, 2006; Schultz Soft Water, 2014). In contrast to other methods, filtered water is regarded as healthier since essential mineral salts remain in the treated water (Pomelo, 2022).

2.2.1 Sand Filter Systems

A cost-effective form of water treatment suitable due to both its low complexity and scalability is sand filtration. As a nature-based technology, sand filtration methods are widely implemented in different sectors with various configurations. It describes a type of water purification system using a granular media filter (CDC, 2022).

Slow Sand Filtration (SSF) is a type of granular media filter. It is a highly efficient method to remove turbidity, microbial contamination, viruses and heavy metals. Limitations of the system

are the inability to remove harmful salts, fluorides and several chemicals (Bruni & Spuhler, 2020b). Because of its simplicity and comparatively affordable price but still highly effective purification, the SSF often is used in small or medium-sized rural communities. (Bruni & Spuhler, 2020b; Maurya et al., 2020).

It is built of several vertical layers of different components and grain sizes. Larger gravel forms the subsoil, from where the water passing through the filter merges and is drained out. On top, the grain size becomes smaller until the filter surface layer, which consists of fine sand of the size 0.15-0.3 mm. The filter is covered by a biofilm called the “Schmutzdecke” (german for dirt layer) (Bruni & Spuhler, 2020b; Maurya et al., 2020). The water to be treated is introduced onto the top, where it percolates due to hydrostatic pressure through the filter system. During the filtration process, physical and biological mechanisms contribute to the final result (Maurya et al., 2020). The main physical mechanisms involved are retention and adsorption. On the other hand, the biological activities of predation and grazing contribute to the removal and inactivation of pathogens. Among the parameters that affect the effectiveness of the filter are temperature, filtration rate, the particle size of medium and bed depth. Especially the filtration rate is crucial to its full potential since sufficient time needs to be attributed to biological purification (Bruni & Spuhler, 2020b; Maurya et al., 2020).

In contrast to the SSF, only physical mechanisms occur within the rapid sand filtration (RSF). Therefore, it has to be accompanied by post-treatment such as chlorine or ozone disinfection. In return, the flow-through can be increased manifold with lower space requirements. As a consequence, many industrialised countries use this technology in combination with flocculation and coagulation, sedimentation and disinfection for treating large quantities of drinking water (Bruni & Spuhler, 2020a). Mechanical straining and physical adsorption are the main mechanisms in the filtration process. To prevent accumulation and further clogging of the filtration media, the facility needs to be backwashed regularly, which increases the operational expenses and the installation complexity (Bruni & Spuhler, 2020a).

2.2.2 Carbon In Water treatment

Carbonaceous material is an established adsorbent in filter processes for a long time. The effectiveness of a filter depends on the surface area, pore size and distribution and surface functional groups (Enaime et al., 2020). Besides, different carbons or modifications are required based on the type of contamination to be removed (Bhatnagar et al., 2013). The most common application is activated carbon which provides an enormous specific surface area. It is used to remove colour, taste and odour during water treatment (Raghavachari & Seetharama, 1935; Reiff, 2016). The enormous surface area is obtained through pores of various diameters. Very small particles are retained in these pores and are thus removed from the

water (Reiff, 2016). The ability of biochar to remove pollutants from water depends directly on the feedstock, the thermal conversion technology and the operating parameters (Enaime et al., 2020). As explained in chapter 2.1.2, higher temperatures lead to better pore size distribution, while lower temperatures, as with HTC, result in more functional groups. The HC is therefore superior to reactive contaminants and has fewer micropollutants.

2.3 Escherichia Coli

Escherichia coli (*E. coli*) is a bacteria which is found in the faeces of all warm-blooded animals and is widely used as a faecal indicator organism for faecal contamination (Desmarchelier & Fegan, 2016; Foppen & Schijven, 2006; Schön, 1999). Most strains are harmless organisms and essential for a healthy intestinal tract (Desmarchelier & Fegan, 2016). Other members of the *E. coli* species can cause infections with disease patterns like diarrhoeal disease, urinary tract infections and sepsis/meningitis (Desmarchelier & Fegan, 2016).

E. coli is a thermotolerant coliform with a size of 2.0- 6.0 µm*1.1-1.5 µm. Coliform is a general term for gram-negative, rod-shaped, facultatively anaerobic bacteria (Desmarchelier & Fegan, 2016). It is asporogenous (non-spore-forming) and uses carbon sources, including glucose and acetate for growth (Batt, 2014). Some *E. coli* strains are motile using several flagella others are nonmotile. Depending on the strain, they use additional tools like pili or fimbriae for surface attachment (Desmarchelier & Fegan, 2016). The cell surface of *E. coli* is negatively charged (Foppen & Schijven, 2006; Liang et al., 2016). The strains are differentiated based on their fermentative properties and further biochemical tests. Different pathogenic groups can be distinguished based on serological Lipopolysaccharides (LPS) (Desmarchelier & Fegan, 2016; Schön, 1999). Depending on the temperature of the environment, *E. coli* live in an optimal pH range of 6.5 to 7.5 (Davey, 1994, as cited in Philip et al., 2018)

In a water body environment, the viability of *E. coli* decreases, and a natural die-off occurs. As Foppen & Schijven (2006) described, an average die-off coefficient of 0.15 d^{-1} and 0.5 d^{-1} at 10 °C and 20 °C, respectively. Effects such as shrinking and loss of integrity in the cell membrane can be observed after several hours, depending on the surroundings (Kerr et al., 1999, as cited in Foppen & Schijven, 2006). A change to a viable but non-culturable state (VBNC) was also observed (Arana et al., 2004, as cited in Foppen & Schijven, 2006). Water transportation is influenced by a number of physical, chemical and biological parameters in the environment. The primary factor in adhesion emanation from *E. coli* is the difference in zeta potential and surface charge of the bacteria and the minerals in the filter (Foppen & Schijven, 2006).

3 Material & Methodology

This chapter addresses the materials and methods used. A detailed list of equipment used is provided in Appendix A.

3.1 Sample Collection

To meet the aim of the research, various types of organic matter were compiled as tentative supplements to the faecal feedstock. The selection was made in favour of three alternative components frequently found in households or communities. Which are regular kitchen waste, green waste and coffee grounds.

3.1.1 Organic Matter

Figure 2: Set-up at the sampling site.

The faecal matter was sampled at a composting toilet company, Kompotoi AG in Zürich Altstetten (Kompotoi AG, 2012). Face masks and long gloves were used throughout the sampling procedures to assure biosafety. A plastic foil was spread on the ground to contain any dropped material (Figure 2).

Because of the practice of the company, faecal matter was mixed with wood litter, toilet paper and some urine, whereby the largest proportion was wood litter. To obtain enough faecal matter, the container was searched for the desired resource with a shovel. After the sampling was finished on site, all reusable material as well as the outside of the boxes were cleaned with ethanol and paper towels. In total, 6 plastic buckets of 6 L capacity (Fischer Söhne AG, Muri (CHE)) were acquired and brought to the lab. The collected materials were sterilized at 121 °C for 20 minutes (VX-150, Syntex GmbH, Linden DEU), before being introduced into the laboratory facilities. After sterilization, the buckets were placed in the fresh air to outgas.

The coffee grounds were collected from local coffee shops. Thereby, one bucket of coffee grounds of 5.8 Litre could be collected. The grounds were autoclaved to prevent the development of mould. Another bucket of 5.8 Litre was filled with green waste from the garden at ZHAW Campus Grüental. Freshly cut grass and plants, as well as already dried grass and straw, were collected. The kitchen waste was taken from household's organic waste, consisting

of eggshells, dry bread and various types of food waste, such as the seeds of sweet peppers, carrot peelings and tomato panicles.

From each resource, a representative sample was dried in an oven (FED 260, Binder GmbH, Tuttlingen DEU) at 105 °C overnight for chemical analysis. The remainder was stored at 4 °C degrees.

3.1.2 Lake Water

The water used for the *E. coli* flushing experiment was collected at Lake Zurich, Wädenswil. For sampling, 6-litre plastic canisters (Fischer Söhne AG, Muri CHE) were filled from the shoreline at a bathing area. The water was stored in a temperate room at about 21 °C degrees. During the experimental phase, the lake water was replaced once. The storage period was one to two months before it was incubated with *E coli*.

3.2 Hydrothermal Carbonisation

For the carbonisation process, the Benchscale low-cost Reactor (BLR) from Chung et.al (2021) was used. The aim was a realistic setting to practice the functionality of the BLR. To this end, materials were not processed in a laboratory, but rather kept unchanged wherever possible. The Hydrothermal Carbonisation (HTC) took place at the ZHAW campus Grüental, where the BLR (Figure 3 and Figure 4) was situated (Chung et al., 2021). The 2-litre reactor was filled to 2/3 of its volume, with a 1/3 safety margin to leave enough head space for water expansion. Sufficient water content was crucial to prevent the mixture from burning. Therefore, only 16-23 % of dry organic matter was introduced per run (Table 1). As an energy source, a camping stove (Primus, Stockholm SWE) was used which heated the reactor from below. To measure energy consumption, the cartridge was weighed (MLT4002T, Mettler-Toledo GmbH, Greifensee CHE) before and after the reaction. The energy content of the gas mixture was set at 49.4 MJ/kg based on an empirical value from reference gas mixtures. During the hydrothermal carbonisation process temperature and pressure values were noted in an interval of 3 minutes. The camping stove was ignited with an ordinary stove lighter. After the reactor was heated up to the set temperature it was kept at that level for the required duration. The temperature was regulated by controlling the gas ventil. As soon as the specified time had elapsed, the gas was disconnected, and the reactor was left to stand without further intervention.

Figure 3: BLR reactor (left) and lid (right) with temperature and pressure sensor as well as pressure emergency release ventil.

Figure 4: BLR set-up as seen from behind with gas canister and camera (top left).

Due to the safety regulations at ZHAW, the HTC experiments were carried out in a designated laboratory equipped with safety devices. Temperature and pressure values were observed via a webcam outside the reactor room. On the day following the HTC, the gas produced during the reaction was released through a ventilation valve. Because the gas might contain hazardous chemical components, a gas mask (3M, Rüschlikon CHE) with special filters (ABEK1, 3M, Rüschlikon CHE) was worn. Also, the air in the laboratory was processed via an active ventilation system. After the gas release, the entire reactor was weighted (FB60, Mettler-Toledo GmbH, Abstadt DEU) and then opened to obtain a more accurate mass comparison. The slurry was transferred to a clean, labelled bucket to be transferred to the analytical laboratory. Lastly, the reactor was cleaned with water and paper towels and prepared for the next experiment.

To learn about the process and to get familiar with the procedure, a preliminary test was performed using deionised water.

After the final experiment, the reactor was filled with 5 % Hydrogen peroxide around 2/3 and heated at a moderate temperature for one hour.

3.2.1 Experimental Parameter

The natural composition of the samples rendered it difficult to achieve identical mixing ratios across the series. The heterogeneous mixture of wood, toilet paper and faeces is integrally referred to as faeces. According to best effort, similar proportions and consistencies were

selected for each HTC series. However, a more precise measurement was not chosen, since this study was designed to reflect the conditions of places in need as closely as possible. Table 1 presents the experimental parameters along with the ingredients and the precise weights. In general, a relation of 1:1 between faeces and additives was aimed for. However, the sample of garden litter proved to be bulky. For that reason, the grass stems were cut down to fit the reactor. Moreover, the moisture content seemed low, hence more water was introduced than in previous experiments.

Table 1: List of the performed HTC and the relevant parameters.

Run	Name	Series	Temperature [°C]	Reaction time	Composition	Weight wet [g]
1	Manure_180_1	FM180	180	7 minutes	Faeces	590
					Water	396
2	Manure_200_1	HC200M	200	9 minutes	Faeces	600
					Water	300
3	Manure_180_30	HC180M	180	36 minutes	Faeces	400
					Water	200
4	HTC Coffee	HCC	180	33 minutes	Faeces	350
					Coffee grounds	350
					Water	300
5	HTC Green	HCG	180	36 minutes	Faeces	350
					Green Waste	175
					Water	475
6	HTC Kitchen	HCK	180	36 minutes	Faeces	351
					Kitchen Waste	352
					Water	300

The components in Table 1 were mixed into a pulp either directly in the reactor or a separate bucket. This was introduced following a poor outcome of the first run. To every mixture, except the first one, an additional 200 mL of deionized water (not in Table 1) was added to the reactor without mixing. In the case of series HCC and HCK, the water was already in the reactor when the mixture was added. In runs 2, 3 and 5 the blend was covered with water after filling the reactor.

3.2.2 Post Processing

The first step after harvesting, the slurry was separated into the HC and PW by filtration using 11 µm pore size filtration paper (1001-125, Whatman plc, Maidstone GBR). For that, two vacuum pumps (CF5423050, Merck Millipore, Darmstadt DEU and PC3001 Varia select, Faust Laborbedarf AG, Schaffhausen CHE) were connected to Erlenmeyer flasks equipped with a Büchner funnel (Figure 5). Both, PW, and wet HC were weighed and stored in a 500 mL plastic bottle (Kautex, Bonn DEU) at 7 °C.

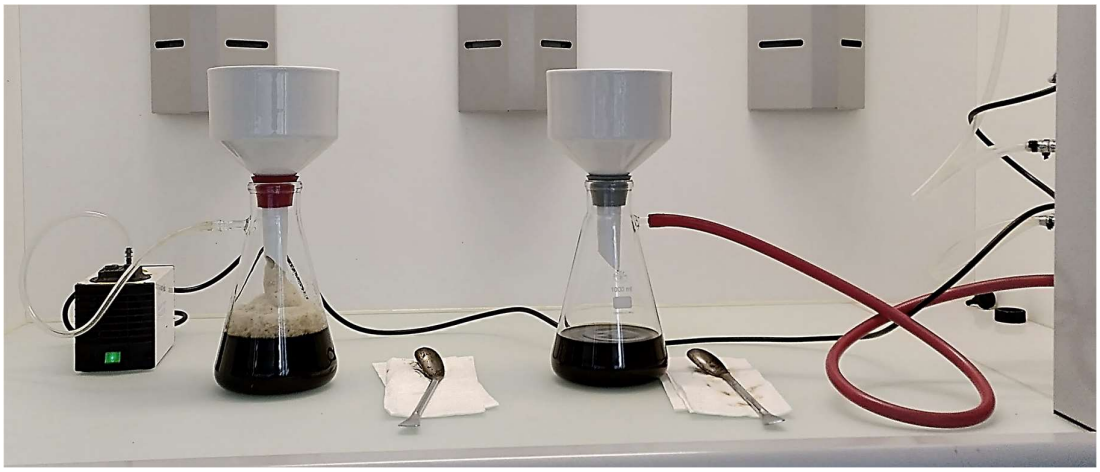


Figure 5: Vacuum filtration of the slurry.

About half of the HC was dried in an oven at 105 °C overnight. The dry weight of the sample was measured and then ground into a homogeneous powder. To do so, the material was first shredded with a blender (LaHuko, Shenzhen CHN) and powdered using a ball mill (MM400, Retsch GmbH, Haan DEU). The sample is filled in containers together with a marble. It then was oscillated for 2 minutes at 25 Hz. The powder was filled in 50 mL tubes (430829, Corning Science Mexico S.A., Reynosa MEX) and stored at 7 °C for further investigation.

3.2.3 Hydrochar Characterisation

For advanced processing, the following parameters were measured: i) pH value, ii) Electric conductivity, iii) Density, iv) Ash content, v) Calorific value, vi) Total content of carbon, hydrogen, nitrogen, and oxygen (CHNO). In addition, specific surface area (Brunauer-Emmet-Teller, BET) and zeta-potential were measured at ZHAW Institute for Chemistry and Biotechnology.

The pH-Value was measured using Hach Lange Multisonde (HQ40d, Hach Lange GmbH, Düsseldorf DEU). The pH sensor was immersed in the PW, which served as the liquid equivalent of the hydrochar. To measure the density of the HC, 5 g of powdered HC was centrifuged for 2 minutes at 4347 rcf (5810R, Eppendorf AG, Hamburg DEU). The centrifugation was aimed to obtain uniform compaction within the samples. The volume of the powder was measured, and density was derived from the formula m/V according to DIN EN ISO 787-11.

The ash content of the HC was measured in triplicates. Each 1 g of powdered sample was placed in an ashing furnace (L 4/11 BO, Nabertherm GmbH, Bremen DEU) overnight. The program was set to heat up to 250 °C for 30 min, and hold for one hour at 250 °C to heat up to 550 °C with full power. Hold at 550 °C for 4 hours to end the program. The time was set to finish the program in the morning of the next day. Then, the crucibles were put in a desiccator to cool. Finally, residuals were measured again to obtain the ash content.

A calorimeter system (C200, IKA®-Werke GmbH & CO. KG, Staufen DE) was used to measure the heating value. Therefore, 0.5 g of powdered HC was introduced to a metallic vessel, and it was filled with oxygen up to 30 bar. The sample was ignited in the calorimeter, which contained the vessel immersed in a known amount of water. The energy release from the combustion was automatically measured by monitoring the temperature increase of the water in the instrument. To ensure a water temperature between 18-25 °C, ice had to be added due to very hot temperatures at that time. The procedure was carried out following the internal standard operating procedure (SOP), based on the operational guidelines of the company (IKA Werke, 2021).

For CHN analysis, 0.1 gram of sample was prepared in aluminium foils and compacted into droplet form. For this, a scale with an accuracy of 0.1 mg was used (CPA64, Sartorious AG, Göttingen DEU). The samples were analysed by a specialist at the lab. The TrueSpec CHN instrument (Leco Cooperation, St. Joseph USA) and the total content method 950C Jan20 were used.

3.3 *Escherichia Coli*

The *Escherichia coli* used for this research was provided by the ZHAW Life Science Department Institution for Chemistry and Biotechnology. In particular, the strain was ZHW 34, which is non-pathogenic. Therefore, two agar plates containing several colonies were stored in the fridge at 7 °C and used for bacterial culture for column experiments (chapter 3.3.2 *Escherichia Coli Preparation*).

All activities that included the handling of *E. coli* were carried out with gloves and under an air extraction hood.

3.3.1 Agar Plates

As a medium for the *E. coli* counts, MacCONCEY agar plates were used. Granucult MacCONKEY (MAC) Agar granulate (1.00205.0500, Merck KGaA, Darmstadt DEU) was used for the production of these plates. The recipe on the bottle specifies 50 g of the dehydrated medium per litre of purified water. Due to previous experience of the agar medium overflowing in the autoclave, only 70 % of the bottle was filled. Consequently, 35 g of the medium was dissolved in 700 mL of water in a glass bottle of one litre capacity. To measure the medium, a balance (ML4002T, Mettler-Toledo GmbH, Greifensee CHE) with 0.01 g accuracy was used. The glass bottle was placed in an 80 °C hot water bath (TW12 CH, Julabo Labrotechnik GmbH, Seelbach DEU) to facilitate the dissolution of the agar medium in water. Then the bottles were autoclaved at 121 °C for 15 minutes. Before cooling, the agar medium was poured into sterile

Petri dishes (391-0559, VWR international GmbH, Dietikon CHE) and set aside. After cooling, agar plates were stored in a temperate room at about 21 °C degrees.

Large quantities of agar plates were needed for this project. Consequently, up to 400 plates were poured at a time on so-called AGAR days. To prevent premature cooling and solidification, the bottles were temporarily stored in an oven at 80 °C.

3.3.2 *Escherichia Coli* Preparation

When required, one colony from one of the donor plates was transferred into a sealable glass tube containing LB-Miller broth (LB Broth Miller, VWR BHD chemicals, Leuven BEL) for 24 hours at 37 °C in an incubator oven (innova4000, New Brunwick Scientific GmbH, Nürtingen DEU). In the broth, the bacteria can grow optimally. By incubating them in the broth, it can be assumed that the concentration is sufficiently high to achieve a detectable effect in the experiments. After the incubation, the *E coli* were either directly used or stored in the fridge (for max one week). From the LB Broth with *E. coli* suspension, the coliforms were obtained for the flushing experiments. Before its usage, the bacteria were washed to prevent adulteration. To do so, 3 mL of *E. coli* culture was introduced in a 15 mL tube and centrifuged at 4347 rcf for 3 minutes. The supernatant was removed and the *E. coli* on the bottom of the tube was resuspended in 9 mL 0.85 % NaCl saline solution with a Vortex (Si-T256, Scientific Industries Inc., Bohemia USA) (chapter 3.3.3). The saline solution was centrifuged again at 4347 rcf for 3 minutes. This procedure was repeated at least 2 times. Eventually, the *E. coli* were resuspended in 3 mL of 0.85 % saline solution and ready for use.

3.3.3 Dilution Series With Saline Solution

A stock of 0.85 % NaCl saline solution was prepared to be used during several plate counting experiments. Thus, 1 litre of deionized water was mixed with 8.5 g of NaCl. The saline solution used for the flushing experiment was autoclaved. The Bottle was labelled with content, name and date and equipped with a bottle-top dispenser.

To have countable numbers of colonies on the plates, different dilutions of *E. coli* were processed. 10-fold series of dilution was prepared using 15 mL tubes (525-1081, VWR international GmbH, Dietikon CHE) filled with 9 mL 0.85 % NaCl solution. 1 mL of the relevant sample was introduced to the first tube and vortexed for a few seconds. Then 1 mL was transferred to the next tube until proper dilution was obtained.

3.3.4 Bacterial Plating And Counting

To apply the bacteria on the McConkey agar plates, pure ethanol (1.00983.1000, Merck Millipore, Darmstadt DEU) and an ethanol lamp for disinfection as well as two metal Petri dish

spatulas for distribution were used. First, the plate was labelled with bacteria, dilution, replicate and date. The sample containing *E. coli* was mixed with the vortex and 100 µL was pipetted onto the plate. After, the spatula was used to spread the sample evenly on the plate. Disinfection of the spatula was performed straight after application using an alcohol lamp. The two spatulas were alternately used ensuring that the metal was cooled down enough not to harm the *E. coli*.

The plates were incubated at 37 °C overnight. Then, the bacterial colonies on the plates were counted in Colony Forming Unit (CFU). In the event of an excessive number of colonies, only a quarter was counted and projected. This method was also used when part of the plate was unreadable.

The bacterial count was determined with the Formula 1:

$$log_{10}(\sum colony\ [CFU] \div \sum volume\ of\ initial\ sample\ plated\ [ml]) \quad (1)$$

3.3.5 Die-Off Test In Lake Water

To assess the viability of *E. coli* bacteria in the lake water used for the column experiment, several die-off tests were conducted. Therefore, 1 mL of *E. coli* stock was introduced in 1 L of lake water to achieve a 10^{-3} dilution. It was then stored at room temperature. Every workday for one week, the active *E. coli* cells were analysed by plate counting technique using McConkey Petri dishes. Earlier in the week usually 10^{-6}, 10^{-5} and 10^{-4} dilutions were used, then it was changed to 10^{-4} and 10^{-3} dilutions depending on the results of the previous day.

For the first execution, two bottles of *E. coli*-introduced lake water were prepared. One bottle was stored in the fridge at 7 °C the other at room temperature.

3.4 Column Experiment

The column experiments took place in the laboratory of the Soil Ecology Research Group. Just as the postprocessing and the majority of the HC analysis.

3.4.1 Column Preparation

For the experiment, Plexiglas columns with a length of 240 mm and an inner diameter of 26 mm were used. The provider of the columns was Adro AG in Andelfingen, Switzerland. Both ends of the column were closed with rubber plugs (Faust Laborbedarf, Schaffhausen CHE). The plugs have two openings, of which only one was used to flush water. Hence, one was taped off. To avoid the sand to reflux in the pipe of the tank, a six-layered mosquito net (LD-VB423-03, Windhager Handelsgesellschaft, Thalgau AUT) was placed over the in- and outflow. Thereby it was important to ensure full contact between the rubber plug and the tube,

otherwise, the column can get leaks. Sand (44990, Landi Schweiz AG, Dotzingen CHE) with a grain size range of 1 mm to 125 μm was used as the major filtration medium (Guan et al., 2020). The Sand was hand-washed 3 times before drying in the oven overnight and sieved to the desired grain size. Only four of the six previously derived HC (Table 1, p. 18) were used as an additive media to the sand column. For each type of HC, three columns were produced. Therefore, wet HC was mixed with sand in a 1.5 % w/w dry weight ratio (Chung et al., 2017; Edewi, 2014). The sand-hydrochar mixture was introduced into the columns. The mixture was compacted using a glass rod to minimize air-saturated pores which might result in interference in the water flow through throughout the columns. When full, the column was closed with the second rubber plug and secured with Parafilm (PM-996, Bemis, Neenah USA). Each column was numbered and listed in Excel with several characteristics such as content, planned test, laboratory name and code and other measurements done before the main test (Table 6, p. 36).

3.4.2 Experimental Set-Up

The columns were fixed on a rack and connected to a peristaltic pump (BT100-3J, Longer Precision Pump Co., Ltd, Baoding CHN). Therefore, the lower output was connected by the silicone hose of the pump, while the upper exit led to an empty bucket using a different silicone hose (Raulab FG Slidtec, Faust Laborbedarf AG, Schaffhausen CHE). The silicone hoses from the pump were connected to the input liquid (Figure 6). Hence, the flow direction ran vertically upwards.

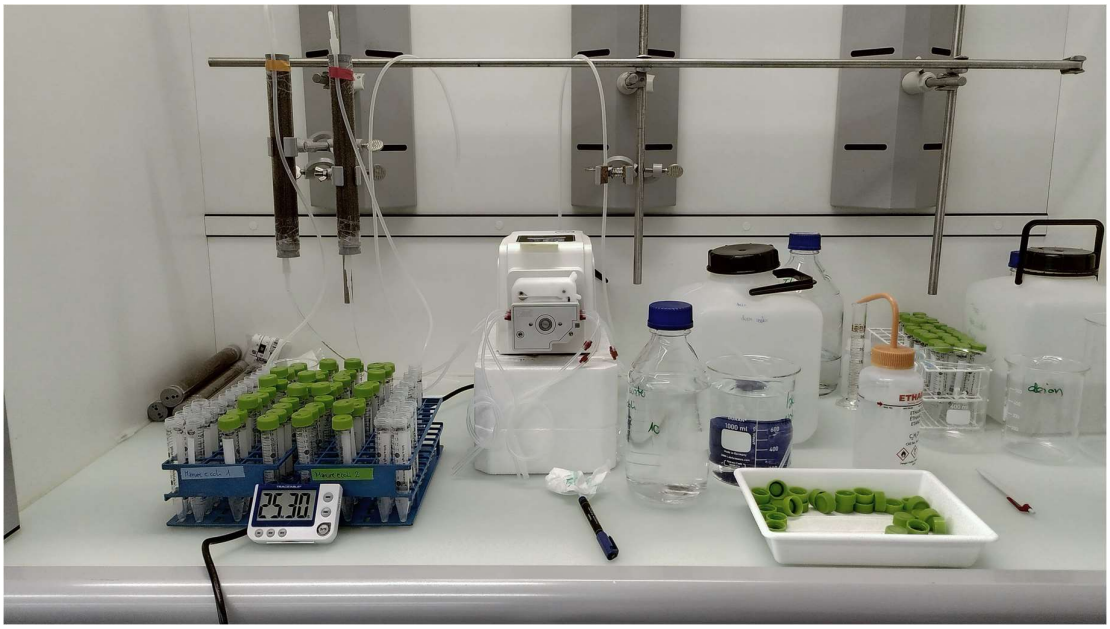


Figure 6: Experimental set-up for E. coli flushing.

Before the main experiments, the columns were washed with deionized water until the electric conductivity of the output stabilised.

3.4.3 Chloride Tracer Test (CTT)

Based on the CTT, the pore volume (PV) of the filter column was assessed and the experimental procedure for the *E. coli* test was designed. The flow rate was set to 3 mL/min and the experiment was designed for 50 minutes. Every minute, 3 mL of column effluent was collected into a 50 mL tube. The tube was filled with 27 mL of deionised water to have enough volume for electric conductivity measurement. Initially, a 0.85 % NaCl solution was pumped into the column for 20 minutes. Then, after 20 samples (i.e., 20 minutes), deionised water was fed to the columns for 30 minutes. 3 mL of the inflowing saline solution was introduced in 27 mL deionized water without filtration. The measured EC was defined as control-value (C0). The electric conductivity of the effluent sample (C) was measured and plotted on a graph showing the C/C0 over time. It is therefore a value between 0 to 1 and indicates proportional outflow and retention. Based on the linear increase in EC during the experiment, the PV was determined at the point where C/C0 reached 0.5.

3.4.4 *Escherichia Coli* Flushing

One day prior to the experiment, 1 mL of *E. coli* was introduced into 1 L of lake water. Consequently, the contaminated water used was diluted 10^{-3} times relative to the bacteria incubated in LB Broth. The *E. coli* could adjust overnight to the new environment.

The flow rate was set to 3 mL/min and the experiment was designed for 130 minutes respectively 40 minutes for the columns which were containing exclusively sand. During the main experiment, a sample of 3 mL was collected every minute in a 15 mL tube (Figure 6). The tubes were numbered from 1 to 40 for each minute of the experiment. Initially, one PV of approximately 50 mL of lake water seeded with *E. coli* suspension was fed into the column. Then, plain lake water was introduced to the column until 40 minutes. For a few selected columns, the *E. coli*-contaminated lake water was fed for another 90 minutes. During this period, samples were taken once every 30 minutes. Which means three times a sample of 3 mL to test the *E. coli* concentration in the outflow over a longer period. Meanwhile, a dilution series with 0.85 % saline solution was prepared. Based on the die-off results and the first run with the sand column, the dilutions to be used for analysis were determined. The procedure to plate the Petri dishes is described in section 3.3.4. Samples 1-7 were stored at 4 °C in the fridge without plating. For samples 8-11 and 36-40, the effluent was once plated without extra dilution and a second plate with 10^{-1} dilution was prepared. For samples 12-35 a 10^{-1} was used two times. It was to obtain at least two readable plates per sample. For columns 5, 6, 13, and 14 (Table 6, p. 36), only the even-numbered samples were plated. The agar plates were labelled with name, date, and laboratory code, consisting of content, replica number, sample number and dilution. The plates were incubated overnight and evaluated the next day.

3.5 Statistical Evaluation

The data were managed using Microsoft Excel for Microsoft 365 MSO (version 2202 build 10.0.14931.20652). For data analysis, RStudio (version 4.2.1) for Windows was used. Results were visualised using line plots, bar plots or box plots (standard implementation in R, version 4.2.1). In boxplots, the 25 % and 75 % quantiles mark the edges of the box, and the line within denotes the 50 % quantile (median). The length of the whiskers is at most 1.5 times the length of the quartile distance measured from the top of the box. Furthermore, a principal component analysis (PCA) was visualised with the packages "factoextra" and "ggplot".

4 Results

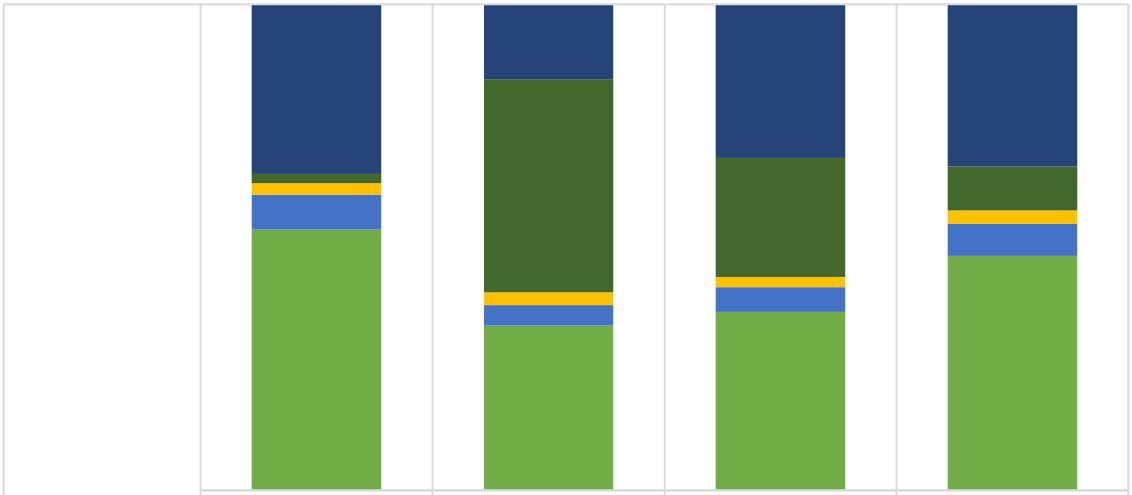
This chapter covers the results throughout the thesis. The subchapters are organised, as previously, into the different phases of the thesis.

4.1 Source Material

The raw material proved to be widely diverse. Clear differences in water content are evident. While kitchen waste had almost the same moisture content as faecal waste, garden waste was considerably drier (Table 2). This was reflected in the formula during carbonisation. The calorific value (on dry basis) has a range of over 10 MJ/kg from the lowest energy content in kitchen waste (12.22 MJ/kg) to the highest in the coffee grounds with 22.81 MJ/kg.

Table 2: Analysed parameter of the source material.

Name	Water [%]	Calorific value [MJ/kg]
Faeces (TW)	70	20.19
Coffee grounds (CG)	48	22.81
Green Waste (GW)	36	14.57
Kitchen Waste (KW)	71	12.22



	CG	KW	GW	TW
Oxygen [%]	34.89	15.39	31.60	33.42
Ash [%]	1.95	43.92	24.51	8.95
Nitrogen [%]	2.4	2.5	2.1	2.8
Hydrogen [%]	7.1	4.2	5.0	6.6
Carbon [%]	53.7	33.9	36.8	48.3

Figure 7: Graphic presentation of the organic compounds and ash content, forming the dry matter of the material. Where CG = Coffee grounds, KW = Kitchen Waste, GW = Green Waste and TW = Toilet Waste.

Figure 7 demonstrates the elemental composition of the test materials. The carbon content is highest in the coffee grounds (53.7 %), whereas the ashes content, i.e., the inorganic components, in the kitchen waste (43.92 %), is particularly high. The reason could be the eggshells

in the mix since it mainly consists of calcium carbonates. For green waste, the ash, organic carbon, and oxygen components are roughly divided into thirds.

4.2 Hydrothermal Carbonisation

One second residual time at 180 °C was not enough to complete the carbonisation. Consequently, the result looked slurry-like in terms that the Faeces was evenly mixed with the water, wood and toilet paper. Unfortunately, the water did not mix with the material, and the different components were still clearly recognisable as such. It still smelled like manure and also was brownish. In addition, the pressure curve of the run on page 28 (Figure 8, top left) indicates a water-bound reaction. Therefore, the first run did not work. Considering this, appropriate adjustments were made to the next experiment, which improved the overall results (3.2.1). Table 3 summarises the energy consumption of each run. All further experiments were considered successful due to the result's smell, consistency, and the elevated end pressure in the reactor. To improve the comparability of the energy consumption, the data is presented based on the consumption for one kg of HC production.

Table 3: Energy consumption of the run and per kg HC harvest according to Table 4 on page 29. Declared with content material and serial acronyms.

Run	Material	Serie	Energy consumption [MJ]	Consumption per kg HC [MJ/kg]
1	TW	FM180	4.717	-
2	TW	HC180M	7.089	55.364
3	TW	HC200M	7.312	88.945
4	CW + TW	HCC	8.071	38.489
5	GW + TW	HCG	6.554	44.737
6	KW + TW	HCK	6.918	50.456

It is not surprising to discover that the first run, which failed, consumed the least energy. Significantly, the hydrothermal treatment of the faeces-coffee grounds mixture (HCC) required the highest energy consumption. However, it is also the HCC-hydrochar that consumed the least energy when extrapolated to the kg HC produced. This mixture also displayed one of the highest pressures during the experiment, which furthermore reacted strongly to fluctuations in temperature (Figure 8). The highest energy demand per kg harvest is found with the HC200M set-up. Low energy demand is observed in both consumption values of the faeces-green waste mixture (HCG). Nevertheless, residues from the feedstocks are consistent during post-processing, particularly in HCG and HCK. Eggshells were unchanged in the slurry. Tomato panicles and stems of grass were identifiable by their shape. The overall reaction curves in Figure 8 show distinguishable differences in pressure development. As the pressure inside the reactor primarily follows the saturated steam pressure, an increased pressure above the saturation indicates varying gas production. At 180 °C the vapour saturation occurs with 10 bar and 15.5 bar at 200 °C (Gloor, 2014). The end pressure at around 20 °C would be around 0.02 bar without additional gas production from the feedstock.

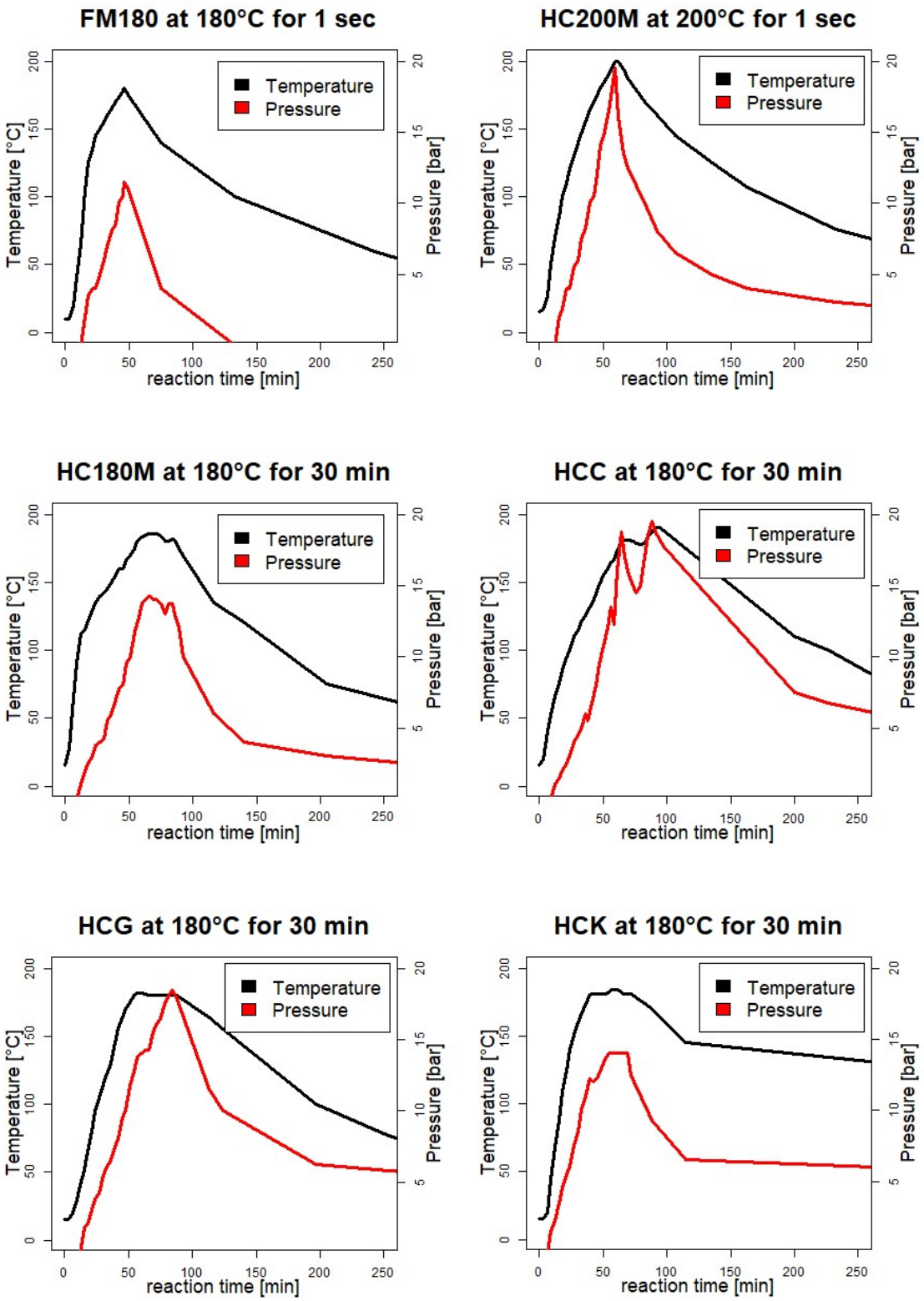


Figure 8: Reaction curves with temperature and pressure of each run individually.

The remaining pressure in all the reactions indicates gasification during the reaction (Figure 8). This is facilitated by the loss of solid mass of about -6 % in nearly every reaction (Table 4). In

the case of the HC180M, something must have been incorrectly transferred in the data since an increase in mass is impossible. The solid mass refers to the dry weight of the raw material.

Table 4: Overview of the harvest and loss in the solid matter during HTC Reaction

Run	Serie	input solid matter [%]	input liquid [%]	output HC [%]	output PW [%]	Solid loss [%]
2	HC200M	16.35	83.65	10.59	89.41	-5.76
3	HC180M	16.35	83.65	17.69	76.92	+1.15
4	HCC	23.88	76.12	17.74	80.92	-6.13
5	HCG	18.06	81.94	12.10	84.86	-5.96
6	HCK	17.38	82.62	11.67	85.69	-5.70

The HCC and HCG series, which required relatively little energy per kg harvested, also appear to possess a higher solid material content and simultaneously a higher rate of dry matter loss in the reaction.

4.3 Hydrochar Characterisation

Depending on the original mixture, filtering the slurry required varying efforts. This is also indicated by the moisture content after filtration (Table 5) and reflects differences in the hydrophobicity of the hydrochar.

Table 5: Characterisation of HC.

Run	Serie	Calorific Value Feedstock [MJ/kg]	Calorific Value HC [MJ/kg]	Density [kg/m^3]	pH	EC [mS/cm]	Water content [%]
2	HC200M	20.186	24.858	609	5.2	0.0557	64.25
3	HC180M	20.186	21.881	587	7.5	0.142	72.22
4	HCC	21.851	24.471	588	4.7	0.0472	61.76
5	HCG	17.288	21.545	630	5	0.0723	61.48
6	HCK	16.230	20.364	710	5.6	0.0702	51.22

According to the specialist performing the test, the surface areas of the samples are considered relatively small but comparable. A similar study showed a BET area of 15-28 m^2/g, whereby half of these hydrochars were activated by additional treatment (Edewi, 2014). The Zeta potential also seems comparable. The HC200M, with the smallest surface area, has the most negative charge, followed by the HCG which has the next smaller surface area (Figure 9).

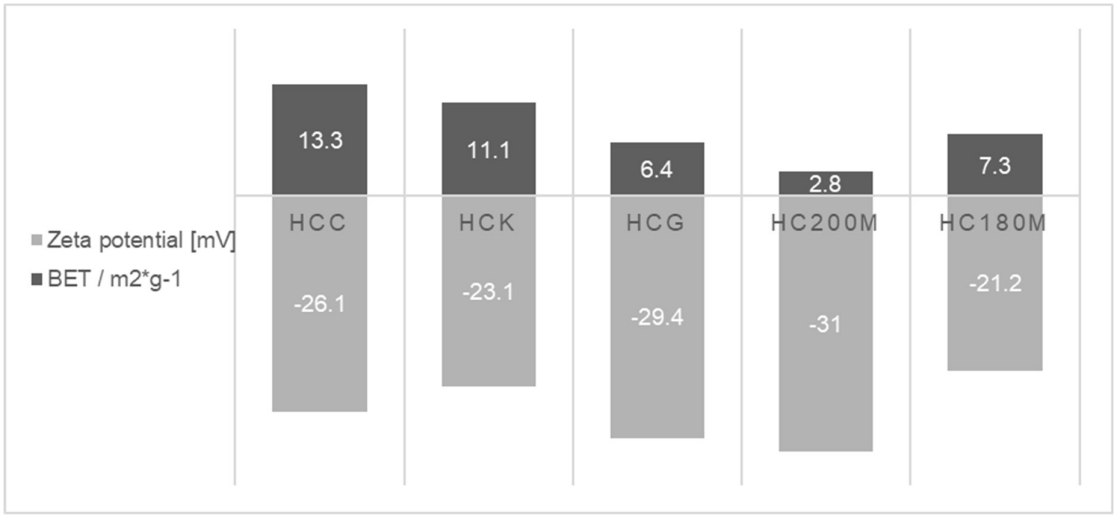
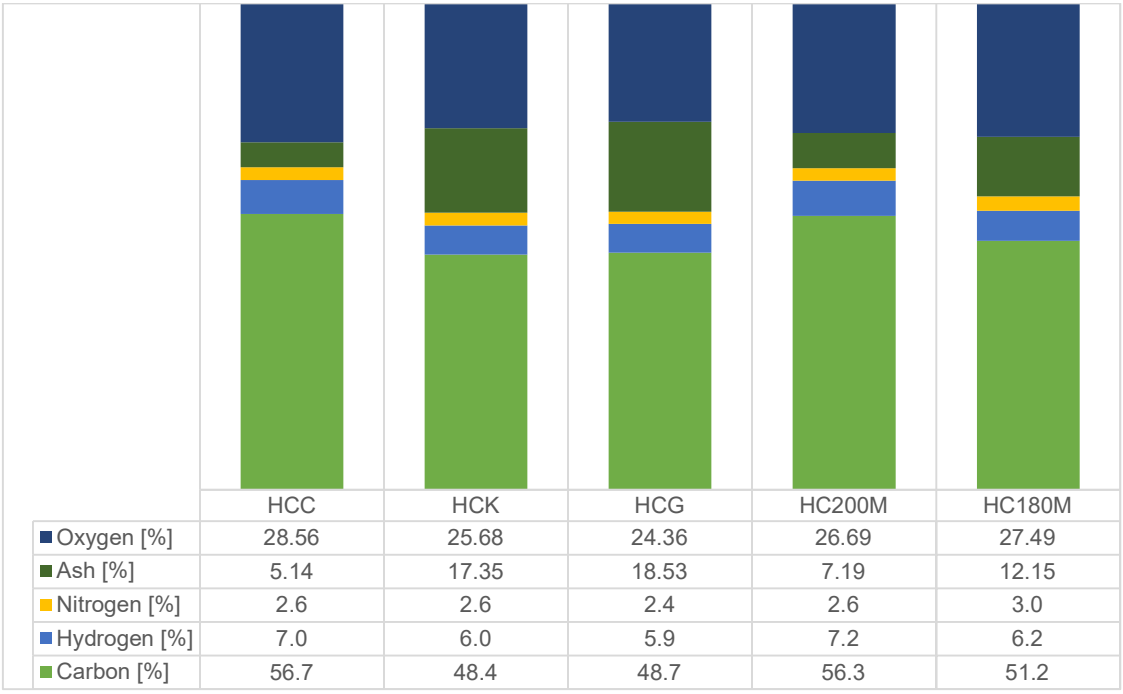


Figure 9: Determined area of the HC per gram in the positive meets the negative Zeta.



	HCC	HCK	HCG	HC200M	HC180M
Oxygen [%]	28.56	25.68	24.36	26.69	27.49
Ash [%]	5.14	17.35	18.53	7.19	12.15
Nitrogen [%]	2.6	2.6	2.4	2.6	3.0
Hydrogen [%]	7.0	6.0	5.9	7.2	6.2
Carbon [%]	56.7	48.4	48.7	56.3	51.2

Figure 10: graphic presentation of the organic compounds and ash content, forming dry matter of the different hydrochar

Figure 10 displays the altered composition of the HC. The carbon content of all hydrochars has increased, whereas the oxygen content has decreased relative to the initial material (Figure 7). The percentages of nitrogen and hydrogen change only marginally. Different developments in ash content can be seen in the HC types. This is explained partly, through the mixture with other materials with higher respectively lower contents in the feedstock. The HCC series has not only the highest carbon content but also the highest oxygen content. HCK contains the lowest level of carbon.

A statistical evaluation of relationships and variations between parameters and HC appeared to be difficult, as only a few measurements were performed. Correspondingly, a principal component analysis (PCA) illustrates the key parameters responsible for the majority of the variations across HC (Figure 11). The analysis suggests a positive correlation between calorific value [MJ/kg] and oxygen, hydrogen, and carbon content. On the other hand, there is a negative correlation between calorific value [MJ/kg] and ash content or density. Electric conductivity and pH are highly correlated with nitrogen content as well as the zeta potential. Figure 11 also indicates that the hydrochar from the HCC and the HC200M series are influenced by similar principal components like calorific value and oxygen content. The HCG appears to be fairly close to these two, although it is more characterised by the dry mass. HC180M is mainly defined through nitrogen, electric conductivity, and water content. The parameter affecting the HCK is ash content and the density connected to it.

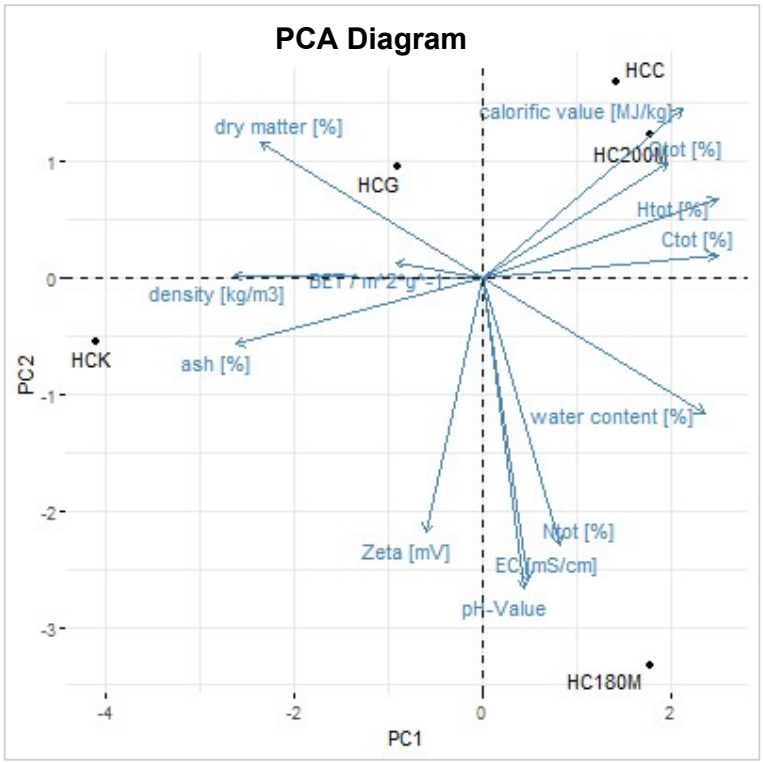


Figure 11: PCA plot of all measured and calculated HC characteristics.

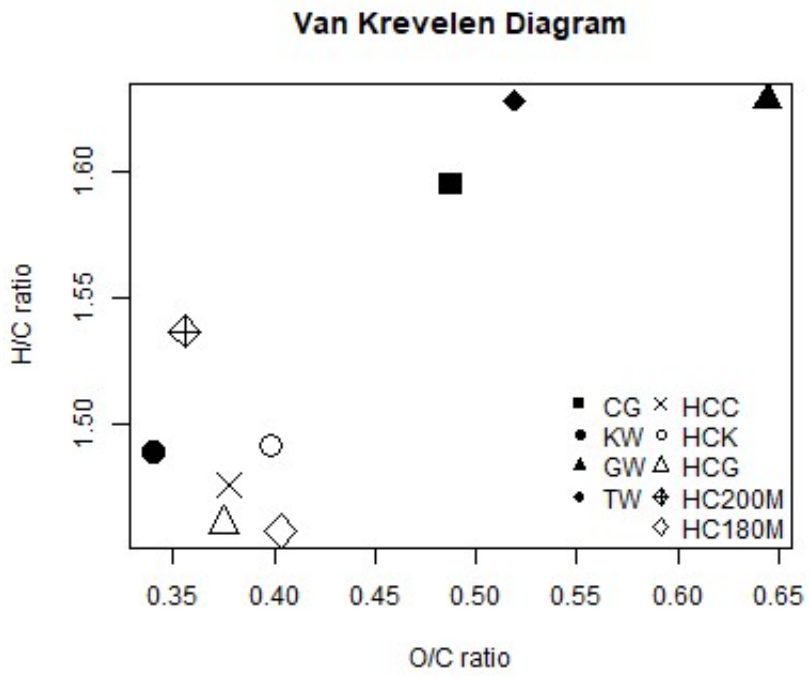


Figure 12: Van Krevelen Diagram to compare the degree of carbonisation between source and HC.

The Van Krevelen Diagram in Figure 12 displays the carbonisation process. In general, hydrochar with a high H/C can be associated with fewer aromatic compounds, whereas a high O/C ratio implies lower hydrophobicity and higher polarity (Tekin et al., 2014). The HC200M would have fewer aromatic compounds than all the other HC series. De-oxygenation is lowest for HC180M and HCK. While HC180M shows high water content hence lower hydrophobicity. The opposite is the situation with HCK. These display low water content and thus evidently high hydrophobicity. Compared to the feedstock, a definite movement is evident. Since the HCC, HCK and HCG samples consist of mixed samples, the changes can be influenced by both the mixture and the carbonisation. A clear interpretation is therefore not feasible in these cases. The samples HC180M and HC200M on the other hand, contain the same input materials. It appears that the factor reaction time enhances dehydration, whereas the factor temperature stimulates deoxygenation. An interesting observation might be the low ratio of kitchen waste samples, which may be explainable by the general high ash content.

Figure 13: Ash colour of the different materials. CG, KW, GW, TW, HCC, HCK, HCG, HC200, HC180 (from left)

Figure 13 demonstrates the fascinating colouring of the ash of the different materials and hydrochars. Each set of ash heaps showed similar colour and texture, apart from that of the HCK. The latter has two colours, dark grey in the middle and a very light shade of grey on the outside, which is assumed to be related to the ashes of the faeces. In the ash of the HC, the original material is easily recognisable, regardless of the carbonisation process.

4.4 Chloride Tracer Tests

The symmetric-sigmoidal shape of the curves in Figure 14 indicates low chemical interactions within the column. This is further indicated by the maximum C/C0 level, which lies close to 1 throughout the plateau phase. Thus, the NaCl has not been retained in the column. In general, these two features indicate good integrity of the columns. The filter media is homogeneously and physically equally weighted packed in the column.

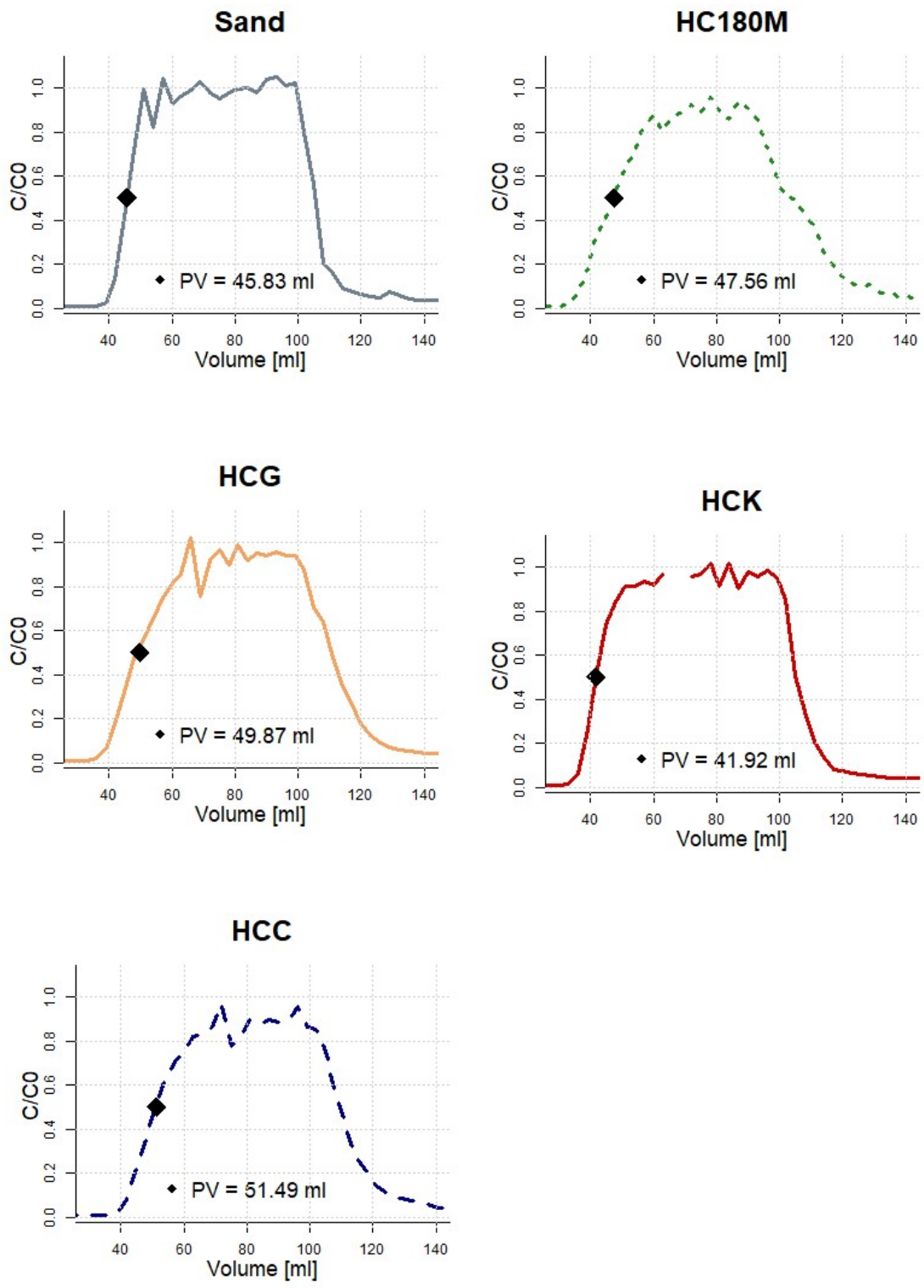


Figure 14: Curve of the Chloride Tracer Test showing the C/C0 from the EC over the flushed Volume.

All pore volumes featured in the graphs are comparable in a range of 9.57 mL and a mean of 47.33 ml. The highest PV of 51.49 mL was observed at HCC and the lowest PV of 41.92 mL was from HCK.

4.5 *Escherichia Coli* Die-Off Test

Two complete die-off tests in Zürich Lake water were conducted. These resulted in a die-off rate of -0.33 d^{-1} and -0.1 d^{-1} at room temperature, respectively. The assays were performed with different batches of water samples in June and September, different seasons of the year. Another die-off examination, where the sample was stored in the fridge, resulted in a rate of -0.13 d^{-1}. Based on this data, it was determined that the *E. coli* suspension would be one day out when the experiments were performed. At that time, there is no significant die-off.

4.6 *Escherichia Coli* Removal Efficiency In Sand Column

Table 6 presents information on all the column flushing experiments performed. The negative control test performed with the sand-only column was triplicated. However, an investigation into the reasons yielded no conclusive results. Therefore, the third flushing experiment with sand was excluded from the analysis. Nevertheless, the measurements are listed in Table 6 and Figure 16. The parameters EC and pH in Table 6 on page 36 refer to the environmental conditions in the liquid phase of the columns to which the *E. coli* were exposed during the experiment. They were measured before the flushing experiment to record column-induced changes in the water. The values were collected at a later stage when possible relevant differences were noticed. This is why there are no comparative values available for columns 1-6. The rpm for 3 mL/min was an essential setting to use the pump but was not integrated into any further assessments. Following the methodology, the columns were washed until the EC level stabilised, which was approximately 45 µS/cm. That measurement is still around 30 µS/cm above the EC of the input water, but negligible considering the disproportionate extra time required to reduce the EC further. The EC of the lake water also varied between 233 to 249 µS/cm. Elevated pH values were observed in the columns with hydrochar containing kitchen waste in the feedstock.

Table 6: Overview of all sand column experiments including material and laboratory codes and effluent EC and pH before the main experiment.

Nr	Serie	Test	Code	rpm for 3ml/min	EC [µS/cm]	pH	PV [ml]
1	sand	Chloride tracer		22	-	-	45.825
2	sand	*E. coli*	Se1	25	-	-	45.825
3	sand	*E. coli*	Se2	20	-	-	45.825
4	HC180M	Chloride tracer		28	-	-	47.561
5	HC180M	*E. coli*	Me1	22	-	-	47.561
6	HC180M	*E. coli*	Me2	22	-	-	47.561
7	HCC	*E. coli*	Ce1	18	45.7	7.31	51.5
8	HCC	Chloride tracer		20	61.3	6.41	51.5
9	HCC	*E. coli*	Ce2	16	47.8	7.11	51.5
10	HCK	*E. coli*	Ke2	16	42.4	8.98	41.92
11	HCK	Chloride tracer		17.5	53.7	-	41.92
12	HCK	*E. coli*	Ke1	21	45.9	9	41.92
13	HCG	*E. coli*	Ge1	19	49	8.71	49.865
14	HCG	*E. coli*	Ge2	19	48.8	8.79	49.865
15	HCG	Chloride tracer		17	41.5	8.72	49.865
16	sand	*E. coli*	Se3	20	46.3	8.67	45.825

The test results regarding the filter experiments are scattered. While there are very high removal efficiency rates, some results are low (Table 7). The differences are not just between different HC types but also within the replicated experiments. Especially in the sand column with manure waste were the results questionable. In both repetitions, a negative removal rate was measured. This would mean extraordinary growth during the filtration process. Considering that it is very unlikely that *E. coli* grows measurable in such conditions and time, there might be an error in the experimental procedures e.g., enumeration of the control sample. A negative removal quote was also observed in Se2 and Me2. The mean standard deviation of 43.43 % in the sand column is exceptionally wide. This is because of substantial discrepancies between the replicates and can be also seen in HCG. The removal efficiency with hydrochar from HCK was on average 77 % the best result followed by the sand filter supplemented with HCC with an average of 36 % (Table 7). The columns with the lowest mean removal results are the HCG hydrochar with 7 % efficiency, which is below the pure sand filter column. The column with an average growth of 46 % was HC180M.

Table 7: Average removal efficiency and standard deviation.

Run	Serie	Mean removal efficiency [%]	Mean standard deviation [%]
1	Sand	16	43.43
2	HC180M	-46	19.92
3	HCG	7	35.78
4	HCK	77	18.93
5	HCC	36	18.97

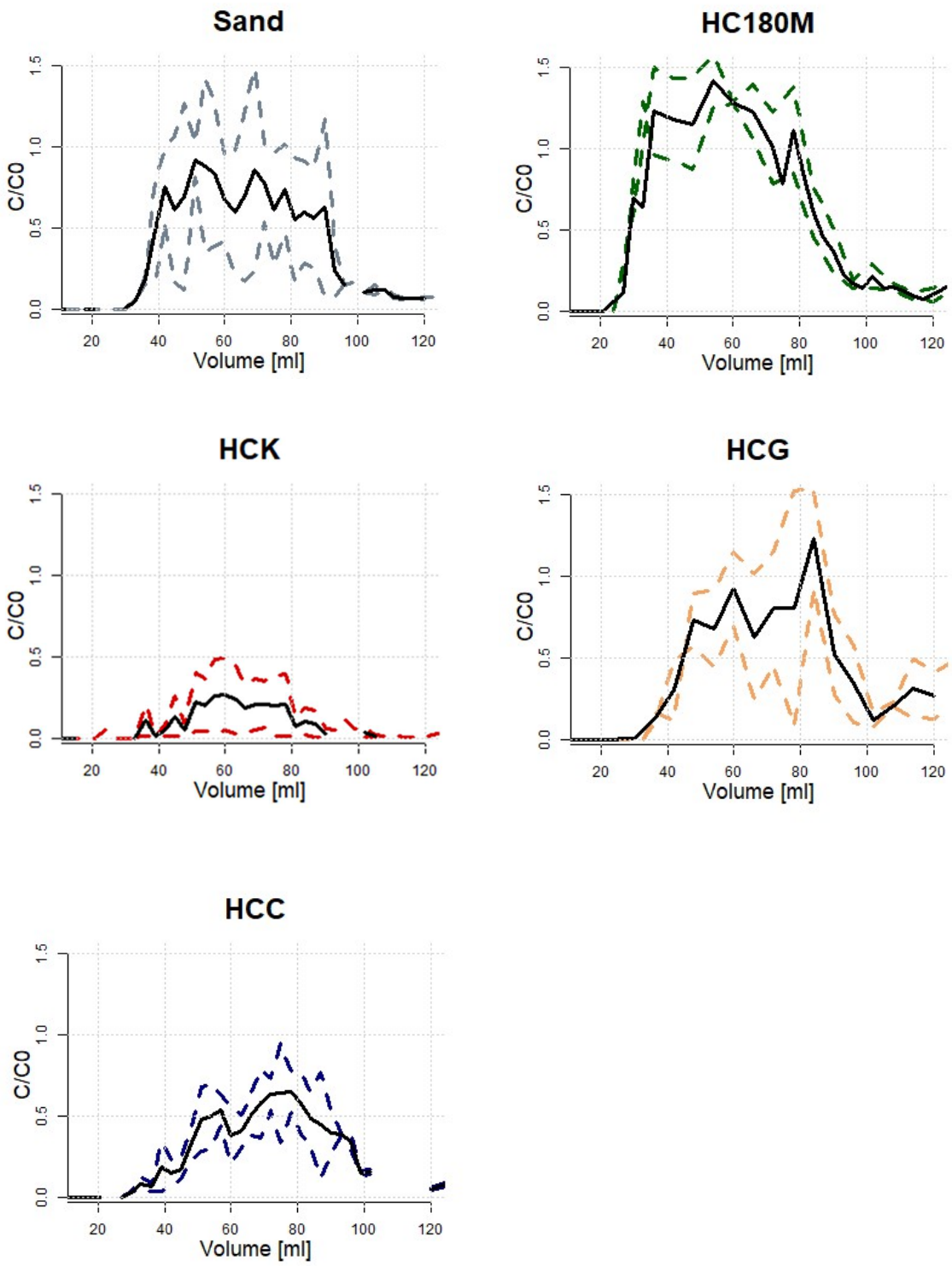


Figure 15: Flow curve of the E. coli effluent experiment with duplicates indicated by dashed lines and with the mean value expressed in black.

The symmetrical shape of the flow curve in Figure 15 is comparable with the CTT curve in Figure 14 on page 34. In this experimental set-up, however, the restraint is evident, as are fluctuations in the sigmoidal shape. This occurs naturally with living organisms, even in the

laboratory, given how erratic nature is. Nevertheless, the differences in outcome are particularly apparent within the group. In the case of the sand filter (top left) and the filter with faeces and green waste (middle right), the differences between the measurements are high, which is reflected in the standard deviation (Table 7). In the case of the column with kitchen waste, the variance is only during the peak flow. The lower curve also misses the symmetrical shape due to a very high removal quote (middle left).

4.6.1 Experimental Control Group

The CFU/mL of *E. coli* in the contaminated lake water was measured in the beginning to determine the concentration of the input. Similar to the CTT, these values were used to calculate the C/C0, whereby C represents the respective filtration values. Consequently, in a filtration process, the C is not expected to be greater than the C0 (control). Because extraordinary growth within 40 minutes appeared in some result, which is unprobeable, the initial control bacteria which was used for the calculations was further analysed as well.

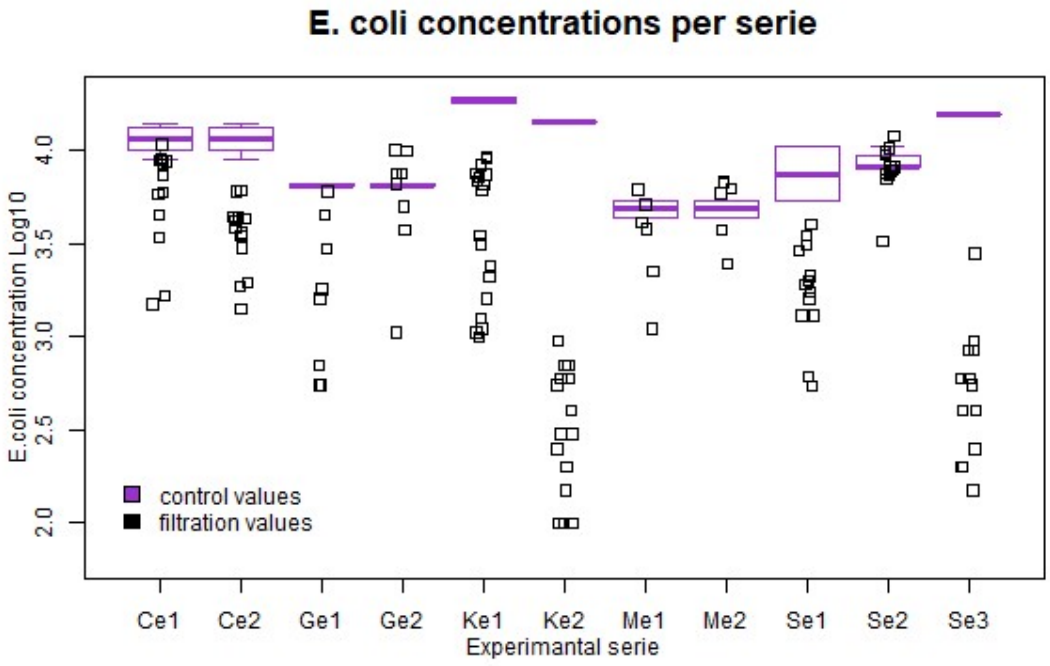


Figure 16: A comparison of logarithmical E. coli concentrations during the plateau phase in the experiment (black squares). Visualised with the control concentrations used in the process. Where the experimental series refers to the code name per replica displayed in Table 6.

Depending on the development of the bacteria in the LB-broth and the lake water, the concentration or the control is different in each batch used. The standard deviation of all control samples of 0.2061243 Log_{10} within the control values is evident in Figure 16. A variance in the plateau values appears in the filter samples as well. The results of Ke2 and Se3 are exceptionally low. Although the controls in the Ge and Me experiments are comparatively small, their

filter values are only marginally smaller relative to the other experiments. This results in a reduced mean removal efficiency (Table 7, p. 36) and in the case of Ge2 and Se2 a negative removal.

4.6.2 Contaminations

During the experiments, miscellaneous contaminations occurred which partly affected the results (Figure 18). To find the source of the contamination, various substances related to the process have been tested. This way, the air ventilation as well as the room air, the fresh agar plates, and deionized water could be excluded. In addition, two contaminants could be traced back to the source. Although the saline solution was autoclaved (chapter 3.3.3), over time contamination occurred within the bottle. By replacing the solution and cleaning out the bottle attachment for dosage, it was possible to eliminate this contaminant. Similar findings apply to the lake water, which was repeatedly checked and found to be tainted after almost two months. However, it was not possible to conclusively identify contamination occurring in the sand column itself (Figure 17). The development of mould in the HC is suspected, considering that the sand-exclusive columns were inconspicuous.

Figure 17: Outflow column 10 (Sand supplemented with HCK), before E. coli flushing. The grown colonies on the agar plate must originate in the column.

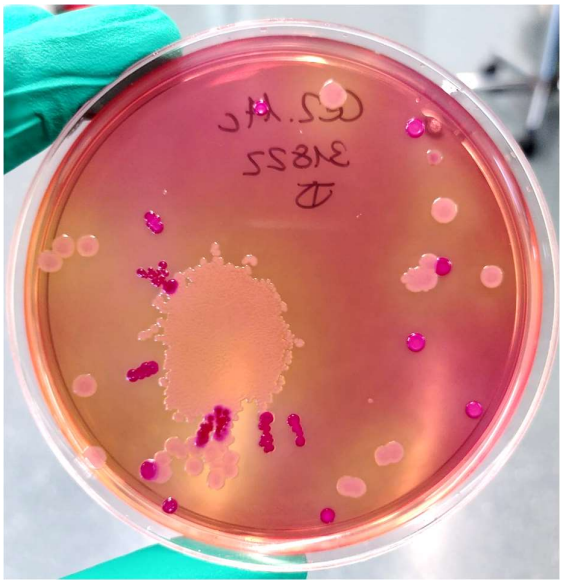


Figure 18: Sample plate 14 during Sand filtration with HCC addition.

5 Discussion

As described in the introduction, three main questions have been investigated in this thesis. How does the HTC process work best, how do the HC characteristics influence the *E. coli* removal and what performances may be expected from each type of HC? This chapter is divided according to these questions examining the process, the HC and lastly the removal performance.

5.1 Hydrothermal Carbonisation Process

The improved outcome after the first attempt may have several reasons. Two of the obvious factors are duration and temperature of hydrothermal treatment, which were increased and prolonged, respectively. Furthermore, preliminary homogenisation might well have had a significant influence. In the first experiment, it was noticed that the process could not (yet) occur effectively, especially in the interior part of the solid mass. Therefore, it is likely that the homogenisation facilitated the heat transfer or vapour and gas pervasion in the feedstock. Moreover, the Van Krevelen diagram (Figure 12) demonstrated more complete carbonisation when heated at a reduced temperature for a prolonged period of exposure. Regarding the energy consumption per kilogram of HC harvested, nothing contradicts a prolonged reaction time (Table 3).

Even without being tested in these experiments, the hygienisation can be considered successful. When looking at the temperature profiles (Figure 8), the temperature exceeded 120 °C for more than 20 minutes in all attempts, which describes the standard parameters when autoclaving. Additionally, Ducey et al. (2017) described that 30 minutes at 150-200 °C even eliminates DNA.

As described in chapter 3.2.1, in some cases, the extra water was introduced to the reactor before the feedstock. In the other cases, the material was covered with additional water. This was due to burning on the bottom of the reactor when the feedstock was covered with water. In consequence, the temperature gradient increased at a slower rate when the water was put in the reactor first (Figure 8). These are observations over the experiments with different feedstock and mass concentrations which could be triggered randomly or by other parameters. In general, a lower material content is associated with a faster temperature rise but slower pressure development. With the BLR, deviations in temperature development can also be caused by combustion, during which the gas canister loses power.

5.2 Hydrochar Characteristics

Hydrothermal treatment elevated the energy content of the HC compared to the feedstock in all the experiments (Table 8). Furthermore, high energy consumption in the HTC reaction does not imply an elevated energy content in the hydrochar. Ranking the feedstock and the HC from lowest to highest energy content, almost no changes were observed. In other words, feedstock with low energy content also has low calorific values (i.e., energy content) in HC, despite being mixed with faeces. An exception is the HC that was processed at 200 °C. This sample gained 3 MJ/kg more compared to the equivalent at 180 °C. In addition, it consumed less energy during HTC in total. Hence, the most increase in energy can be observed when processing at higher temperatures for a limited period of time. An increased gain in energy is also noticeable with HCG and HCK. It might be a specific ingredient in the mixture that favours energy densification, or there could be an unknown synergetic impact between faecal and other organic substances. However, the reason for this is not evident.

Table 8: Energy consumption contrasted with the calorific value of the HC and the source material.

Run	Energy consumption [MJ/kg]	Calorific Value feedstock [MJ/kg]	Calorific Value HC [MJ/kg]	Increase [MJ/kg]
HC200M	55.364	20.186	24.8575	+4.67
HC180M	88.945	20.186	21.8805	+1.69
HCC	38.489	21.851	24.471	+2.62
HCG	44.737	17.288	21.5445	+4.26
HCK	50.456	16.230	20.364	+4.13

Residues within the HC, like the eggshells, grass stem or remaining wood chips, are either inorganic components or more complex organic matter, and thus, more challenging to carbonise. In the theoretical section (2.1.1), it was mentioned that lignin, a special structure of organic carbon, for example, undergoes different reactions during hydrocarbonisation (Olszewski et al., 2019). This possibly played a partial role in the case of the green waste or the wood chips with a high content of such lignin. Inorganic material content is reflected in the ash content. As long as the residues do not negatively change the characteristics of the HC, they are negligible.

5.3 *Escherichia Coli* Removal Efficiency

Physical adsorption and mechanical straining are the main mechanisms for pollutant removal using sand filters of the type applied in this project (chapter 2.2.1). Blockage and adsorption can be enhanced by high surface area and small pore volume (PV) of the column. However, these results do not demonstrate the positive effects of a smaller PV of columns on the removal of *E. coli*, presumably because the coliforms are too small to be retained by physical exclusion. In the case of *E. coli*, whose cell is negatively charged, lower negative zeta potential is beneficial to a lower repulsive force (Foppen & Schijven, 2006). Low hydrophilicity, interpreted via the water content, enhances the colloid deposition (Enaime et al., 2020).

Applied to the columns (Table 7), the HCK (77 % removal efficiency) exhibits, the smallest PV in the column, the second-highest BET, and the second-lowest negative zeta potential. As well as the lowest water content (i.e., stronger hydrophobicity). Thus, this HC has great potential for a good result. The second-best result (HCC) shows the largest PV in the column, the highest BET and a median zeta potential. The column with the lowest removal rate of 7 % from the HCG can be attributed to a minor BET and a strong negative zeta potential. Based on the observation, the characteristics of HC180M do not clearly explain the negative removal of 46 % during the experiment. The properties are not distinctive from the other series because of a favourable zeta potential but low hydrophobicity. Although it is not certain whether this has any effect on the results, the HC180M shows the highest EC (0.142 mS/cm) and the highest pH (7.5). In comparison, the median value of all HC is pH 5.1 and 0.063 mS/cm.

The best *E. coli* removal was achieved by the co-HTC process using the kitchen waste and human faeces. The characteristics of the HC with a large surface area, higher hydrophobicity, and less negative surface charge (i.e., weak electrostatic repulsion between HC and *E. coli*) are advantageous. In addition, a low PV in the filter indicates potential for retention. The drawback associated with this HC for this experiment was its high content of calcium carbonate in eggshells, which presumably caused a change in water pH in the outflow. On the other hand, HCG has a similar ash content (Figure 10) that did not display any discrepancies and was not further investigated. Thus, the ash content is a sensitive unknown parameter in terms of constituents and potential effects requiring more research. One option could be repeating experiments using eggshells as the main additives, provided that drinking water quality is high, despite the high pH value of 9 in the effluent (most values range from 6.5-8.5) (WHO, 2007). An alternative approach would be the selection of kitchen residues with high organic content. However, this would alter the composition considerably and invalidate the results obtained here, something to consider regardless.

The composition of kitchen waste varies because of diverse factors such as dietary habits, as well as cultural and regional factors and more, which renders a general characterisation difficult. Furthermore, a comparatively large increase in the calorific value was observed during co-HTC. Whether this was coincidental ought to be examined in a future experiment. Nevertheless, it should be considered whether this type of hydrochar would suit for energetic use. A distinct advantage of kitchen waste is that it is ubiquitous and thus provides a constant source. In contrast, coffee grounds for HCC may prove difficult to obtain in the required quantity. Hence, this option is limited to specific circumstances, for instance with involvement of a coffee shop. Nevertheless, the result with HCC appears promising. In contrary to the HCK, the quality of the effluent showed no changes while the result of 36 % is good for the dimension of the column. Compared to the commonly applied height of at least one metre, retention time and surface area are reduced in smaller columns. Regarding the other two HC types, using a green

waste-manure mixture and manure only, both results were lower than those of sand filtration without additives (16 %). Therefore, these two do not bring any additional benefit to this intended application. With its high Zeta potential, the HC with green waste might be useful for the removal of other components, preferably with positive surface charges e.g. heavy metals.

By comparing the characteristics of the hydrochars with the results, it appears that no individual factor determining the result can be identified. The most promising parameter with HCK is hydrophobicity. Hydrochars with also good hydrophobicity are HCG (7 %) and HCC (36 %). HCC has the highest specific surface area but only median zeta potential and hydrophobicity. And the most favourable zeta potential was obtained from HC180M. The difference lies in the fact that, apart from the best hydrophobicity, BET and zeta potential were also favourable for HCK, while for HCG all the other considered parameters were unfavourable. Therefore, it is reasonable to assume that the result was achieved through a combination of multiple favourable parameters.

There are various methods to influence the characteristics of the HC during or after the thermal treatment (Bhatnagar et al., 2013). For example, the surface area can be modified after the process by physical, or chemical activations. However, this involves additional labour and expenses. Another possibility involves the parameters during HTC (Sharma et al., 2020). Accordingly, it appears in this study that the reaction time is of special importance (HC200M has the smallest specific surface area).

Other factors that may have influenced the outcome are the conditions that prevailed in the columns. For instance, the high pH value measuring up to 9 in the effluent of the columns containing HCK may have deteriorated the environment in which *E. coli* survive and resulted in increased inactivation. Davey (1994) described the optimal pH range in the environment for *E. coli* between 6.5 and 7.5 (as cited in Philip et al., 2018). The elevated pH might be related to the increased content of inorganic matter. Furthermore, intra-column contamination was observed. This microorganism might have harmed the *E. coli* with e.g., predation or production of toxins. The contamination itself could be from mould production in the moist HC. Given that the HCK had been one of the most recent tests, it had been in the refrigerator for around two months. This applies to the HCC as well. This leads to another contributing factor which is the condition of the HC. Because moist hydrochar was used, it is more susceptible to mould and therefore, should be used fresh. Furthermore, it still contained PW and thus, took longer to wash in the columns. Preferential flow paths within the column might be the explanation as to why the EC stabilised at 45 µS/cm while the input showed an EC of about 15 µS/cm. Considering a general EC value of about 240 µS/cm in lake water, this should not pose a problem. What could be considered is the effect of a column that is not thoroughly cleaned. On the other hand, the results of the CTT in chapter 4.4 indicated good integrity of the columns, which would

contradict a prominent preferential flow. Additionally, mould contamination or increased pH in the effluent could interfere with the *E. coli,* or worse, could be an unwanted contamination sign causing deterioration of the drinking water quality.

6 Conclusion

This chapter refers back to the research questions and is structured into two parts. In the first part, the research questions are repeated and replied briefly. In the second section, specific recommendations for upcoming experiments are outlined.

6.1 Research questions

What methodological parameters should be specifically considered for the HTC practice with a low-cost reactor system?

Significantly improved results can be seen by homogenising the material before the treatment. The van Krevelen Diagram (Figure 12) revealed that hydrocarbonisation was more complete at 180 °C for a prolonged duration compared to 200 °C for a second (touch & down). Further parameters comprise the filling quantity of the reactor, or the proportion of dry matter and its loss. In this case, recommendations cannot be provided on account of the limited data. This would require another study with multiple replications. The same applies to the calorific value or calorific gain and energy consumption.

What is the mechanism of adsorptive removal for E. coli in sand-hydrochar filtration?

It is not possible to point out one single parameter responsible for *E. coli* removal. The evidence suggests that the interaction of several exceeded factors, which are defined as favourable, may have a greater effect than a few outstanding ones. The best performance of HCK can be explained because all considered values, such as hydrophobicity, BET and zeta potential, were over the median values.

Is it possible to use hydrochar from the HTC process of human waste supplemented with common organic wastes for water treatment and if so, which mix is suited best?

In summary, HC from coffee grounds and faecal matter and a faeces-kitchen waste mixture offers a solid foundation for further experimentation. More than 30 % removal in a filter column of 20 cm is considerable. An improved efficiency can be expected when operating a regular sized filter system. However, there are several issues to be answered. The introduction of kitchen waste requires more validation and research to avoid the leaking of undesirable substances. In this case, it is assumed that the composition of the inorganic compounds is disclosed as eggshells and hence mostly calcium carbonate. This might be different in other situations. Because of the heterogenicity of the mix, impurities may occur, causing adverse effects in the worst scenario. An example would be when plastic waste is present in food waste or if inorganic pesticides are found in green waste. The composition of Coffee Grounds would be more regulated and consistent.

Then there are the logistics, which were mentioned in the discussion. Waste streams like faeces, domestic waste, etc. are constant resource flows, whereas charcoal filters are occasionally needed when a clean sand filter is put into operation. Hence, supply and demand do not coincide in HC production and HC usage. Consequently, there would probably remain plenty of it unused and would have to be stored or repurposed. Therefore, other possible applications for this hydrocarbon should also be considered. Another option would be to integrate the produced HC into a business model for sand filter production.

6.2 Recommendations

The following recommendations are provided in case the sand filtration experiments are repeated or similar ones are conducted. First of all, selecting fewer types of HC in more replicas is more practical. In this way, flawed series can be identified and possibly eliminated. Secondly, all the media should be replaced regularly or should be prepared fresh for every experiment, since contaminations can develop. Furthermore, testing the water quality in the effluent is of interest. Not only the removal efficiency of the tested substance is important but as well the content of the water in general. Thereby, it can be established whether undesired substances are detached from the carbon. It would also be interesting to perform the experiments with the sand filter by using both moist and dried HC. The moist HC ought to be washed before its integration into the filter. Thereby, potential impurities might be eliminated in advance. The reason behind this recommendation relates to the storage of the HC. Since the intervals at which HC filter media are renewed and those at which sanitation facilities require emptying and hygienisation vary, a direct application of the HC in this manner is improbable. This would increase the risk of mould and recommends a treatment such as drying the hydrochar.

Finally, this study investigated the technical possibility. However, societal acceptance of such a filtration medium has not been addressed yet. This differs according to geographical, cultural, and socio-demographic structures and such a proposal might already founder in the beginning. Therefore, a societal and ethnical feasibility study is to be undertaken. Ideally in connection with a prospective study on implementation sites aiming at scaling up the low-cost reactor.

In general, there is potential for at least two types of source materials. However, the realisation in terms of implementation, effect, material management and acceptance seem to pose challenges for which it seems questionable to what extent these are worth it.

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Appendix

Appendix A List of Materials

Device	Usage	Provider	Type	City	Country	Additions
Ashing furnace	ash content	Nabertherm GmbH	L 4/11 BO	Bremen	Germany	
Autoclave	sterilize	Syntec GmbH & Co. KG	VX-150	Linden	Germany	
Balance	weight	Mettler-Toledo GmbH	ML4002T	Greifensee	Switzerland	d = 0.01g
Balance	weight	Mettler-Toledo GmbH	XSR1203S	Greifensee	Switzerland	d = 1mg
Balance	weight	Mettler-Toledo GmbH	FB60	Albstadt	Germany	max 60 kg
Blender	grind	LaHuko		Shenzhen	China	
Caliometer	calorific value	IKA®-Werke GmbH & CO. KG	C200	Staufen	Germany	
Camera	observation	Microsoft		Redmont	United States	
Centrifuge	separate	Eppendorf AG	5810R	Hamburg	Germany	
CHN instrument		Leco Coperation	TruSpec CHN	St. Joseph	United States	
Column	column set up	Adro AG	ROHR - Plexi-glas/Acrylglas Transpar-ent	Andelfingen	Switzerland	
Filter papers 11µm	filtration	Whatman plc	1001-125	Maidstone	United King-dom	
Gas canister	energy source	Primus AG	Primus Powergas	Stockholm	Sweden	Propane/Isobutan Mix
Gas mask	protection	3M	A1P2R	Rüschlikon	Switzerland	
Gas mask filter	protection	3M	ABEK1	Rüschlikon	Switzerland	
Grinder	grind	Retsch GmbH	MM400	Haan	Germany	
Incubationoven	incubation	New Brunwick Scientific GmbH	innova 4000	Nürtingen	Germany	
Mosquito net	column set up	Windhager Han-delsgesellschaft	Fliegengitter	Thalgau	Austria	LD-VB423-03

Multisensor	analysis	Hach Lange GmbH	HQ40d	Düsseldorf	Germany	
Oven	heat	Binder GmbH	FED 260	Tuttlingen	Germany	
Parafilm	column set up	Bemis	PM-996	Neenah	United States	
Petri dishes		VWR international GmbH	391-0559	Dietikon	Switzerland	
Pipette	pipette	Mettler-Toledo Rainin	Pipet-Lite XLS	Oakland	United States	
Plastic bottles	storage	Kautex		Bonn	Germany	
Plastic buckets	storage	Berry Superfos	2256-1B	Taastrup	Denmark	
Plastic canister 6L	sample	Fischer Söhne AG	6 Liter	Muri	Switzerland	
Plastic tubes 15 ml	*E. coli* test	VWR international Gmbh	525-1081	Dietikon	Switzerland	
Plastic tubes 50 ml	CCT, storage	Corning Science Mexico S.A. de C.V.	430829	Reynosa	Mexico	
Precision scale	weight	Sartorius AG	CPA64	Göttingen	Germany	d = 0.1 mg
Pump	pump	Longer Precision Pump Co., Ltd.	BT100-3J	Baoding	China	
Rubber plug	column set up	Faust Laborbedarf AG		Schaffhausen	Switzerland	Art. Nr. 9230423
Sand	column set up	Landi Schweiz AG	Sand Capito 25 kg	Dotzingen	Switzerland	Art. Nr. 44990
Sieve shaker	sieve	Retsch GmbH	AS200 digit cA	Haan	Germany	
Silicon hose	column set up	Faust Laborbedarf AG	Raulab FG Slidtec	Schaffhausen	Switzerland	Art.nr. 9205003
Vacuum pump	filtration	Merck Millipore	XF5423050	Darmstadt	Germany	
Vacuum pump	filtration	Faust Laborbedarf AG	PC 3001 Vario select	Schaffhausen	Switzerland	
Vortex	mix	Scientific Industries Inc.	Si-T256	Bohemia	United States	
Water bath	heat	Julabo Labortechnik GmbH	TW12 CH	Seelbach	Germany	