Greywater
Characteristics, Biodegradability and Reuse of some Greywaters

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Vorwort des Herausgebers

Die Autorin hat eine Fragestellung aufgegriffen, die fast zeitgleich von einer berufsständischen und regelsetzenden Vereinigung (DWA – Deutsche Vereinigung für Wasser, Abwasser und Abfall) erkannt und schon in einem Entwurf eines Arbeitsblattes gemündet ist. (Ein Arbeitsblatt stellt die höchste Stufe der Verbindlichkeit eines Regelwerkes dar und setzt voraus, dass genügend praktische Anwendungsfälle, aber auch genügend praktische Erfahrung vorliegen.) Aus diesem Sachverhalt heraus wird deutlich, dass sich Frau Weingärtner nicht unbedingt an die vorderste Front technisch-wissenschaftlicher Entwicklung begeben will; vielmehr konzentriert sie sich und ihre Untersuchungen – nicht nur experimenteller Art - auf ein praktisch zu lösendes Problem, dessen Anwendungshäufigkeit und Lösungsdringlichkeit in Zukunft zunehmen wird. Die in englischer Sprache gehaltene Schrift umfasst zehn Kapitel, einschließlich einer die Motivation erläuternden Einleitung und einer mit Umsetzung benannten Zusammenfassung am Ende. Die Autorin stellt eingangs fest, dass es keine übereinstimmenden Definitionen von sog. Grauwasser und vor allem keine in den verschiedensten relevanten Literaturquellen übereinstimmenden Angaben zu Inhaltsstoffen und deren Größenordnung gibt. So definiert sie selbst, insbesondere im Hinblick auf ihre eigenen Untersuchungen und ebenso auf die spätere Verwendung ihrer Erkenntnisse zur praktischen Grauwassernutzung Grauwasser als eine Sammlung von Strömen aus Dusche, Bad, Handwaschbecken und Waschmaschinen; sie schließt, vor allem aus Gründen der allzu hohen (biochemischen) Abbautendenzen Abflüsse aus dem Küchenbereich aus. Würde man diese mit einbeziehen – die für biochemischen Abbau der Grauwasserinhaltsstoffe bei der angestrebten biologischen Reinigung vorteilhaft wirken würden – wäre die ebenfalls erwünschte Speicherfähigkeit, so sagt sie, in Frage gestellt.

Ausgehend von der Divergenz der Berichte über Inhaltsstoffe und Höhe der einzelnen Komponenten beschließt sie die Herkunft und Größe der einzelnen Inhaltsstoffe (oder -stoffgruppen) aus entsprechenden Anwendungsfällen und Nutzercharakteristika, sowie aus den dazugehörigen Statistiken, abzuleiten. Über Stofffrachten und zum Einsatz kommende Wassermengen kann sie nicht nur eine plausible Grauwasserzusammensetzung erarbeiten, sondern auch erste Hinweise ableiten, wo Schwerpunkte weiterer Analysen liegen sollten. Ebenso ergibt sich unter anderem auch, wie unterschiedliches Nutzerverhalten die Grauwasserzusammensetzung spürbar verändern kann. Mit einem von ihr definierten synthetischen Grauwasser werden experimentelle Untersuchungen angestellt, die zum einen die uneingeschränkte biochemische Abbaubarkeit eruieren sollen und zum anderen den tatsächlichen Abbau in einem für solche dezentralen, also kleinen Anschlussgrößen passenden biochemischen Reaktor, einen Scheibentauchkörper belegen sollen. Die knapp gehaltenen Untersuchungen ergeben, dass mit den von ihr für das zuvor definierten synthetische Grauwasser ausgewählten Stoffen und Stoffgruppen biochemische Abbaubarkeit gegeben ist. Auch ein üblicher Bioreaktor würde funktionieren. Ebenso lassen die knappen Untersuchungen mit dem Laborscheibentauchkörper erkennen, dass die bisher geltenden konstruktiven und betriebstechnischen Hinweise aus dem einschlägigen Regelwerk modifiziert werden müssen, wenn man zum einen ein Zuwachsen der Scheiben verhindern will und zum anderen (noch nicht im Einzelnen definierte, aber plausible) Ablaufbedingungen erreichen will. – Auch hier empfiehlt sie weitere Detailuntersuchungen. Schließlich werden auch nichttechnischen Randbedingungen für die Anwendung von Grauwassernutzungskonzepten, wie Anpassung von Regelwerken und Richtlinien, Nutzerinformation und -gewinnung, Betrieb im Hinblick auf Personal und Überwachung und vieles mehr angesprochen. Interessant wird dieser Abschnitt durch einen Vergleich australischer und deutscher „Stakeholder“, wie die Autorin dies nennt, also Beteiligte (Aufsicht, Betreiber, Industrie etc.) Hier zeigt Frau Weingärtner, alles im Vergleich mit Australien, genauer New South Wales, dass die monetären Anreize für Grauwasserreinigung und -wiederverwendung in Deutschland aufgrund günstigerer Kostenrandbedingungen besser sein sollten, dass aber die hoheitlichen Regelwerke noch nicht genügend weit entwickelt sind.

Karlsruhe im November 2013

Der
Herausgeber
Hermann H. Hahn

Abstract

The traditional centralized water and wastewater structure in Germany faces challenges concerning the management of the large supply networks, sewer systems and wastewater treatment plants. Large sections of the structure are in need of rehabilitation while the future capacity demand impacted by demographic changes is hardly foreseeable. Therefore, more flexible solutions for future water and wastewater management are needed. The reclamation of greywater – domestic wastewater without urine and feces – is one opportunity to be more independent of central water supply and sanitation structures. Furthermore, water consumption and wastewater production are decreased by reusing greywater resulting in financial savings for users.

Based on experiences with greywater systems in Germany and other countries, the actual implementation of greywater reclamation raises questions. Compared to the established water and wastewater management, de- or semicentralized systems face other frame conditions. Not only are these specific conditions defined by technical and legal aspects, but also depend on the impact of affected stakeholders.

Consequently, this work deals with both technical and socio-economic aspects. Technical aspects focus on the characterization of greywater based on the incoming components. Not only is the biodegradability of greywater determined using a Rotating Biological Contactor, but also by assessing the degradability impacts of relevant personal care and household products. Socio-economic aspects are determined by referring to a region with more experiences concerning greywater system implementation. A stakeholder analysis in New South Wales, Australia, is introduced. In comparison, the German conditions are addressed and recommendations are concluded.

The results of this work indicate that kitchen greywater should be excluded from greywater collection in Germany. Ingredients from bathroom and laundry greywater show good biological degradability according to the normative definition of biodegradability. However, the usage of household cleaners needs further attention, since some inhibition effects were determined. For the treatment of greywater with a Rotating Biological Contactor, modified design parameters were developed focusing on constructional aspects and lower organic disk loads. Using the Rotating biological Contactor, a compliance of effluent quality with the current German recommendations was difficult. However, frame conditions like quality criteria and other legal aspects need to be discussed and defined to create a save background for investments in greywater treatment.

Zusammenfassung

Die in Deutschland bisher üblichen zentralen Wasser- und Abwasserstrukturen stehen vor erheblichen Herausforderungen hinsichtlich des künftigen Betriebs der großen Wasserversorgungsnetzwerke, Kanalisationssysteme und Kläranlagen. Weite Teile dieser Bauwerke sind sanierungsbedürftig. Dabei ist ihre künftige Auslastung angesichts des demografischen Wandels nur schwer abschätzbar. Flexiblere Lösungen werden in der Wasserwirtschaft benötigt. Die Wiederverwendung von Grauwasser – häusliches fäkalienfreies Abwasser – ist eine Möglichkeit Wasser unabhängiger von zentralen Ver- und Entsorgungsnetzwerken zu nutzen. Zudem schlagen sich reduzierte Wasserumsätze in finanziellen Einsparungen für Wassernutzer nieder.

Die bisherigen Erfahrungen mit Grauwassersystemen in Deutschland und anderen Ländern haben unterschiedliche Fragestellungen aufgeworfen. Im Vergleich zu den etablierten Wasserver- und entsorgungssystemen unterliegen de- bzw. semizentrale anderen Randbedingungen. Diese sind nicht nur von technischen und legalen Aspekten bestimmt, sondern auch von den beteiligten Interessengruppen.

Daher umfasst die vorliegende Arbeit technische sowie sozio-ökonomische Faktoren. Die technischen Fragestellungen beschreiben zunächst die Zusammensetzung von Grauwasser durch die unterschiedlichen erfassten Stoffe. Folgend wird die biologische Abbaubarkeit nicht nur unter Verwendung eines Scheibentauchkörpers, sondern auch durch die Beurteilung von Pflege- und Haushaltsprodukten hinsichtlich ihres Einflusses untersucht.

Unter Verweis auf eine Region mit weitreichenden Erfahrungen bezüglich der Nutzung von Grauwasser wurden sozio-ökonomische Zusammenhänge erschlossen. Eine Akteursanalyse wurde in New South Wales, Australien, durchgeführt. Im Vergleich dazu wurden die deutschen Bedingungen erfasst und entsprechende Empfehlungen wurden erarbeitet.

Die Ergebnisse der vorliegenden Arbeit zeigen auf, dass Küchenabwässer, sofern möglich, von der Grauwassersammlung ausgeschlossen werden sollten. Die Inhaltsstoffe des Grauwassers aus Badezimmern und Waschmaschinen hingegen zeigen entsprechend der normativen Definition gute biologische Abbaubarkeiten. Die Nutzung von Haushaltsreinigern sollte jedoch künftig näher untersucht werden, da Hemmwirkungen nachgewiesen werden konnten. Anhand der Grauwasserbehandlung mit einem Scheibentauchkörper wurden Bemessungsparameter bezüglich der Scheibenbelastung und baulicher Ausführung modifiziert. Die Einhaltung der in Deutschland empfohlenen Abflussqualität war mit der Grauwasserbehandlung im Scheibentauchkörper schwierig. Rahmenbedingungen der Grauwasserreinigung, wie die Qualitätsanforderungen für das gereinigte Wasser aber auch andere rechtliche Aspekte, müssen jedoch weiter diskutiert und definiert werden um eine sichere Grundlage für Investitionen in Grauwassersysteme zu schaffen.

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Abbreviations

BOD_x	Biochemical Oxygen Demand in x days
c	Capita
COD	Chemical Oxygen Demand
COD_d	Dissolved COD
DIN	Deutsche Industrie Norm (German Industry Standard)
EC	Electrical Conductivity
MBR	Membrane Bio Reactor
pH	*potentia hydrogenii*
RBC	Rotating Biological Contactor
SI	International System of Units
T	Temperature
TOC	Total Organic Carbon
TSS	Total Suspended Solids
UV	Ultra Violet
VSS	Volatile Suspended Solids

Further abbreviations are used according to the SI-System.

1 Introduction

“Water management involves all activities concerning natural water resources, not only their availability at all times and all hands, but, above all, the preservation of these resources” (translated according to Hahn, 2006).

Water is essential for all life. While humanity is facing profound changes of demographic and climatic nature, water management is challenged not only to maintain, but also improve water supply and sanitation. In Germany, the history of water management has generated a large and valuable network for water supply and sanitation. Yet, demographic changes make the long-term operation of centralized structures difficult. Thus, more flexible structures are needed: New technologies that are i. a. characterized by source separated collection and treatment of waste(water) streams as well as decentralized operation (Hahn, 2006) are under development. The reclamation of greywater is one of these technologies and the focus of this work. For greywater reuse in Germany, questions concerning the greywater treatment process and the frame conditions of a technology implementation are determined to enhance the adoption of greywater reclamation.

1.1 Greywater reuse – Definition

Greywater is defined as domestic wastewater excluding fecal matter and urine (DIN EN 1085, 2007).

Treated greywater can be used to substitute tap water where drinking water quality is not required, e. g. for toilet flushing, laundry or irrigation (cf. Figure 1.1). Thus, by reusing greywater, the overall consumption of tap water is reduced.

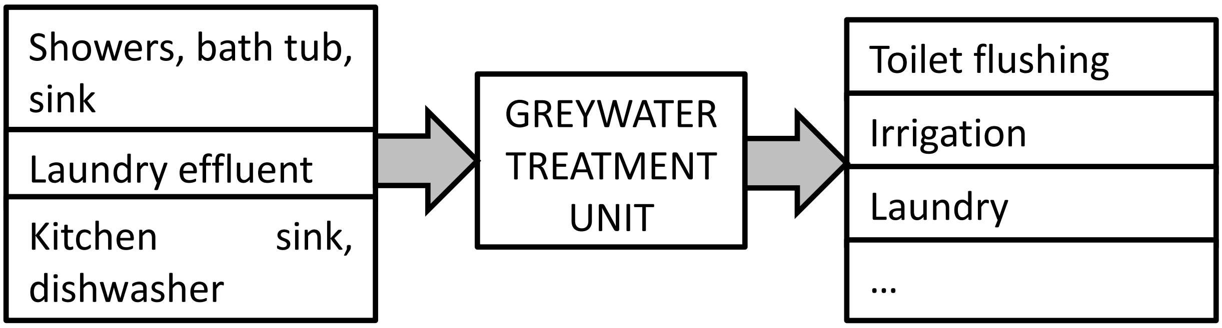

Figure 1.1: Exemplary overview greywater reuse scheme

The definitions of greywater[1] vary in different countries. Generally, wastewater originating from toilets (blackwater) is excluded, due to the high loads of feces and urine, whereas wastewater originating from bathtubs, showers and hand washbasins is included in each definition of greywater

With respect to wastewater generated by washing machines, dishwashers and kitchen sinks, definitions of greywater can vary from country to country. However, kitchen greywater is often excluded from the practical greywater collection.

1.2 Practical experiences

Greywater reuse has been researched in Germany but also in other countries, e. g. in Israel (Friedler et al., 2005), Morocco (Merz et al., 2007), the UK (Hills et al., 2001), Sweden (Fittschen and Niemczynowicz, 1997), Australia (Diaper, 2004), or the USA (Rose et al., 1991).

In some of these countries, greywater is an established means to save water and has thus been implemented into legislation (e. g. California, Australia). Codes of practice concerning greywater were developed, mainly in the last decade. In Germany, greywater reuse is, together with source separating sanitation systems, addressed by the German Water Association (DWA, 2008; DWA-A 272, draft version, 2013). Yet, the practical implementation proves to be a complex challenge.

1.2.1 State of the art

Different greywater reuse systems have been determined worldwide: the extent of covered greywater sources varied, as did the reuse application and the treatment technology. While the variation of source combinations is one reason for an inconsistent data base concerning greywater characteristics, the neglect of regional differences and temporal impacts is another one.

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[1] The term “greywater” is used in this work. In addition, “grey water”, “graywater”, and “gray water” are used equivalently in international literature.

Biological treatment, covering the wide range of technologies known from conventional wastewater treatment, is the established treatment technology (Pidou, 2007). Yet, the characteristics of greywater indicate impeded biodegradability and laboratory tests verified this assumption (Jefferson et al., 2001). Thus, greywater treatment is seen critical for practicable application. However, practical experiences showed satisfying effluent qualities (e. g. Bullermann et al., 2001). Thus, the biodegradation of greywater in a biological treatment system is one of the topics of this work.

An aspect not considered before is the potential impact of commonly used household chemicals entering the greywater treatment system. Yet, ingredients of household cleaners can be toxic and caustic and thus damage the biological system which is essential to maintain effluent quality.

1.2.2 Service water quality

Untreated greywater caused hygienic and aesthetic problems in the past. Not only was the domestic use of untreated greywater rejected due to the health risks associated with increasing counts of indicator organisms, but also due to the occurrence of malodors and slime (biofilm) formation in greywater pipes and storages (e.g. flushing tanks) (Nolde, 2005).

Biofilm formation and bad odors are caused by the degradation processes of organic compounds in greywater. These degradation processes deplete oxygen in the water, causing anaerobic conditions and, as a result, malodor.

As a consequence, the German recommendations for indoors greywater reuse quality define maximum BOD_7 = 5 mg/L and a minimum oxygen saturation of 50 % (≈ 5 mg O_2/L) (SenBer, 2007). Therefore, the occurrence of anaerobic conditions is practically excluded at least for a week of storage time. Based on prior experiences, biological treatment is recommended (Mehlhart, 2005; SenBer, 2007; Pidou et al., 2007).

1.3 Scope and structure of this work

This work focusses on two main aspects of greywater reuse in Germany. The first aspect focusses on the treatment process by determining greywater characterization and biodegradability. The second aspect takes into account the wider frame conditions, beyond technical aspects. These frame conditions, which are crucial for the technical implementation of greywater reuse, were approached by determining the practice of greywater reclamation in New South Wales (Australia), where greywater systems are more common than in Germany.

1.3.1 Overview of greywater characterization and biodegradability

Based on the practical experiences and state of the art, the first part of this work focuses on greywater itself – its characterization – and on its biodegradability. The aims of the analyses are:

- Characterizing greywater by determining its composition. Based on data for ‘resulting greywater’, the composition of greywater was analyzed more deeply by regarding the ‘greywater streams’ and their respective ‘components’ (Figure 1.2).
  The characterization of greywater is based on literature data (Chapter 4.2), own sampling (Chapter 4.3) and an approach developed in this work using statistical consumption data (Chapter 4.5).
- Determining the biodegradability of selected greywater components using the Zahn-Wellens-Test: the characterization of greywater shows the relevance of personal care products and laundry detergents as greywater components. Both component groups are a source of organic substances (surfactants/xenobiotics) with questionable biodegradability. Thus, the biodegradability of respective products was tested (Chapter 5).
- Identifying potential inhibition effects by household cleaners on biological greywater treatment (Chapter 6).
- Treating greywater with a Rotating Biological Contactor and modifying its respective design parameters according to the specifics of greywater (Chapter 7).

Figure 1.2 gives an overview of the aspects considered in the process related chapters. Sections of it will be used in the respective chapters to give orientation.

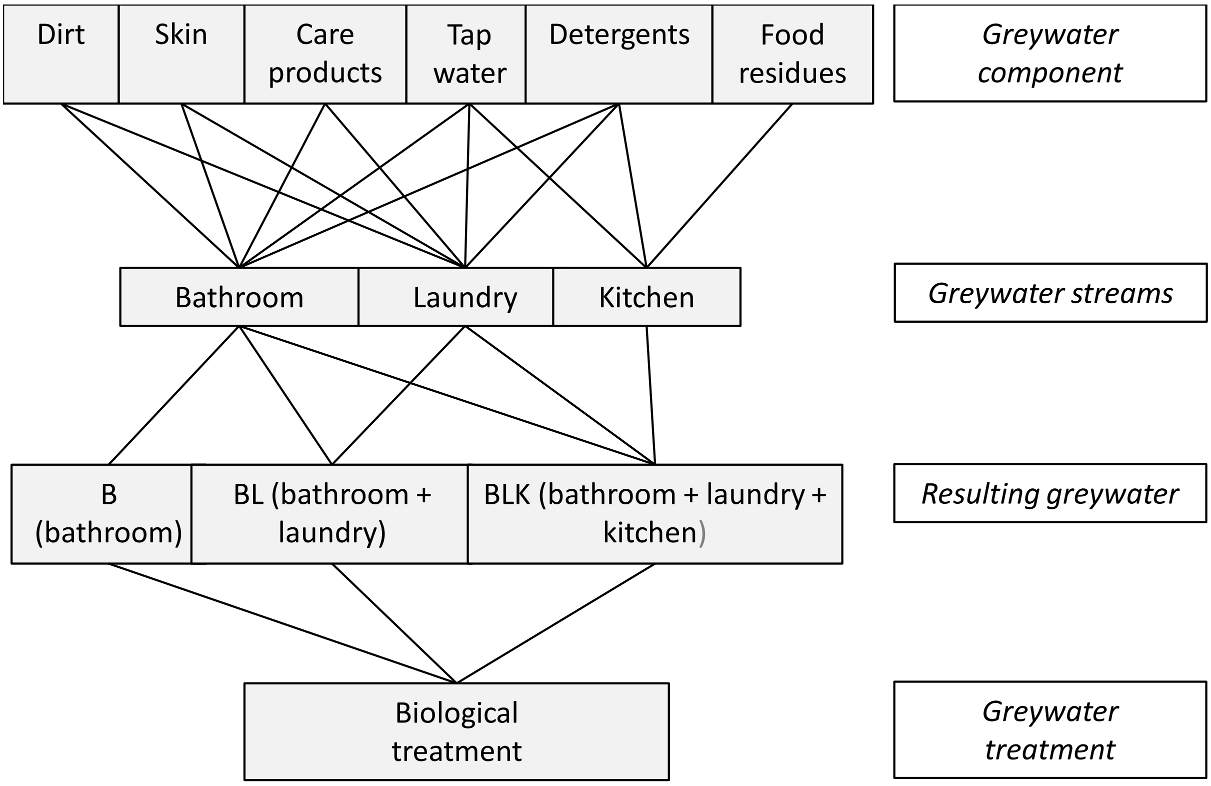


Figure 1.2: Schematic overview – general greywater composition and treatment

1.4 Implementation of greywater reuse

Following technical, process related aspects of greywater treatment, the frame conditions for the implementation of greywater reuse were explored (Chapter 9). Legislative and socio economic factors were covered using a comparative stakeholder analysis, which is based on experiences with greywater reclamation in New South Wales, Australia. Conclusions concerning the implementation of greywater reuse in Germany are drawn and the actual development of guidelines is addressed.

2 Introduction to biological greywater treatment

In the following chapter, the basic principles of biological wastewater treatment are explained and specific aspects of greywater treatment are pointed out.

2.1 Biological wastewater treatment - principles

The aim of biological greywater treatment is to remove organic substances from the water. The microbial processes used during treatment, are basically the same that occur in the degradation processes in untreated greywater described above (Chapter 1.2.2). Yet, the systematic treatment optimizes the conditions for microbial degradation processes to focus them in the treatment unit. Organic substrate is used by a diverse group of microorganisms as chemical energy source and to provide carbon for microbial growth. Thus, these microorganisms are classified as chemoorganoheterotrophs.

Table 2.1: Classification of microbial processes in greywater

Energy source	**Electron donor**	**Carbon source**
Chemical reaction (Oxidation)	Organic Carbon	Organic
Chemo-	*organo-*	*heterotroph*

2.2 Metabolism

The different oxidation stages of organic carbon deliver energy that is stored by transforming ADP to ATP (Adenosindi- and -triphosphate). This is illustrated in Figure 2.1, using the oxidation of glucose as an example: furthermore, the role of oxygen as electron acceptor is demonstrated.

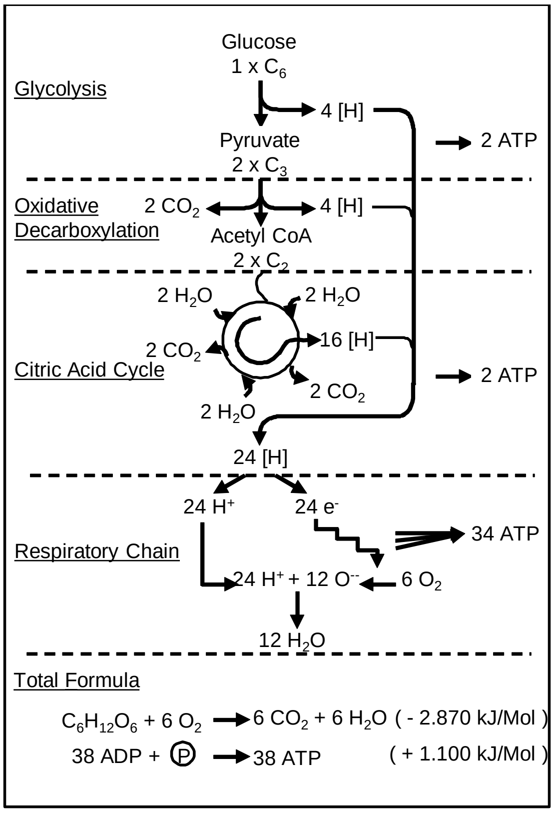


Figure 2.1: Aerobic degradation of Glucose (Mudrack and Kunst, 2003)

Glucose is an organic compound. During the biological degradation process, Glucose is disassembled following the steps shown in Figure 2.1: Glycolysis → Oxidative Decarboxylation of Pyruvate → Citric Acid Cycle → Respiratory Chain. The overall degradation of Glucose is exothermic. Thus, (combustion) energy (2.870 kJ/Mol) is released. This energy is partially available for microorganisms by transforming ADP to ATP (1.100 kJ/Mol). The difference between the total potential combustion energy of glucose and the energy stored as ATP is lost during the degradation process (heat loss: 2.870 – 1.100 = 1.770 kJ/Mol).

Organic compounds not only serve as energy source: The metabolism of energy is defined as **catabolism**. However, organic carbon also serves as source for **anabolism**, the synthesis of new biomass.

For anabolism, both carbon and nutrients are needed (cf. Table 2.2). The major nutrient is nitrogen, which is an essential element of proteins. Proteins are structural macromolecule in cells and, moreover, the integral part of enzymes.

Table 2.2: Typical concentrations of elements in heterotrophic microorganisms (aerobic processes), according to Henze and Harremoes 2002

	g/kg VSS	g/kg COD	g/kg TOC
Carbon C	400-600	300-400	1000
Nitrogen N	80-120	55-85	150-250
Phosphorus P	10-25	7-18	25-55
Sulphur S	5-15	4-11	12-30
Iron Fe	5-15	4-11	12-30

2.2.1 Ratio of anabolism to metabolism

Both, anabolism and catabolism, remove organic carbon from greywater. While catabolism mineralizes organic carbon to water and carbon dioxide, anabolism transforms organic carbon into biomass. As shown in Table 2.3, the ratio of anabolism to metabolism depends on the substrate supply (Gallert and Winter, 2005). It is expressed as the Yield-factor. The yield (Y) is the ratio of biomass growth (ΔX) per mass of metabolized substrate (ΔS), (Henze and Harremoes, 2002):

$$Y = \frac{\Delta X}{\Delta S} \qquad 2.1$$

Table 2.3: Impact of substrate on Yield (Henze and Harremoes, 2002)

Organism	**Yield g COD_{Cell}/g $COD_{Substrate}$**
Bacteria with substrate for growth	0.60
Bacteria with much substrate and extensive storage	0.95
Bacteria with very little substrate	0.00

The impact of substrate supply on bacterial growth is quantified in the Monod-equation:

$$\mu = \mu_{max} \frac{S}{K_S + S} \qquad 2.2$$

$\mu_{(max)}$	(Maximum) specific growth rate [h^{-1} or d^{-1}]
S	Concentration of the limiting substrate [mg/L]
K_S	Monod constant: Half-velocity constant (S when $\mu = 0.5\ \mu_{max}$); [mg/L]

2.3 Kinetic quantification of degradation

The Yield-factor links the biomass growth to the substrate removal. Thus, the kinetic of substrate removal follows a similar form like Monod (Equation 2.2) and is described by the equation of Michaelis-Menten:

$$V = V_{max} \cdot \frac{S}{k_m + S} \tag{2.3}$$

V	Degradation velocity [mg/(L·h)]
V_{max}	Maximum degradation velocity [mg/(L·h)]
S	Substrate concentration [mg/L]
k_m	Michaelis-Menten constant: substrate concentration with ½ V_{max} [mg/L]

The substrate removal is based on enzymatic reactions, like e. g. the different degradation steps of glucose illustrated in Figure 2.1. While Michaelis-Menten is, in the strict sense, referring to a single specific enzymatic reaction, the degradation of organic carbon in wastewater is based on a combination of various enzymatic reactions. Yet, in practice, the Michaelis-Menten equation is applicable to reflect the degradation of organic substrate groups.

2.4 Enzymatic reaction principles

In the enzymatic reaction, the enzyme serves as catalyst. It processes one substrate component after another without being used up. An enzyme is normally a large, complex protein (Segel, 1975). This complex structure has an ‘active site’ serving as docking point for the substrate molecule, which is catalyzed by the enzyme.

The velocity of the catalytic reaction is defined by its different steps: Formation of Enzyme-substrate complex (equilibrium reaction) and the generation of the product.

$$E + S \underset{k_{-1}}{\overset{k_1}{\rightleftarrows}} ES \xrightarrow{k_P} E + P \tag{2.4}$$

E	Enzyme
S	Substrate
ES	Enzyme-substrate complex
P	Product
k_i	Kinetic constants

The Michaelis-Menten constant k_m is defined by the reaction constants:

$$k_m = \frac{k_{-1} + k_P}{k_1} \tag{2.5}$$

2.4.1 Inhibition

The enzymatic reaction can be disturbed by inhibitors in each specific step of the enzymatic reaction (Equation 2.4), leading to different inhibition mechanisms (Segel, 1976) illustrated in Figure 2.2:

Competitive inhibition: a competitive inhibitor combines with the enzyme in a way that prevents the substrate from binding properly to the active site of the enzyme. Thus, the reaction of the substrate is not catalyzed. Competitive inhibitors often resemble the substrate, bind to the enzyme at the active site and block it for the substrate. As a consequence, the kinetic parameter k_m (Equations 2.3 and 2.5) is increased.

Uncompetitive inhibition: An uncompetitive inhibitor binds to the enzyme-substrate complex and thus prevents the generation of the product. The kinetic parameters v_{max} and k_m Equations 2.3 and 2.5) are both decreased.

Noncompetitive inhibition: A noncompetitive inhibitor and the substrate can bind to the enzyme independently from each other. If the inhibitor and the substrate are bound to the enzyme at the same time, the catalytic reaction will be blocked. Thus, the kinetic parameter v_{max} (Equations 2.3 and 2.5) is decreased.

linear mixed-type inhibition: the linear mixed-type inhibition is a form of a noncompetitive inhibition but the dissociation constants k_i (Equations 2.5) are altered. Thus, v_{max} and k_m Equations 2.3 and 2.5) are impacted: k_m is increased and v_{max} is reduced.

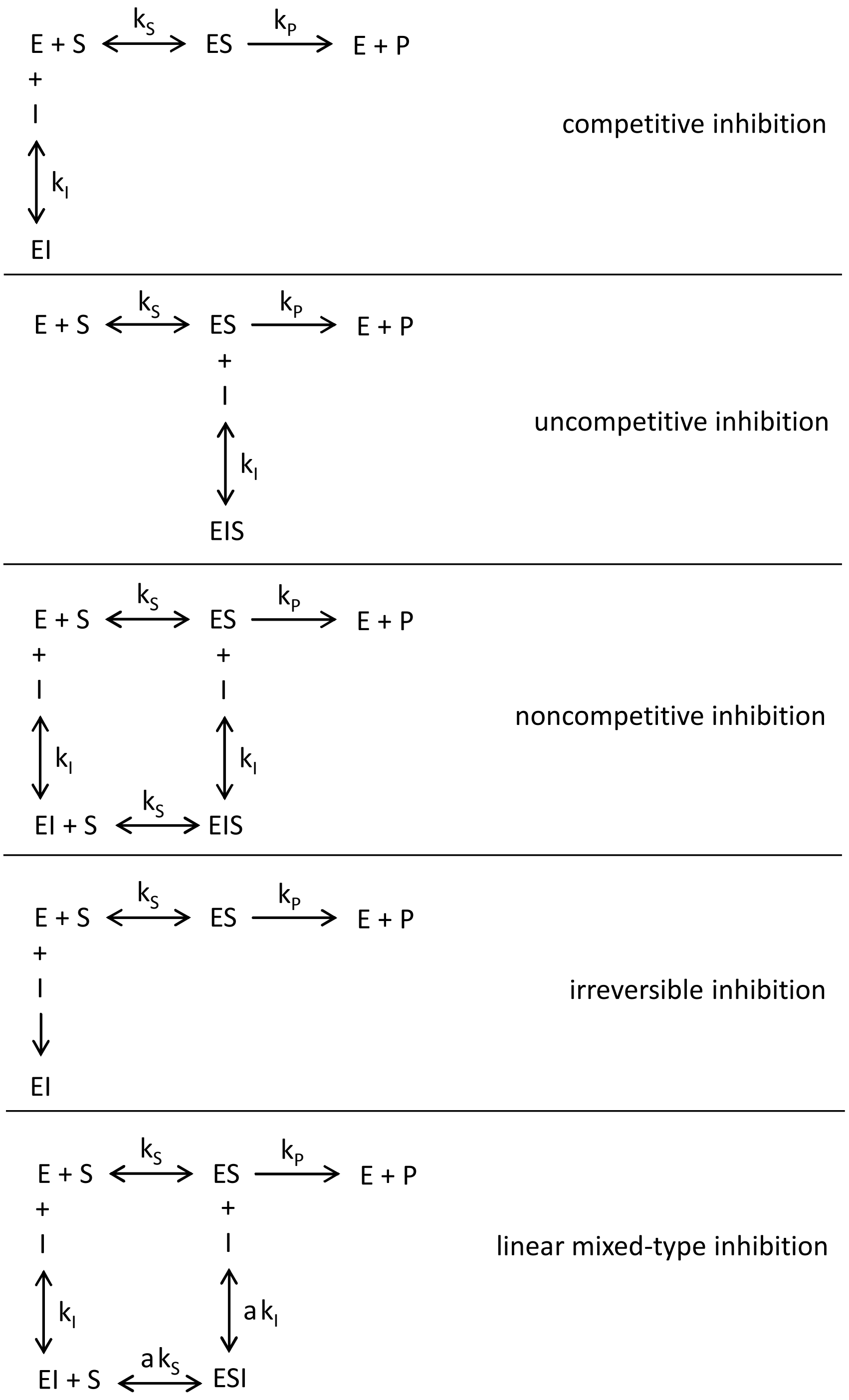


Figure 2.2: Inhibition mechanisms (Segel, 1976)

Inhibition can be caused by organic substances, e. g. by competing with a substrate for the same reactive site of an enzyme. Furthermore, salts in high concentrations impact enzymatic reactions (cf. Table 2.7).

While the inhibition mechanisms described above only cover basic principles, the range of factors impacting enzymatic reaction is wider (e. g. described in Segel, 1975). In addition to specific inhibition mechanisms, unspecific denaturation processes can reversibly or irreversibly damage enzymes, e. g. by extreme pH values or temperatures (c. f. Chapter 0).

2.4.2 Determination of kinetic parameters

The recordings of a substrate degradation following Michaelis-Menten (Equation 2.3) are illustrated in Figure 2.3.

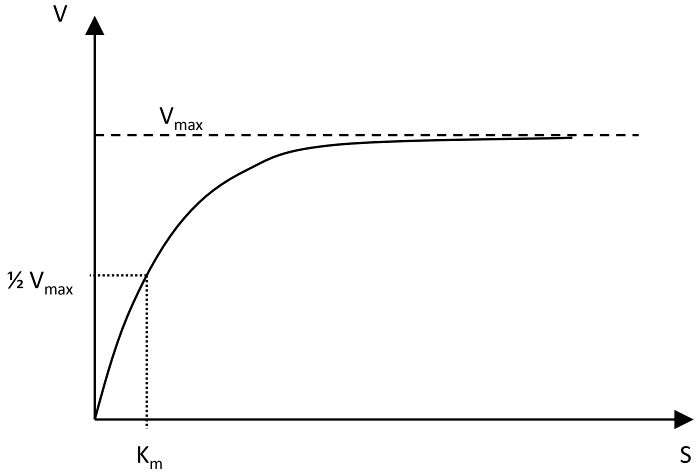


Figure 2.3: Substrate degradation according to Michaelis-Menten

To determine the kinetic parameters V_{max} and k_m, Equation 2.3 can be linearized according to Lineweaver and Burk (1934):

$$\frac{1}{V}=\frac{k_m+S}{S\cdot V_{max}}=\frac{k_m}{V_{max}}\cdot\frac{1}{S}+\frac{1}{V_{max}} \qquad 2.6$$

In the graph (Figure 2.4) of Equation 2.1, the y-intercept is $1/V_{max}$ and the x-intercept is $-1/k_m$. Thus, Michaelis-Menten parameters and their changes can be calculated using linear regression.

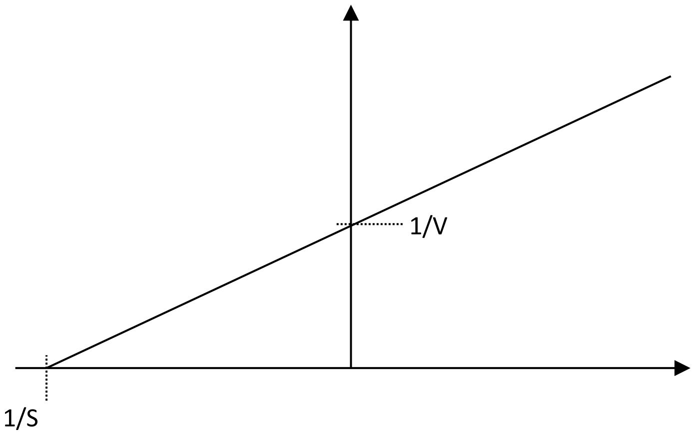
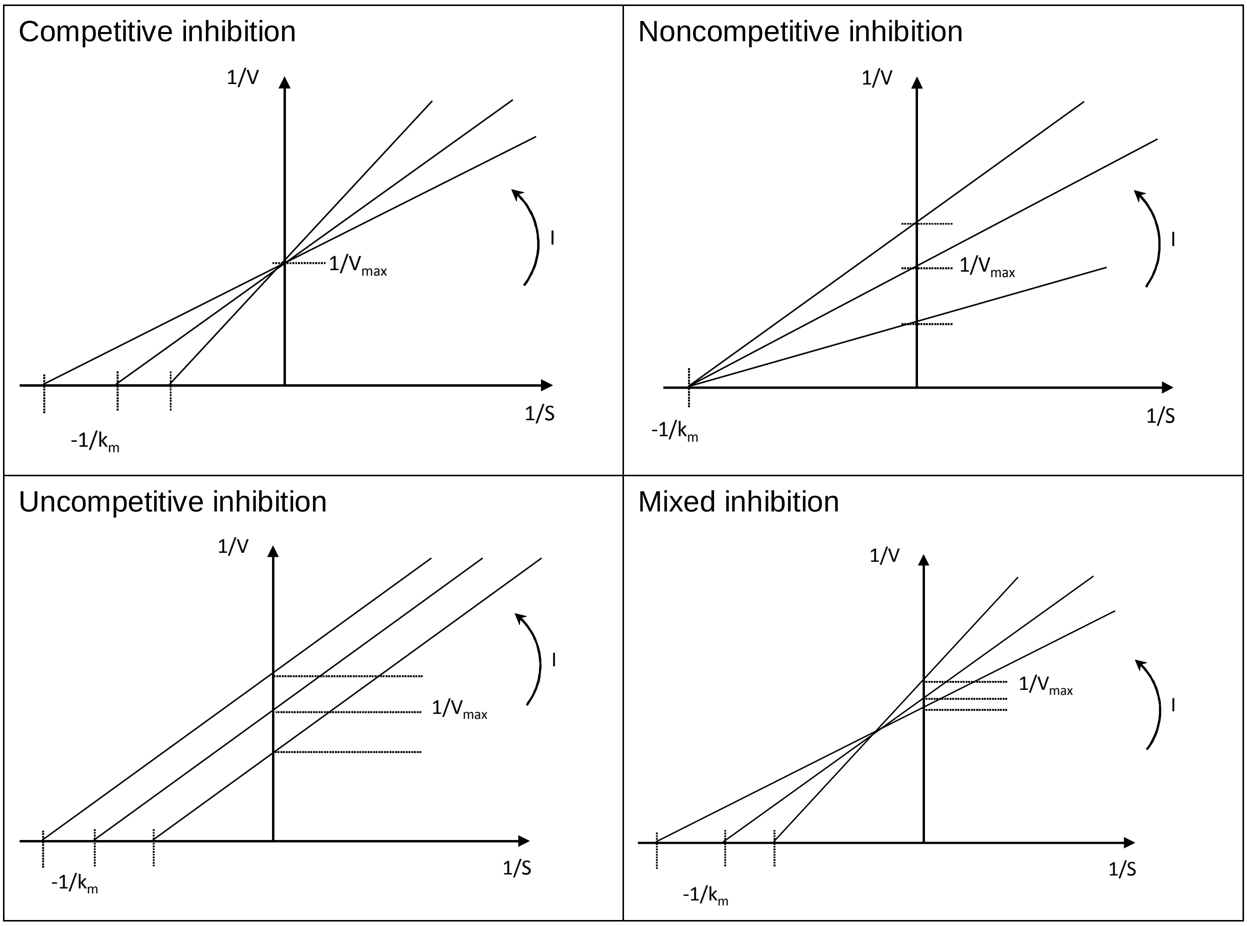


Figure 2.4: Lineweaver-Burk linearization

The different inhibition mechanisms impact the Lineweaver-Burk graph as shown in Figure 2.5.


Competitive inhibition

Noncompetitive inhibition

Uncompetitive inhibition

Mixed inhibition

Figure 2.5: Lineweaver-Burk graphs resulting from different inhibition mechanisms (according to Segel, 1976)

The changes of the kinetic parameters k_m and v_{max} (Equations 2.3 and 2.5) caused by inhibition (Chapter 2.4.1) are visualized in the Lineweaver-Burk graphs. Thus, Lineweaver-Burk can be used to graphically determine inhibition effects.

The principles of enzymatic kinetics according to Michaelis-Menten refer to a single enzymatic reaction. Yet, the degradation of organic substances in wastewater is based on a sum of different enzymatic reactions. Applying Michaelis-Menten kinetics or the Monod equation (if reference is given to growth) refers to the bottle-neck enzymatic reaction of the energy metabolism or for growth.

2.5 Wastewater parameters – Introduction and indications for biological treatment

In wastewater treatment, pollutants are determined as sum parameters according to their properties and their impact. In the following, the main parameters relevant for this work are discussed. Furthermore, indications of these parameters for biological treatment are introduced.

2.5.1 Organic compounds

Organic compounds are carbon based molecules. Their oxidation (cf. Figure 2.1) is exothermic and thus a potential energy source for microorganism. In wastewater, one of the main parameters representing organic carbon is the “chemical oxygen demand” – COD. It is the sum of oxygen needed to completely mineralize the organic carbon (Gujer, 2007).

However, microorganisms in biological wastewater treatment do not completely mineralize organic carbon: a part of the organic compounds is transformed to biomass (cf. Yield factor, Equation 2.1) and the specific suitable enzymes are needed. Thus, organic molecules that are very rare or afford very complex enzymatic reactions are not degraded.

The sum of organic carbon that is biologically oxidized within a specific time span is determined by the “biochemical oxygen demand” – BOD. It is normally referring to the oxygen demand in 5 days at 20 °C and thus is specified as BOD_5 (Gujer, 2007).

COD/BOD-ratio

Since the BOD is determining the biological degraded part of COD, the ratio of COD to BOD is an indicator for biological degradability. Typical ratios of COD/BOD are shown in Table 2.4:

Table 2.4: COD/BOD ratios in domestic wastewater (Henze and Harremoes, 2002)

Ratio	**Low**	**Typical**	**High**
COD/BOD	1.5-2.0	2.0-2.5	2.5-3.5

Smaller ratios of COD/BOD indicate better biodegradability than higher values. Table 2.5 shows qualitative classification of biodegradability according to the COD/BOD-ratio.

Table 2.5: COD/BOD$_5$-ratios and indicated biodegradability (Defrain, 2004)

Biodegradability	**Direct**	**Easy**	**Very slow**
COD/BOD$_5$-ratio	< 2	2 - 5	> 5

Since the actual biodegradability of organic carbon in a treatment system is depending on further features, e. g. on adapted biomass, the COD/BOD-ratio is only of limited information value. Yet, it enables an estimation of biodegradability based on customary wastewater parameters.

Xenobiotic substances and surfactants

The term “xenobiotic” comprises substances that are foreign to a biotic system. In the context of wastewater treatment, these substances are pollutants that are of artificial origin. This has two consequences. First, the degradability of xenobiotics is restricted since it depends on the availability of the respective suitable enzyme. Second, xenobiotics can harm microorganisms and thus impact their function to degrade pollutants, e. g. by inhibiting enzymatic reactions (cf. Figure 2.2 and Figure 2.5).

Surfactants are a group of substances also known for potential impact on biological systems. Some surfactants are xenobiotics. Moreover, surfactants can harm microorganisms in biological treatment and can be of limited degradability.

Both, xenobiotic substances and surfactants have limited biodegradabilities. For this reason, residues of these substances can remain in treated wastewater. Biological systems that come into contact with this water can be damaged.

Xenobiotic substances and surfactants mainly consist of organic carbon. Surfactants can easily be determined analytically. Yet, the range of xenobiotic substances and their various impact mechanisms cannot be traced by one analytic test. Thus, the detection and quantification of xenobiotic substances is complex (e. g. described in Eriksson et al., 2003).

2.5.2 Nutrients

Nitrogen and Phosphorus

Two major elements, nitrogen and Phosphorus, are essential for biodegradation. Phosphorus is needed for catabolism in ADP and ATP (cf. Figure 2.1). Nitrogen is an essential component of biomass and enzymes (which are responsible for biodegradation). In regard of the removal of organic substances, the optimum ratio of COD:N:P lays between 100:20:1 (Metcalf and Eddy, 1991) and 100:10:1 (Beardsley and Coffey, 1985). While excess loads of nitrogen and Phosphorus have to be removed in wastewater treatment, a deficiency of these elements impedes biological treatment.

Nitrogen and Phosphorus are covered by different wastewater parameters (Table 2.6) according to the respective information that is needed.

Table 2.6: Common indicators for nutrients in wastewater (according to Gujer, 2007)

Compound	Labeling	Remark
Ammonium, Ammonia	NH_4^+(-N)	
Organic Nitrogen	N_{org}	
Total Kjeldahl Nitrogen	TKN	Sum of NH_4^+-N and N_{org}
Nitrite, Nitrate	NO_2^-(-N), NO_3^-(-N)	
Total Nitrogen (bound)	TN, N_{tot}, TN_b	All nitrogen forms except N_2
N_2	-	Hardly soluble in water, not determined
Phosphate Phosphorus, ortho-Phosphate	PO_4^{3-}(-P)	
Total Phosphorus	TP, P_{tot}	

Further nutrients

Further nutrients are, similar to nitrogen and Phosphorus, needed for biological organisms. Yet, the dosages are smaller than those of nitrogen and Phosphorus.

Table 2.7: Further nutrients and their role for bacterial metabolism (Burgess et al., 1999, qtd. in Jefferson et al., 2001)

Nutrient	Role of nutrient
S	Compound of proteins (Slonczewski and Foster, 2012)
Ca	Cell transport systems and osmotic balance in all bacteria. Increase growth rates.
K	Cell transport system and osmotic balance in bacteria.
Fe	Growth factor in bacteria, fungi and algae. Electron transport in cytochromes. Synthesis of catalase, peroxidase and aconitase.
Mg	Enzyme activator for a number of kinases and phosphotransferase in heterotrophic bacteria.
Mn	Activates bacterial enzymes. Can inhibit metabolism at 1mg/L.
Cu	Bacterial enzyme activator required in trace quantities. Can inhibit metabolism.
Zn	Bacterial metallic enzyme activator of carbonic anhydrase and carboxypeptidase A. Dissociable on active site of enzymes. Stimulates cell growth. Toxic at 1 mg/L. Can exacerbate toxic effects of other metals and inhibit metabolism.
Mo	Common limiting nutrient (Grau, 1991)
Co	Bacterial metallic enzyme activator. Dissociable on active site of enzymes. Activates carboxypeptidase for synthesis of vitamin B_{12} (cyanocobalamin) but otherwise toxic. Can inhibit metabolism.

2.5.3 Further physico-chemical characteristics impacting biodegradation

Salinity

The concentrations of salts in general, and of specific toxic salts, impact enzymatic reactions. Thus, salts can serve as inhibitors of enzymatic reactions (cf. Figure 2.2 and Figure 2.5). Salinity is represented by the electric conductivity EC. Not only is the salinity defined by pollutants in the wastewater, but also by the tap water quality. Tap water with high mineral concentrations, especially with high levels of carbonates (hard water), comes with high EC, but does not directly impact biological degradation. However, a deficiency of minerals would lead to a deficiency of nutrients (cf. Table 2.7).

pH

Normally, aerobic wastewater treatment happens in a neutral pH-range (6-8) with neutrophil microorganisms. Extreme changes in pH-values (reversibly) impede biodegradation or even (irreversibly) damage microorganisms.

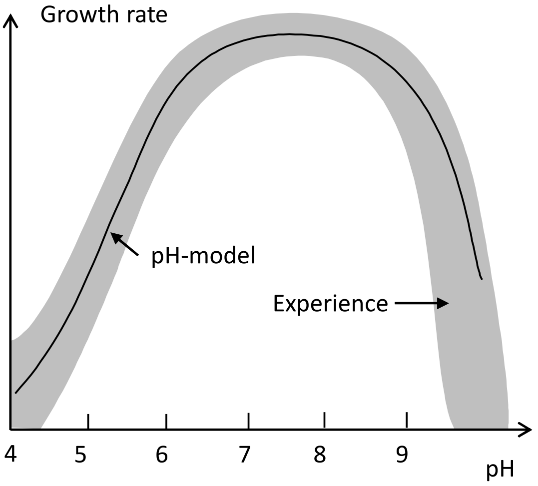


Figure 2.6: pH dependency for aerobic heterotrophic processes (Henze and Harremoes, 2002)

Temperature

Microorganisms have adapted to different temperature ranges and are accordingly classified. For aerobic waste water treatment, the psychrophilic (< 15 °C) and mesophilic (15-45 °C) range dominate.

The main impacts of increasing temperatures are higher enzymatic reaction rates following Arrhenius equation (Segel, 1975):

$$k = Ae^{-E_a/(RT)} \tag{2.7}$$

k	Reaction rate [e.g. mg/h^{-1}]
A	Constant for specific reaction [-]
E_a	Activation energy [J/mol]
R	Universal gas constant [8.314 J/(K·mol)]
T	Temperature [K]

The Q_{10}-rule (German: RGT-Regel) illustrates the increase of reaction rates caused by a temperature increase of 10 K:

$$Q_{10} = \left(\frac{R_2}{R_1}\right)^{10K/(T_2-T_1)} \tag{2.8}$$

Q_{10} Temperature coefficient [-]

R_i Reaction rates [e.g. mg/h^{-1}]

T_i Reaction Temperatures [K]

Q_{10} normally ranges from 2 to 4. Yet, exemptions can be found (Borucki et al., 1995).

Yet, enzymatic reaction rates decrease at very high or very low temperatures due to denaturation processes and the impact of decreasing membrane fluidity (cf. Figure 2.7).

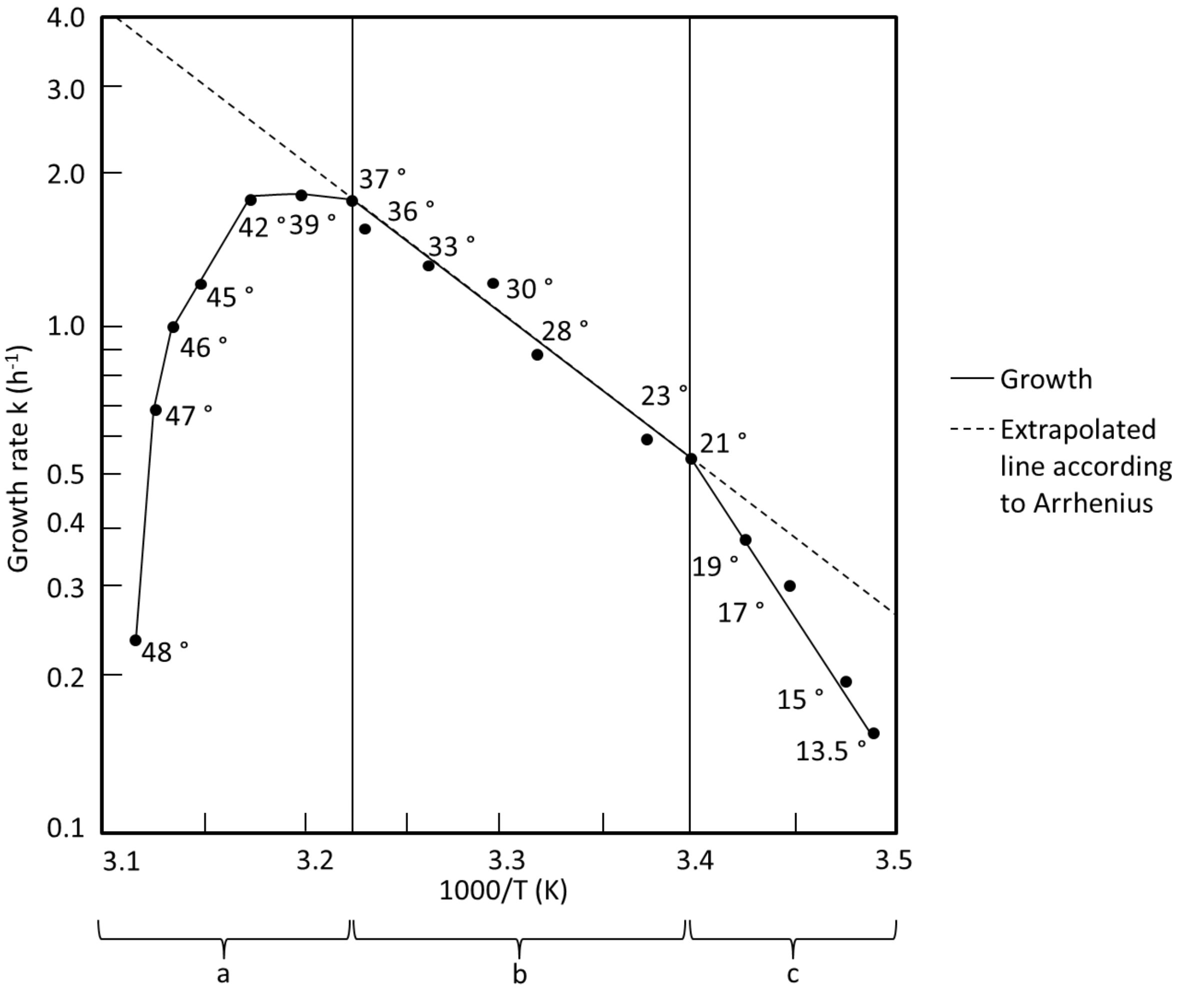


Figure 2.7: Relation between temperature (°C and K) and growth rate (k) of the mesophilic Eschericia coli. Temperature of x-axis described as 1000/T based on Kelvin (suitable scale). a: at high temperatures, growth rates decrease due to denaturation of enzymes. b: growth rates according to Arrhenius' law. c: Enzymatic activity decreases according to Arrhenius' law AND due to reduced membrane fluidity. (Slonczewski and Foster, 2012)

For mesophilic metabolism, the temperature optimum for degradation of organic compounds ranges from 37 to 42 °C. Yet, the degradation process is rapidly impeded at temperatures exceeding 42 °C.

2.6 Realization of biological treatment systems

The biological treatment unit does not work isolated but is embedded in a system. In the case of greywater, the general system setup is shown in Figure 2.8.

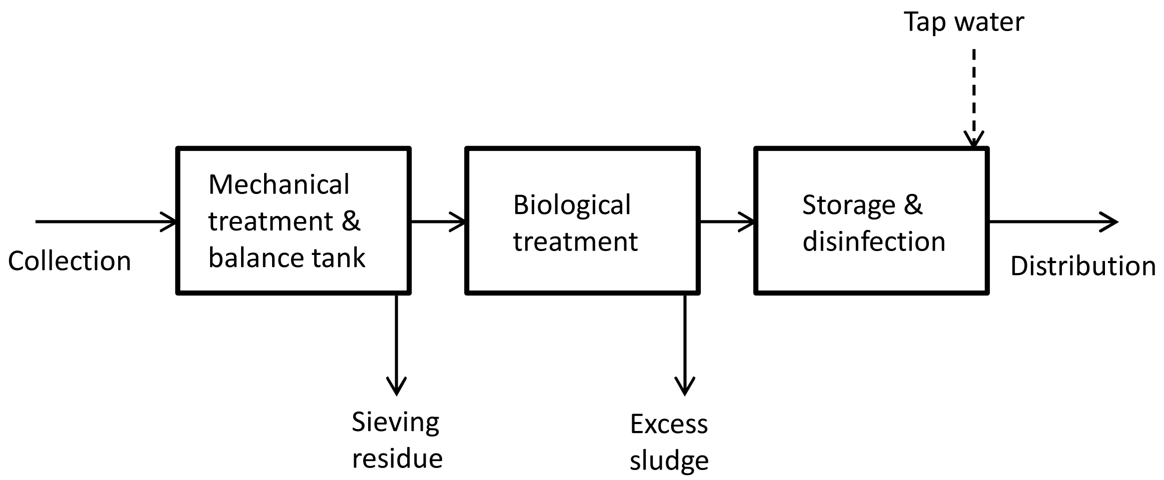


Figure 2.8: General overview greywater system: construction elements and flows

In the following, the different system units are described. Greywater specific system characteristics are explained.

Collection

For the collection of greywater, effluent pipes from the greywater sources have to be separated from the other wastewater pipes. Since greywater treatment systems are preferably installed in the basement, greywater collection is gravity driven.

Mechanical treatment

Mechanical treatment serves two purposes: Firstly, the organic fraction entering the following biological treatment unit is reduced. Thus, the treatment effort in the biological unit is reduced. Secondly, following treatment steps are protected from potential damages, e. g. caused by clogging.

Mechanical treatment for greywater is normally realized by screening. Yet, greywater including kitchen effluents should also have a grease trap and a sedimentation unit could be considered.

First storage tank

The first storage tank balances the incoming greywater volume. A construction serving also as sedimentation is possible.

Biological treatment unit

The purpose of the biological treatment unit is to reduce organic substances. Considering the moderate climate and the low organic loads of greywater, aerobic treatment is indicated. Therefore, oxygen needs to be available for the microorganisms. Furthermore, enough biomass has to be kept in the unit. Depending on the biological treatment technology, excess biomass has to be removed subsequently.

Second storage tank

The second storage tank holds the treated greywater for its later usage. A tap water feed should be installed to secure service water supply.

Disinfection

To guarantee hygienic safety, the treated greywater is disinfected before further usage. Chemical disinfection is an option. In Germany, UV disinfection is more common.

Some biological treatment technologies produce service qualities that are considered as hygienically safe (e. g. MBR). However, a disinfection unit is often installed as second safety step. Besides process related aspects, an additional separate disinfection unit increases user perception.

Distribution system

The service water pipe system has to be installed without any cross connection to the tap water supply system. Since greywater treatment systems are preferably installed in the basement, a pump is needed to transport the service water to its application. Service water pipes and armatures should be labeled and color coded to avoid confusion.

Additional construction aspects

For detailed construction information concerning greywater systems, the fbr-Information Sheet H 201 (Mehlhart, 2005) should be consulted.

Heat recovery: In case of heat recovery from greywater, system elements upstream from the recovery unit should be insulated to prevent heat losses.

2.6.1 Residual products

Residuals are produced during mechanical and biological treatment. Excess sludge production in greywater treatment systems is very low. In some cases, the produced biomass is simply removed during annual maintenance (oral information of an operator).

However, the disposal of residual products is generally depending on the frame conditions. In a sewered area, residual products are often disposed via the sewer system. In unsewered areas, the disposal of residual products depends on the sanitation scheme: it is possible to collect and dispose residual products together with feces or other organic waste, but this depends on the requirements of the further treatment or re-utilization processes.

2.6.2 Resulting costs

In the general system description, the investment and operational costs for a greywater system are evident as part of direct system costs (Figure 2.9). Furthermore, labor costs, waste treatment costs and indirect cost (charges, insurance, overhead costs) occur. The overall costs of a treatment system thus depend on the technical investment and operational costs, but also on the local level of labor costs and administrative structure.

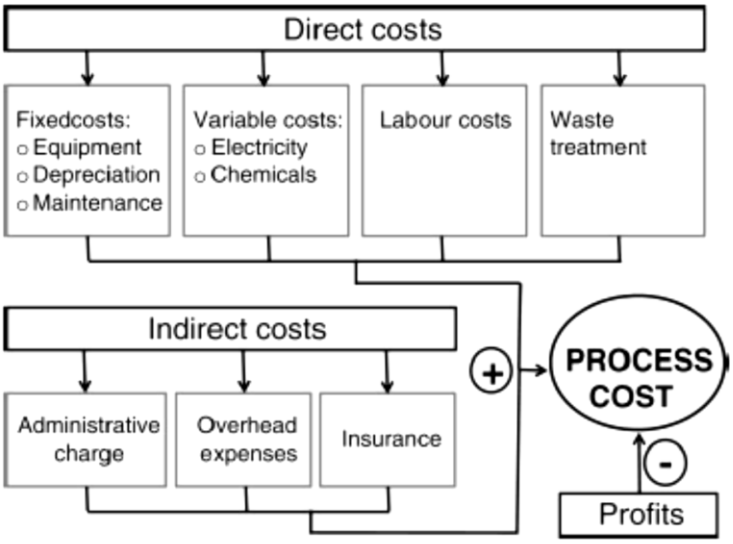


Figure 2.9: Economic evaluation of greywater system costs (Humeau et al., 2011)

The financial benefits of a greywater treatment system are based on the reduced tap water demand and wastewater discharge. Furthermore, financial incentives which support the implementation of alternative sanitation systems may exist (e. g. Hamburg, 2007).

Additionally, external financial benefits or drawbacks can occur, e. g. by changing the wastewater volume and composition in the sewer system and wastewater treatment plant (Penn et al., 2012). Clearly, these externalities are strongly depending on the frame conditions and on the extent of greywater reuse in a specific area.

The draft of the worksheet recently published by the German Water Association summarizes positive and negative factors to pre-determine, whether an alternative sanitation approach could be considered or not (Appendix Table A 1). Direct and external aspects are covered, but an economic quantification has to be done for each specific case.

2.6.3 Biological treatment process – implementation options

Different biological treatment processes have proven to guarantee stable and good effluent quality and are recommended for greywater treatment (Mehlhart, 2005; Sen Ber, 2007):

- Vertical flow reed bed
- Fluidized bed
- Biological contactors
- Membrane bioreactor

The decision for a biological treatment process is based on the requirements and availabilities of space, energy and maintenance. Thus, this work focuses on (Rotating) Biological Contactors (RBC), characterized by low demands for space and energy. Furthermore, RBC technology is based on sessile biomass that has generally proved high efficiencies in greywater treatment (Mehlhart, 2005).

3 Service water quality requirements – principles and experiences

In Germany, the legal regulations concerning domestic water reuse have not been defined yet. In the past, different standards and guidelines served as orientation to publish recommendations for domestic service water requirements. The aim of the current recommendations is to reduce hygienic and environmental risks, and, moreover, to prevent aesthetic problems. Hazardous substances only pose a risk when exposed to a target. Consequently, the quality requirements for service water are based on the respective application. Generally, greywater can be reclaimed for all purposes not requiring drinking water quality.

Greywater quality requirements have already been discussed and investigated in other countries. The respective results and experiences have not been considered in German recommendations, yet. The reason for that might be the fact that the German recommendations go back to 1995 (Nolde, 2005), while other guidelines or research were developed later (cf. Pidou et al., 2007).

3.1 Irrigation

Irrigation is a possible application for treated greywater. Yet, the irrigation water demand on domestic levels, in gardens, is limited to dry and hot seasons. Furthermore, garden irrigation plays a minor role in big housing units.

In Germany, requirements of irrigation water are defined in DIN 19650 (1999). Only hygienic parameters are covered. Yet, surfactants and high levels of salinity can damage soil properties and plants (Shafran et al., 2005; Pinto et al., 2010). Thus, the reclamation of greywater for irrigation purposes needs further research, especially to ensure the preservation of soils.

3.2 Indoor reuse – toilet flushing and washing machines

The reuse of treated greywater as service water for non-potable purposes is mainly focused on toilet flushing. Furthermore, the use in washing machines is possible, but not always well perceived by users.

Toilet flushing water could be ingested e. g. by small children or inhaled as aerosol during flushing. Thus, the hygienic requirements are oriented on parameters from the European Drinking Water Ordinance (TrinkwV, 2001) and on the European Bathing Water Directive (EU 76/160/EEC)[2]. Both are based on the prerequisite that ingested reasonable dosages must not harm the health of people, including immune deficient people (elderly, small children). Thus, the recommendations on toilet flushing water quality are similar.

Table 3.1: Quality parameters of treated greywater reused for toilet flushing or washing machines (SenBer, 2003)

Parameter	**Value**
BOD_7	< 5 mg/L
Oxygen saturation	> 50%
Total coliform bacteria^A	< 100/mL
Faecal coliform bacteria^A	< 10/mL
Pseudomonas aeruginosa^B	< 1/mL

A) Analysis according to EU Guideline 76/160/EEC
B) Analysis according to the TrinkwV, 2001

The content of degradable organics (as BOD_7) is determined to limit substrate for microbial growth. Together with a minimum oxygen concentration, anaerobic conditions causing aesthetic problems are avoided even during storage of several days.

For laundry, the same requirements as for toilet flushing are recommended (Mehlhart, 2005). According to Töpfer et al., 2003 (qtd. in Mehlhart 2005), no hygienic difference was found between dried clothes that were washed with greywater fulfilling the requirements of Table 3.1 and those washed with drinking water.

In Germany, the current recommendations for reclaimed greywater have been widely adapted. Yet, the recommendations are, in comparison to other guidelines addressing greywater quality (cf. Pidou et al., 2007), relatively strict. The experiences with these requirements justify a reevaluation of the German recommendations. Furthermore, a modification e. g. of a BOD limit from BOD_7 = 5 mg/L to BOD_5=10 mg/L would reduce the treatment effort and thus the costs of a system considerably.

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[2] Based on the EU bathing water directive in force until 2006.

However, a revision of the current recommendations or a legally binding definition of quality requirements requires thorough considerations and discussion.

3.3 Further application options

In unsewered areas, the mere disposal of greywater may be the main target. Infiltration and direct discharge require legal approval according to regional guidelines. In the case of infiltration, DIN 4261-1 (2010) needs to be applied.

In some facilities, the use of service water for specific further purposes can be beneficial. For example, the fire department of Hamburg combines reclaimed greywater and rainwater to clean hoses (Hansgrohe AG, press release 2007). Furthermore, greywater can also be used for other cleaning purposes.

Since the most likely application of reclaimed greywater is found indoors, the conditions and corresponding quality requirements are introduced in the following section.

4 Analysis of greywater characteristics

The characteristics of greywater – quantity and composition – define how much tap water can be supplemented and define the effort that is needed for treatment.

Some information concerning the composition of 'resulting greywater' (cf. Figure 4.1, bottom) is available for German conditions. Thus, these literature data were determined (Chapter 4.1 and 4.2). Yet, an understanding of greywater composition - and the factors impacting it - needs a deeper approach. Thus, following the logic of greywater composition (Figure 4.1), the 'greywater streams' (Chapter 4.3) resulting from 'greywater components' (Chapter 4.4) were determined. These considerations were the basis to develop an alternative approach to estimate greywater characteristics (Chapter 4.5).

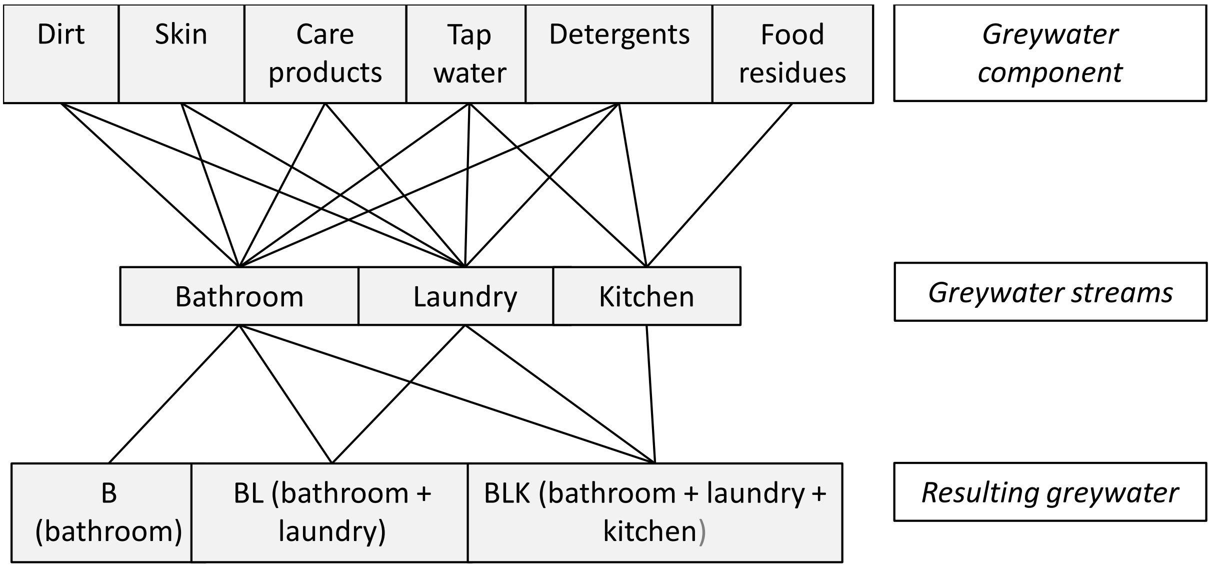

Figure 4.1: Greywater composition - schematic overview for the analysis of greywater characteristics (Chapter 4)

Where indicated, conclusions concerning the biodegradability of greywater were outlined in this chapter.

4.1 Quantities of greywater

Figure 4.2 shows the average daily domestic per-capita water usage in Germany. The highest volumes are needed for personal care (shower, bathing tub, hand washing basin) and toilet flushing, followed by laundry. In German households, irrigation plays a minor role.

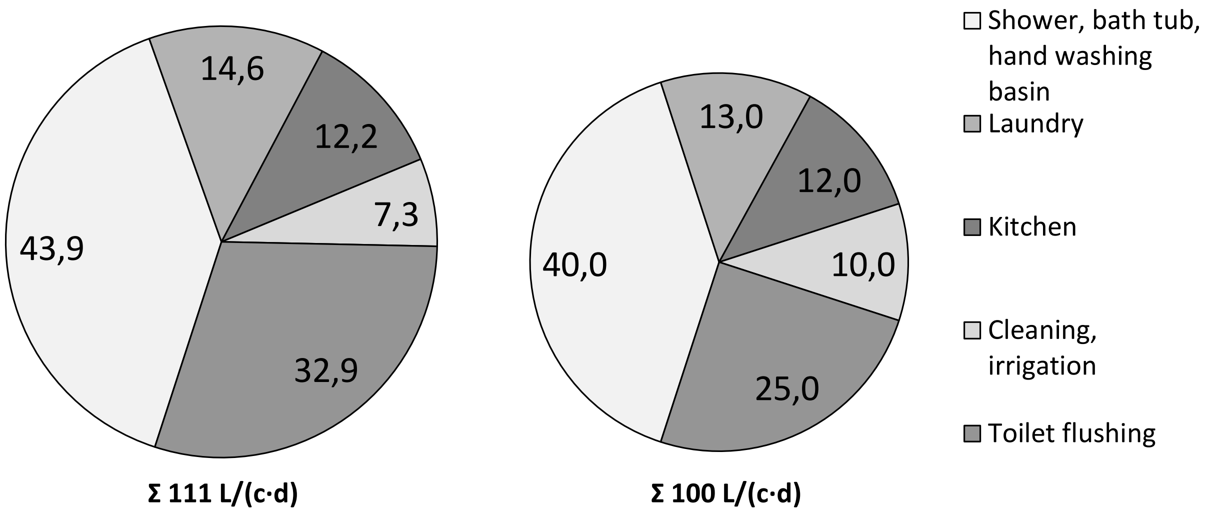

Figure 4.2: left: Domestic water usage in L/(c·d), (data from Bundesverband der deutschen Gas- und Wasserwirtschaft e. V. 2007, published by UBA); right: Average partial water flows (liters per inhabitant and day) for private households in new buildings and sanitary rehabilitated buildings (according to Mehlhart, 2001)

The installation of a greywater system takes place in new or reconstructed buildings. Thus, modern, more water efficient equipment is most likely used in these buildings. Consequently, water consumption is lower.

Greywater originates from personal care (shower, bath tub, hand washing basin; 40 L), laundry (13 L) and kitchen (10 L)[3], generating a total volume of 63 L/(c·d), (cf. Figure 4.2, right). Treated greywater can be reused for laundry (13 L), cleaning, irrigation (10 L) and toilet flushing (25 L), (Mehlhart, 2005), summing up to a maximum demand of 48 L/(c·d). Thus, theoretical maximum greywater generation exceeds greywater demand. Consequently, reasonable configurations concerning the choice of greywater sources should be defined: water volumes and pollution characteristics have to be considered.

4.2 Composition of greywater: wastewater parameters

The main factor influencing the compositions of greywater is its source. Although greywater, in most of the countries, is defined excluding only feces and urine, waste water originating

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[3] cf. Chapter 4.2.3

from kitchen sink/dishwasher or washing machines are commonly not added to the greywater stream. Even though these streams are relatively low in volume, they have high pollution loads. Thus, the major influence of greywater composition is its source. Figure 4.3 gives a schematic overview of major greywater source combinations. Furthermore, the categories are named according to their source to simplify orientation in this work.

- B-greywater is originating from the **b**athroom: showers, bathing tubs and hand washing basins. In the literature, it is sometimes referred to as “light” greywater (e.g. Krishnan et al., 2008).
- BL-greywater includes greywater from the **l**aundry in addition to B-greywater.
- BLK-greywater contains greywater from all possible greywater sources, including **k**itchen greywater. BLK-greywater is also known as “dark” greywater in some publications (e.g. Krishnan et al., 2008).

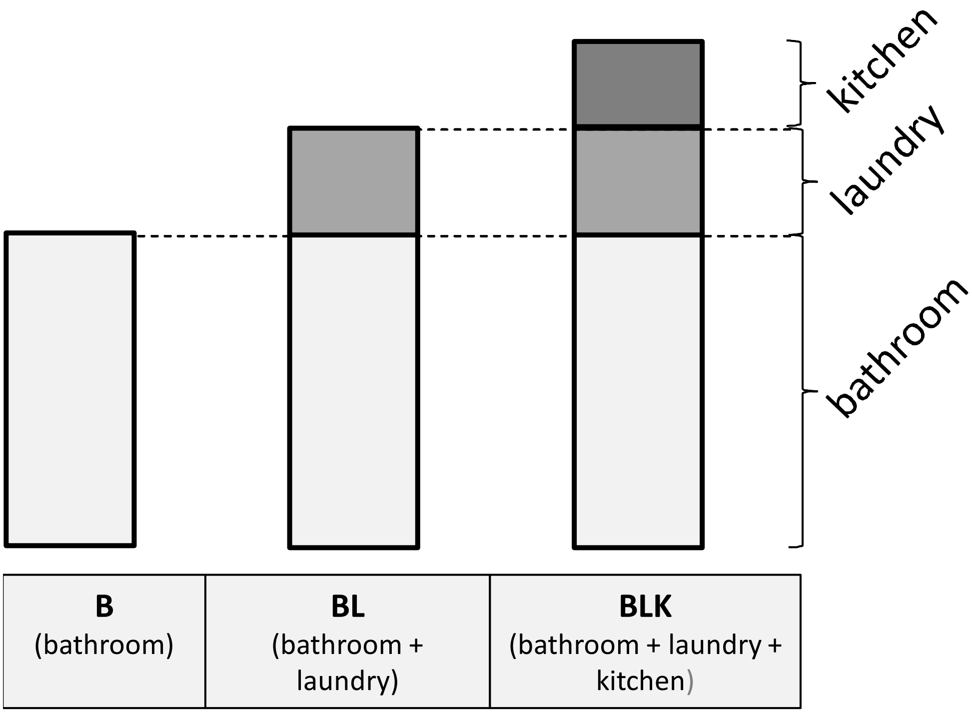

Figure 4.3: Common combinations of greywater sources, their volume ratios and nomenclature

User behavior impacts greywater compositions: consumers use different volumes and kinds of body care and detergents. People produce different amounts of “dirt” (e.g. sweat, dust on body/clothes), and they consume different volumes of water.

In the following, source specific greywater production is illustrated and the corresponding wastewater parameters, based on literature data, are listed.

4.2.1 Bathroom – Shower, bathing tub and hand washing basin

General description: Bathroom greywater is generated during personal care. Thus, personal care products and substances removed during personal cleaning are the main components of bathroom greywater. Furthermore, hair, lint, dust and skin segregation and cells are rinsed off. Bathroom greywater contains fecal contamination, with elevated levels when young children are living in a household (Nolde, 2000).

Table 4.1: B-greywater: Typical values for greywater originating from bathrooms in Germany (Mehlhart, 2005 according to Nolde,1995 and Bullermann, 2001)

Parameter	**Concentrations (ranges and average)**
COD [mg/L]	150-400 ∅ 225
BOD_5 [mg/L]	85-200 ∅ 111
N_{tot}* [mg N/L]	4-16 ∅10
P_{tot}* [mg P/L]	0.5-4 ∅ 1.5
pH [-]	7.5-8.2
Total coliform bacteria [1/mL]	101-106 Median: 105
Fecal coliform bacteria (E. coli) [1/mL]	101-105 Median: 104
* Values vary depending on tap water quality	

4.2.2 Washing machine

General description: Laundry greywater is generated in washing machines. Thus, the main components are laundry detergent and dirt (e. g. hair, lint, dust) which is rinsed of the fabric. Depending on the washing program, laundry greywater can have high temperatures up to 95 °C. Thus, it needs to be buffered before it enters the biological treatments stage.

Table 4.2: BL-greywater: Typical values for greywater originating from bathrooms and washing machines in Germany (Mehlhart, 2005 according to Nolde,1995 and Bullermann, 2001)

Parameter	**Concentration (only reported as ranges)**
COD [mg/L]	250-430
BOD_5 [mg/L]	125-250
Total coliform bacteria [1/mL]	102-106
Fecal coliform bacteria (E. coli) [1/mL]	101-105

4.2.3 Kitchen

General description: 12 L/(c·d) of water are used in the kitchen (cf. Figure 4.2, right). A small part of it is ingested, about 10 L/(c·d) are used for dish washing, the rinsing of food or as boiling water (e. g. for pasta or potatoes) and become greywater.

Pathogens can enter the greywater system when contaminated food, e. g. meat, is rinsed or when raw food particles are drained. Food residues provide a source of nitrogen and Phosphorus due to proteins.

Since detergents for dishwashers can be caustic and have high P-loads[4]. Furthermore, the effluent of greywater can reach high temperatures close to 100 °C.

Table 4.3: Pollutants in kitchen greywater and their characteristics

Substances	**Characteristics**
Food particles, oil, grease	Source of COD Suspended solids Increased risk of clogging Source of pathogens Source of N and P
Detergents	Source of COD Surfactants Dishwasher detergent: caustic Source of P

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[4] According to actual legislative development, the use of Phosphates in dishwasher detergents will be limited in the European Union in 2017 (Regulation (EU) No 259/2012).

Table 4.4: BLK-greywater: Typical values for greywater originating from bathrooms, washing machines and kitchens in Germany (Mehlhart, 2005 according to Nolde,1995 and Bullermann, 2001)

Parameter	**Concentrations (ranges and average)**
COD [mg/L]	400-700 ∅ 535
BOD_5 [mg/L]	250-550 ∅360
N_{tot}^* [mg N/L]	10-17 ∅13
P_{tot}^* [mg P/L]	3-8 ∅5.4
pH [-]	6.9-8
Total coliform bacteria [1/mL]	10^4-10^7
Fecal coliform bacteria (E. coli) [1/mL]	10^4-10^7
* Values vary depending on tap water quality	

4.2.4 Discussion and conclusion

Greywater originating from bathrooms has the lowest concentrations of pollutants and the highest volume compared to greywater from washing machines and kitchens. When washing machine effluent is added to the greywater collection, the concentrations of pollutants are increased, but the generated greywater volume (53 L/(c·d)) is high enough to cover the maximum service water need of 48 L/(c·d), (cf. Chapter 4.1).

The additional collection of kitchen greywater has the benefit of adding a nutrient source to the greywater. Yet, the pollution degree is increased significantly due to high organic loads, while adding only about 10 L/(c·d) to the total greywater volume.

Thus, it is recommended to exclude kitchen effluents from the greywater collection in residential buildings. Yet, under specific circumstances, e. g. when greywater demand is very high due to extensive garden irrigation or in buildings with total stream separation, this recommendation has to be reconsidered.

In the following, this work focuses on the most likely application: BL-greywater originating from bathrooms (shower, bathtub, hand washing basin) and washing machines (laundry).

4.2.5 Implications of greywater characteristics on biodegradability

The origin of greywater pollutions and nutrient levels indicate that a more thorough determination of greywater characteristics with focus on potential impact on biological treatment is required.

Organic substances

The characteristics of organic substances in greywater are different from the total domestic wastewater.

- Greywater is characterized by a COD/BOD$_5$-ratio that is higher than that of the whole domestic wastewater stream with a COD/BOD$_5$ ≈ 2. Thus, lower biodegradability in greywater is indicated.

Table 4.5: COD/BOD$_5$-ratios of greywater (Morck, 2004; Jefferson et al., 2004)

Greywater source	COD/BOD$_5$-ratio
Shower*	2,7
Bath tub**	2,9
Shower**	2,8
Hand basin**	3,6
* Morck, 2004 ** Jefferson et al., 2004	

Yet, according to Table 2.5 the COD/BOD$_5$-ratio of greywater, easy biodegradability is still indicated.

- Greywater does not contain organic material from feces and food residues (cf. Figure 4.4) which include high ratios of solid organic material. Therefore, less organic matter is found during mechanical treatment (e. g. sieving) and sedimentation. Furthermore, the organic matter does not have to be dissolved to become available for further degradation. Yet, the organic matter in greywater is dominated by products containing surfactants (Table 4.6) and complex molecules of anthropogenic origin (e.g. artificial fragrances, preservatives, see Eriksson et al. 2003). Those substances are known for low biodegradability.

Table 4.6: Surfactant concentrations in greywater (Eriksson et al., 2003; Shafran et al., 2005)

Parameter	Unit	Value
Anionionic surfactants	[mg/l]	0,7-44 Ø 17,5
Cationic surfactants	[mg/l]	0,1-2,1

Nutrients

Since blackwater is excluded from greywater, it is lacking feces and urine as major sources of nutrients (see Figure 4.4).

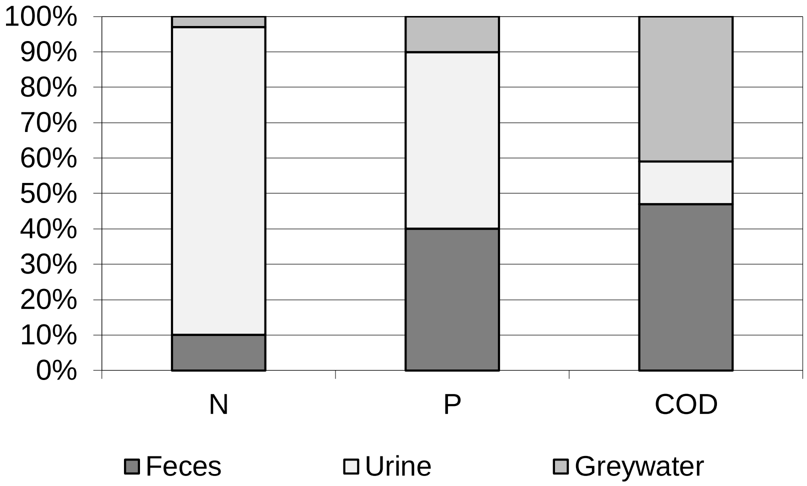

Figure 4.4: Distribution of nitrogen, Phosphorus and COD in domestic wastewater streams (according to Otterpohl, 2002)

As a consequence of the exclusion of urine and feces as a source of nitrogen and Phosphorus, the COD:N:P ratio shows a nutrient deficiency (see Table 4.7)[5] in comparison to

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[5] Concerning phosphorus, the European Union has limited the use of phosphorus in laundry detergents (Regulation (EC) No 648/2004 of the European Parliament). Thus, other countries with differing legislation can have greywater with higher P-Loads

the optimum nutrient ratio (Chapter 2.5.2). Thus, the removal of nutrients is not a process target of greywater treatment in Germany.

Table 4.7: COD:N:P-ratios of greywater (Krishnan et al., 2008; Jefferson et al., 2004)

Greywater source	COD:N:P-ratio
Washing machine, kitchen sink, dish washer*	100:1,82:0,76
Shower**	100:2,25:0,06
Bath tub**	100:2,91:0,05
Hand basin**	100:1,77:0,06
*Krishnan, 2008 ** Jefferson, 2004	

Nitrogen: According to López-Zavalla (2007), nitrogen loads in shower effluents are mainly organic nitrogen, indicating availability for biological metabolism.

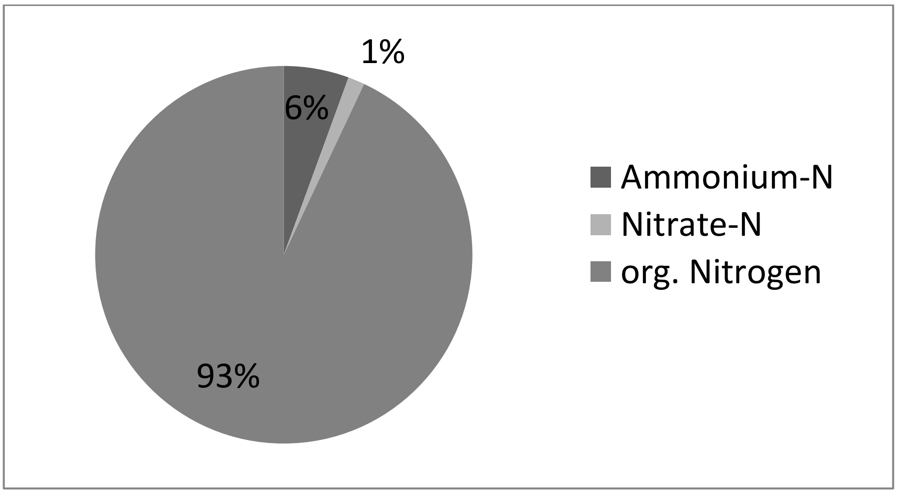


Figure 4.5 Forms of nitrogen in greywater originating from showers (according to López-Zavala, 2007)

Eriksson et al. (2010) determined the presence of inorganic trace elements in bathroom greywater: data concerning nutrients (cf. Table 2.7) showed distinct concentration elevations of Fe, K, and S during greywater generation, while Ca, Mg, Mn and Zn concentrations were predominately defined by the tap water quality. Thus, no general conclusions concerning the impact on biodegradability can be drawn.

pH and Temperature

The given data showed neutral pH values (Table 4.1, Table 4.4), indicating no negative impact on biodegradability (cf. Figure 2.6).

Temperatures of greywater range from 18 - 38 °C, predominantly with temperatures > 25 °C (Eriksson et al., 2002). Thus, high biodegradation rates are indicated (cf. Figure 2.7). The temperatures in a greywater system are strongly depending on the greywater sources and on the length and material of the collection system.

Both pH and temperature can have peak values, e. g. in the effluent of dish washers. Yet, these extremes are buffered in the balance tank before entering the biological treatment unit (cf.Figure 2.8).

Indications of greywater composition on biodegradability

Greywater shows some characteristics that are not beneficial concerning biodegradability. Yet, some factors, like higher temperature levels, enhance biological degradation processes.

Table 4.8: Summary of greywater characteristics potentially impacting biodegradability

Factor	**Impact** (negative: -; positive: +)
COD/BOD_5	-
COD:N:P	-
Further characteristics of organic fractions: - high ratio of xenobiotics, surfactants etc. - mainly in dissolved/dispersed form	 - +
Temperature	+

4.3 Complementing analysis

Sampling from different greywater streams (Figure 4.6) in one household was done to check for compliance with literature data (cf. Table 4.1; 3.2; 3.4). Furthermore, chemical analysis covered more parameters to gather additional information.

Figure 4.6: Overview - Greywater streams

4.3.1 Sampling

Samples were taken in a test household (cf. Table 4.18) which had convenient installations in regard to sampling. The number of samples is not statistically representatively. Yet, the results complement the information given in the literature.

Bathroom

In the bathroom showering water was collected. The shower is installed within the bath tub. The plug of the bathtub was closed during the showering process and the whole water volume of one showering process was collected and a sample was taken.

Laundry

Since the washing machine was located next to the bathtub, the hose was put into the plugged bathtub to collect the effluent of the total washing process.

Kitchen

In the kitchen, the syphon of the sink was opened and a bucket was used to collect the water that was used to clean dishes and cookware.

4.3.2 Results

Shower

Table 4.9: Shower greywater in test household (samples: n=2-5)

Parameter	Unit	Value
COD	mg/L	216
BOD_5	mg/L	118
TNb	mg/L	15.56
NH_4^+-N	mg/L	0.22
PO_4^{3-}-P	mg/L	1.51
pH	-	7.6
Anionic surfactants	mg/L	20.56
Turbidity	NTU	47.4
Conductivity at 25°C	mS/cm	0.744
TSS	mg/L	49.1
VSS	mg/L	44.3
COD/BOD_5	-	1.83
COD/N/P	-	100/7.2/0.96

COD and BOD_5 are in accordance with literature data for bathroom greywater (Table 4.1). Even though the parameters used to indicate nitrogen and phosphorus in the analysis differed from the literature data, the values lay in the same range.

Laundry

Table 4.10: Laundry greywater in test household (samples: n=2), one washing machine load ~ 45 L

Parameter	Unit	Value
COD	mg/L	1541.5
BOD_5^*	mg/L	1242
TNb	mg/L	40.8
NH_4^+-N	mg/L	6.61
PO_4^{3-}-P	mg/L	3.26
pH	-	7.43
Anionic surfactants	mg/L	92.2
Turbidity	NTU	175
Conductivity at 25°C	mS/cm	0.874
TSS	mg/L	271
VSS	mg/L	215
COD/BOD_5^*	-	1.44
COD/N/P	-	100/2.65/0.2
*based on one BOD_5 sample with according COD of 1794 mg/L		

In compliance with literature data (Table 4.2), laundry greywater shows higher organic loads than bathroom greywater. A direct comparison is difficult, since various influences would have to be estimated, e. g. the average water demand of the test household for laundry and high dosage recommendations for laundry detergent, since the test household is supplied with hard tap water.

Kitchen sink

Kitchen Sink (n=1)

Table 4.11: greywater from kitchen sink in test household (n=1)

Parameter	Unit	Value
COD	mg/L	9718
BOD_5	mg/L	4433
TNb	mg/L	63.2
NH_4^+-N	mg/L	6.47
PO_4^{3-}-P	mg/L	18.63
pH	-	5.52
Anionic surfactants	mg/L	6.04
Turbidity	NTU	160
Conductivity at 25°C	mS/cm	2.187
TSS	mg/L	2506
VSS	mg/L	2488
COD/BOD_5	-	2.19
COD/N/P	-	100/0.65/0.19

The sample from the kitchen sink has to be considered carefully, since the representativeness of this single sample is very limited and cannot be set into context with used water volume. Yet, the very high organic load is in compliance with the literature data. Furthermore, the high concentrations of nutrients, especially phosphorus, are also found in the literature (Table 4.4). The high concentrations of total suspended solids (TSS) are characteristic for kitchen greywater and indicate high treatment efforts.

4.3.3 Discussion

COD/BOD-ratio

The ratio of COD/BOD_5 was generally better than literature data suggested (Table 4.7). Therefore, direct and easy biodegradabilities are indicated (cf. Table 2.5).

Anionic surfactants

Anionic surfactants of showering water were in the ranges that literature suggested (Table 4.6). Laundry greywater contained very high levels of anionic surfactants.

Nutrients

Nitrogen

The ratios of Ammonium in TN_b lay in similar ranges as the literature data of showering water (Figure 4.5).

Nutrient ratio

The COD/N/P-ratios in the test household were in similar ranges like the literature data (Table 4.7). Phosphate-P values are slightly higher, but the water supply system of the test household was unfortunately equipped with a P-dosage unit (no detailed information on dosage quantities available).

4.3.4 Summary

Own measurements in the test household are widely conformable to the data found in the literature. Yet, some specific conditions of the test household were regarded. The test household is representative concerning major characteristics like organic loads. Furthermore, this example illustrates conditions that can impact general greywater composition: hard water causes elevated detergent dosages, and nitrogen loads can be highly impacted by tap water quality (cf. Chapter 4.4.1). Yet, conditions like these can easily be assessed by considering tap water qualities, which consequently should be done during planning processes of greywater systems.

4.4 Source oriented determination of greywater characteristics: Background

While it was recommended to exclude kitchen wastewater from the greywater collection (Chapter 4.2.4), to get further insights into the composition of greywater originating from bathrooms and laundry, the sources for substances that accord to wastewater relevant parameters were analyzed.

Both, laundry and bathroom greywater, are mainly generated during cleaning and care processes with water serving as solvent and transport medium for “dirt”. Furthermore, additives are used to enhance cleaning and care processes (Figure 4.7).

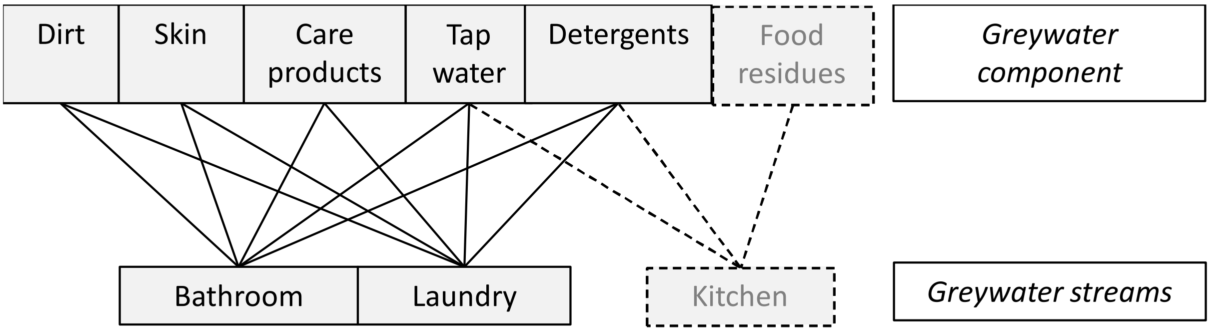


Figure 4.7: Overview greywater composition (kitchen wastewater excluded from further considerations)

In the following, the substances that lead to the characteristic composition of greywater are regarded.

4.4.1 Tap water

The substances in tap water impact the composition of greywater. In the case for nitrogen, tap water in Germany can contain up to 50 mg/L of Nitrate and 0.5 mg/L of Ammonium (TrinkwV, 2001). Thus, the basic nitrogen concentrations of drinking water can be substantially higher than the documented concentrations in greywater (e. g. Table 4.1).

The actual legislation has no limit for phosphorus in tap water. Consequently, phosphorus originating from tap water can also have considerable effects on greywater compositions.

4.4.2 Personal care products

Personal care products in greywater can be classified into two sub-categories:

- Direct application: products that are used during greywater generation, e. g. shampoo or toothpaste. These products serve as cleaning agents or as conditioners. Rinsing those products off with water is part of their application. The loads of these products are equivalent to their consumption during application.
- Indirect application: Products that are not linked to washing or showering processes. Examples are body lotion or perfume. The major constituents of these products are worn off into the fabric of clothes or are rinsed off during showering. The load of

indirectly applied products cannot be calculated but have to be estimated for each greywater stream.

Table 4.12: Important product groups in B-greywater

Product group	Classification
Bath products: shower, liquid bath, bath salt	Direct application
Hair care: conditioner, shampoo, styling agents	Direct and indirect application
Skin care: body lotions, hand care, creams, sun care	Indirect application
Dental care: toothpaste, mouthwash	Direct application
Shaving products: Shaving foam, aftershave	Direct and indirect application
Misc.: Make-up residues, make-up remover, face mask, deodorants, perfumes…	Direct and indirect application

General composition of personal care products in regard of wastewater characteristics

Liquid products mainly contain water. Depending on their purpose, personal care products contain different substances. For example, surfactants are found in cleaning products and glycerin or oils can be used for skin care. Nitrogen is rarely used in personal care products. Furthermore, a lot of personal care products contain preservatives like parabens (Eriksson et al., 2003).

Relevance for greywater treatment

Personal care products are a major source of COD. These organic fractions include surfactants and xenobiotics, which can come with low biodegradabilities. However, according to Eriksson et al. (2009), even preservatives like parabens were found to be readily biodegradable in an existing greywater treatment plant. Other organic micropollutants originating from personal care products were analyzed in greywater by Gulyas et al. (2011). After treatment, some traces of these pollutants were detectable. Yet, concentrations were assessed as being unproblematic in service water.

For the possible impacts of the surfactants in personal care products on biodegradability see Chapter 2.5.1.

4.4.3 Laundry detergents and additives

Laundry detergents and additives exist in liquid or powder form. They are designed to remove dirt from clothes and thus contain surfactants and enzymes (to break down proteins, fat and starch). Furthermore, powder detergents contain salts as filler and Zeolite as softening agent. In contrast, liquid detergents contain preservatives.

Recently, the usage of disinfecting laundry detergents containing hydrogen peroxides arose. Hydrogen peroxide could potentially affect biological treatment of greywater. Yet, it is expected to decompose while oxidizing (reducing COD) during the application in the washing process.

The most common washing additive is fabric softener. Furthermore, additives for different kinds of stains are available. Some of these washing additives contain bleach or caustic substances which can negatively impact the greywater treatment system, others are based on high levels of enzymes addressing special types of stains.

Relevance for greywater treatment

Laundry detergents are a source of COD and contain surfactants (cf. Chapter 2.5.1). Special additives like sanitizing agents can potentially harm the greywater degradation process. Furthermore, preservatives or high levels of salts can impede microbial degradation. Yet, enzymes in washing agents break down organic material in stains. Thus, the first step to degrade this organic material is already taken in the washing machine, making the solved “dirt” easily available for further biodegradation.

4.4.4 Skin segregation

The skin is a constant source of biochemical compounds and a habitat for microorganisms, which get into greywater during personal hygiene, are absorbed by clothes and thus end in the effluent of washing machines.

The human skin is covered by chemicals originating from sebum, keratinization products and sweat:

- Sebum consists of lipids (wax monoesters 25 %, triglyceride 41 %, free fatty acids 16 % and squalene 12%; Nikkari, 1974). An adult produces about 2 g of sebum per day (Raab et al., 1999), which causes COD in greywater.
- Dead skin cells, which are rich in proteins, are produced during keratinization to maintain the protection layer of the skin. The skin cells are a source of COD and organic nitrogen.
- Human perspiration varies, depending on climate and physical activity, between 0.5 and 10 L/(c·d) (Raab et al., 1999). Sweat contains urea, uric acid, amino acids,

> ammonia, lactic acid, sugar, creatine, creatinine, sodium chloride, alkali sulfate, phosphates, calcium and magnesium (Mosher, 1933). Thus, sweat is a source of COD and nitrogen.

According to Mitchel et al. (1949), the total nitrogen output via sweat varies between 71 mg and 5.28 g, depending on ambient temperature and muscular activity. Phosphorus is only present in traces (Mitchel et al., 1949).

Relevance for greywater treatment

Skin segregation is a source of COD and nitrogen. COD-loads are delivered relatively constantly by sebum, keratinization and perspiration, while nitrogen loads vary depending on sweat production. Furthermore, sweat is a source of minerals. In regard to greywater, sweat as a nitrogen source is of special interest since nitrogen availability from other sources is limited.

It was assumed before that skin segregation could play a role in greywater composition since nitrogen levels cannot be explained by other sources (Eriksson et al., 2009). Yet, the total impact of skin segregation has been neglected before.

4.4.5 Dirt

“Dirt” is a rather wide term. In this work, it is used to describe unwanted substances e. g. on the human body, in clothes, or on surfaces. It can be of organic or inorganic origin. Dust, lint, or soil are examples for dirt.

4.4.6 Cleaning agents

The role of cleaning agents in greywater has not been focused in the past. Yet, cleaning agents could impact the treatment system due to their discontinuous application (e. g. once a week) and their chemical characteristics.

Cleaning agents normally contain surfactants (Table 4.13 - Table 4.15) and other organic substances with arguable biodegradability (e.g. fragrances, preservatives). Thus, they are a source of COD. Furthermore, they can have extreme pH values or contain oxidants (e. g. bleach, drain cleaner), which can impact greywater degradation.

While the major volume and substrate loads of greywater are generated on a regular basis (daily showering, dental care), greywater from cleaning is rather produced in a more discrete pattern, e. g. once a week.

General composition of selected cleaners

The general compositions of cleaners commonly entering the greywater system are listed in Table 4.15 and Table 4.16.

All-purpose cleaner is used to clean surfaces with general pollution. Only a part of all-purpose cleaner enters the greywater system, since it is also used to clean surfaces not related to greywater (e. g. floors, with draining of polluted water in toilet).

Table 4.13: General composition of conventional and concentrate all-purpose cleaners (Hauthal, 2004)

Substance	**Content**
Surfactants	5-17 %
Builders	0-15 %
Solvents and hydrotropes (solubilizers)	0-8 %
Fragrance ingredients	< 1 %
Colorants	< 0.02 %
Preservatives	n/a
additionally: acids in acetic all-purpose cleaners: < 10% alkalis, in weakly alkaline all-purpose cleaners: < 1 %	

Bathroom and shower cleaners are used to solve scale and other pollution in tubs, showers and hand washing basins, as well as in toilets. Thus, a high proportion of those cleaners is expected in the greywater system.

Table 4.14: General composition of bathroom and shower cleaners (Hauthal, 2004)

Substance	Content in bathroom cleaners	Content in shower cleaners
Surfactants	0-5 %	0-3 %
Organic acids	0-5 %	0-3 %
Oxidants	optional	-
Complex-forming agents	-	0-3 %
Low-molecular-weight alcohols	-	0-2 %
Colorants, perfume oil	< 1 %	< 1 %
Preservatives	-	< 1 %
pH	3-5	3-6

Abrasives are used to clean persistent pollutions with mechanical assistance. It is often, but not exclusively, used in bathrooms. Therefore, a part of the consumed abrasives can be expected in greywater.

Table 4.15: General composition of abrasives (Hauthal, 2004)

Substance	Content
Surfactants	0-5 %
Abrasives - powder - lotion	 80-90 % 30-40 %
Soda, polyphosphate	0-5 %
Perfume oils, colorant	0-1 %
Water - powder - lotion	 < 5 % up to 100 %

Relevance for greywater treatment

Cleaning agents are a source of COD. Yet organic fractions come as surfactants or xenobiotics, and not only can they be hard to degrade, but have the potential to harm microorganisms of biological treatment systems (e. g. preservatives). Furthermore, caustic substances can potentially damage the construction parts of greywater collection or treatment systems. Thus, the usage of high dosages of specific cleaning agents may have to be constricted.

With 150 mg COD/g, the COD of cleaning agents is relatively small compared to the COD of laundry detergents and personal care products (cf. Chapter 4.5.2).

4.4.7 Misuse

Misuses include the disposal of substances which generally must not be drained. These can be chemicals like solvents or pharmaceuticals which can harm wastewater treatment systems or are not removed in wastewater treatment plants and thus pose a risk to natural water bodies. Since greywater treatment systems are normally smaller than conventional treatment plants, substances are more concentrated and the potential risk for the greywater treatment system is even higher. Consequently, users of greywater treatment systems should strictly follow the rules concerning substances that must generally not be drained.

Urination in the shower is not regarded as misuse in this work. The possible impact would be elevated nutrient levels, which would not harm the treatment system but partially compensate the nutrient deficiency in greywater (cf. Chapter 4.2.5).

4.4.8 Impact of piping and storage

Only minor numbers of microorganisms are initially expected in fresh greywater. Those can originate from the human skin or contamination with dirt or residues of fecal matter. However, greywater offers organic substrate for microorganisms. Thus, microorganisms grow, which can be observed in the biofilm formation in outlets and piping. Thus, pipes and storage serve as retention room for microorganisms.

4.4.9 Summary and context

Table 4.16 and Table 4.17 summarize pollution sources in greywater from bathrooms and washing machines, respectively. This information is the fundament to quantify the pollution loads in greywater in the following chapter (Chapter 4.5).

Furthermore, the high impact of consumer behavior and choice on greywater composition is obvious, since quantities and qualities of products, dirt, skin segregation, and detergents depend on individual lifestyles.

Table 4.16: Pollutants in bathroom greywater and their characteristics

Substances	**Characteristics**
Personal care products	Main source of COD Contain surfactants and xenobiotics
Skin segregation	Source of nitrogen (Urea) Source of COD
Dirt	Suspended solids COD Pathogens
Cleaning agents	Discontinuous application May impact treatment system
Misuse	May impact treatment system

Table 4.17: Pollutants in laundry greywater and their characteristics

Substances	**Characteristics**
Laundry detergent	Source of COD Contain surfactants and xenobiotics
Skin segregation	Source of nitrogen (Urea) Source of COD
Dirt	Suspended solids COD Pathogens
Washing additives	May impact treatment system

4.4.10 Conclusions

The current knowledge about greywater composition is based on the empiric data collected in the past. Relying on these data creates various problems, especially since greywater characteristics show high variability.

- Main fractions of wastewater relevant parameters (especially COD) derive from care products and detergents, being highly influenced by specific user behavior and developments in product design (e. g. washing powder – trend goes to concentrates and to addition of disinfectant agents).

4.5 Source oriented determination of greywater characteristics: Alternative approach

In Germany, the fbr information sheet H 201 (Mehlhart, 2005) gives orientation values for greywater composition. These values are only based on a number of 10 to 100 measurements from 1995 and 2001. Thus, the representativeness of these data must be questioned, especially in regard of changes in user behavior over time.

Instead of relying only on empirical data collection, this work introduces an analytical approach to estimate greywater composition. Statistical data is used to estimate per-capita consumption of products entering greywater. Additionally, the impact of skin segregation and dirt is determined.

The limitations of the methods were considered as far as quantifiable data was available. The result of the analysis was controlled by comparison to empirical data.

4.5.1 Method

Figure 4.8 shows the structure of the approach that was used to analyze greywater composition. COD serves as main pollution indicator. Additional information on nitrogen is given for skin segregation. Thus, the COD loads of personal care products, detergents, skin segregation and dirt were determined. These data, combined with respective water usages, result in COD-concentrations.

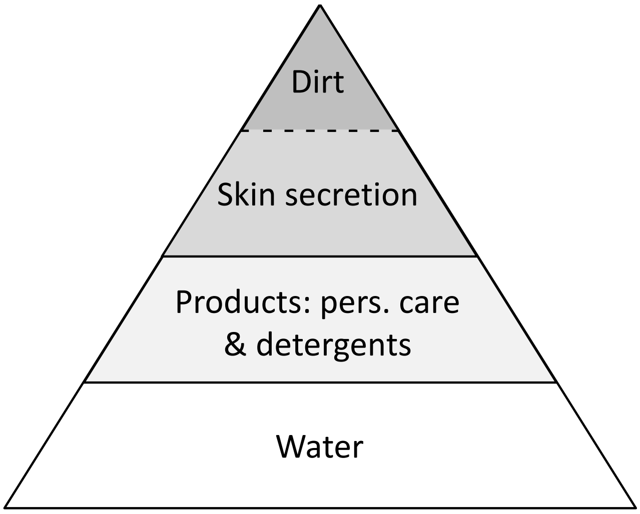


Figure 4.8: General composition of greywater

Since household cleaning happens in discrete events and has low COD-loads, it is not considered in this analysis. The impact of cleaning agents is considered in Chapter 6.

Water: volumes and loads

Greywater systems can be expected to be installed with water saving devices. Thus, water volumes were assumed according to Figure 4.2/right (B-greywater: 40 L, L-greywater: 13 L). The impact of tap water quality has to be considered concerning nitrogen and phosphorus loads.

Products: personal care and detergents

Usage of personal care products and detergents, which were considered to be the major contributor of COD loads, were determined based on market research data.

Per-capita consumption data for laundry detergents were directly available (IKW, 2011). The COD of different laundry detergents (liquid, powder, concentrate) was measured to estimate average COD loads per capita.

Data for personal care products had to be determined by using the number of units sold per year in Germany (datasets by datamonitor, 2011). Thus, to derive per-capita consumption, average unit sizes were estimated:

COD loads from personal care products based on market data

Market research data: the available data set stated the number of sold product units per year. The chosen data set fulfilled the following requirements: consistent methodology for different product groups, consistent time frame (the year of 2010), consistent region (Germany). Other data sets available only covered single product groups or were collected over 20 years ago and thus not considered up-to-date. Combined with Germany's population, the consumption of units per capita was calculated for different product groups.

1. To determine the volume or mass of sold products, average unit sizes per product group were estimated: in a big supermarket, offering a wide range of products of different prize classes, container sizes and count were recorded. This was based on the assumption that products which are sold more often receive more space in the shelves. From these data, the arithmetic weighed mean of container sizes was calculated (cf. Appendix: 2.1). It was assumed, that the density of the products, which mostly come in liquid form and contain high levels of water, is about 1 g/ml.
2. The average COD of different product groups was estimated by analyzing different products.
3. Per-capita COD-loads originating from personal care products were calculated (cf. Appendix Equation A.2.2).

Limitations of the approach to estimate COD-loads of personal care products:

- The wide range of products used during greywater generation could not be considered totally. Therefore, only major contributors were included, which are:

- Bath and shower products: shower, liquid bath, other bath products
- Hair care: conditioner, hair colorants, salon products, shampoo and styling agents
- Hand and body care: mass body care, premium body care, mass hand care, and premium hand care
- Dental care: toothpaste

Minor product groups (small contribution to greywater COD loads) were not considered in research: e. g. mouth wash, face masks, shaving gel, shaving after care, deodorants, and sun care. This causes an underestimation of COD in greywater.

- It is a rough estimation that products which are consumed more often get more shelf-space and count. The validity of this estimation is uncertain.
- Not all sold products end as greywater component. Some products are thrown away before total usage and residues of products remain in containers that are considered empty. This causes an overestimation of product consumption based on the data of sold products. No statistical data was available to quantify this impact.

The overall validity of the analysis thus needs verification.

Skin

Literature research (c. f. Chapter 4.4.4) suggested that skin segregation is a source of COD and nitrogen. Data was not detailed enough to estimate theoretical loads for neither COD nor nitrogen. Thus, the loads impacted by skin segregation were measured.

COD loads from skin and dirt in shower water

- Bathtub: clean and thoroughly rinsed with tap water.
- 25 g of shampoo: agent to solve dirt and skin segregation, sweat, as well as lipids
- Wash cloth: tool to mechanically support washing process
- Volunteers: healthy adults (Table 4.18), having showered 24 h before, no use of skin lotions or hair care products in the last 24 h.

1. A clean bathtub was filled with 50 L of warm tap water (approx. 37 °C), and 25 g of shampoo with known COD. Furthermore, a clean wash cloth was added. After stirring to guarantee a homogeneous mixture and dispersion of possible residues (of detergents etc.) in the bathtub or washcloth, a sample was taken.
2. A volunteer entered the bathtub and thoroughly cleaned hair and skin with the washcloth. After stirring the bath water, a second sample was taken.
3. Both samples were analyzed (parameters). From the difference between the samples, the load due to human skin, including potential dirt contamination, was calculated.

Table 4.18: Impact of skin – test conditions and volunteers

Volunteer	Gender	Age	Physical activities	Ambient temperatures on test day
1	f	29	None in the last 24 h (office worker)	Moderate
2	m	31	Physical work	Moderate

Limitations: Due to limited availability of volunteers, the results can only give a general orientation. The total quantity of skin segregation is only covered partially, since clothes absorb it, too.

4.5.2 Results – consumption data and loads of selected parameters

In the following, the loads of selected wastewater parameters from different sources are presented and discussed.

Personal care products

Table 4.19 shows the calculation data and results for daily COD loads in greywater originating from the use of personal care products.

Table 4.19: Daily COD loads per person based on market research data and average COD of personal care products

Product group	**Number of units sold [mio]**	**Average unit size [mL]**	**Product consumption [mL/(c·d)]**	**Average COD load of product [mg COD/mL]**	**COD load [mg COD/(c·d)]**
Bath and shower products[2)]	381	294.5 n=386	3.76	410 n=5	1543.6
Haircare[3)]	516.8	253.6 n=211	4.40	477 n=14	2097.9
Hand and body care[4)]	151.4	253.7 n=110	1.29	567 n=5	730.4
Toothpaste*	373.7	75.8 n=108	0.95	515 n=5	489.7
Number of inhabitants in Germany in 2010: 81.7[1)]				**Sum:**	**4861.6**
				COD in 40 L: 121.5 mg COD/L	
1) & 2) datamonitor 0165-0012; 3) datamonitor 0165-2242; 4) datamonitor 0165-0114 *) number of units was deducted via the average retail price (1,97 €), market volume and segmentation in: datamonitor 0165-0706					

According to the calculations, the daily per capita load of COD from care products is 4861.6 mg. Based on the per capita reference volume of 40 L of B-greywater, this correlates with 121.5 mg COD/L.

Laundry detergent

While the total per-capita consumption of laundry detergents was well documented, the specific usage of liquid or powder forms and conventional or compact forms was not available. The measured COD values of different products showed high variations ranging from 382 to 935 mg COD/g.

Table 4.20: Daily COD-loads per person from laundry detergents based on statistical consumption data (IKW, 2011) and average COD of detergents

Daily consumption per person [g/(c·d)][1)]	Average COD load of detergents [mg COD/g]	Daily COD load per person [mg COD/(c·d)]	COD in 13 L L-greywater [mg COD/L]
21.1	601.7 n=6	12694.0	976.5
1) Based on 7.7 kg/(p·a) (IKW, 2011)			

Skin segregation and dirt

Skin was suspected to be a contributor not only of COD, but also of nitrogen, while information on phosphorus were imprecise (cf. Chapter 4.4.4) Thus, analysis of nutrient loads was added to COD analysis.

Table 4.21: Per-capita loads of COD, nitrogen and phosphorus originating from skin and dirt in shower water

Parameter	Sample 1 [mg/(c·d)]	Sample 2 [mg/(c·d)]	Concentration in 40 L (mg/L)	∅ in 40 L B-greywater (mg/L)
COD	4150	5400	103.8; 135	**119.4**
Phosphate-P	0.45	1.6	0.01;0.04	**0.03**
TNb	76	234.5	1.9;5.86	**3.88**
Ammonia-N	12.8	17.45	0.32;0.44	**0.38**
Nitrate-N	-	6	0.15	**0.15**
Nitrite-N	-	2.8	0.07	**0.07**

The findings in Table 4.21 are in accordance with theoretical considerations that resulted from information about skin segregation: the differences between the loads of the volunteers show, that perspiration influences pollution loads, especially concerning nitrogen (Chapter 4.4.4). The relation of different nitrogen forms is similar to the data of López-Zavala (2007), (cf. Figure 4.5). Small loads of Phosphate were found in both samples.

4.5.3 Results – COD of greywater based on analytical approach

Bathroom greywater

B-greywater receives the COD loads of personal care products, skin segregation and dirt:

Table 4.22: Bathroom greywater composition analysis: COD

COD load personal care products	COD load skin and dirt	Total COD load	COD concentration in 40 L (Table 4.1)
4861.6 mg COD/(c·d)	4775 mg COD/(c·d)	9636.6 mg COD/(c·d)	**240.9 mg COD/L**

The theoretical value of 240.9 mg COD/L complies well with empirical data (Table 4.1). This indicates that the approach is valid.

Greywater from bathroom and laundry

Table 4.23: BL-Greywater composition analysis: COD

COD load detergents	COD load bathroom (Table 4.22)	COD load from skin and dirt in laundry	Total COD load	COD concentration in 53 L BL-greywater
12694.0 mg COD /(c·d)	9636.6 mg COD/(c·d)	n/a	22330.6 mg COD/(c·d)	421.3 mg COD/L

Even the documented COD concentration of 421.3 mg COD/L almost exceeds the empirical reference data of 250 - 430 mg COD/L (Table 4.2). Furthermore, the result in Table 4.23 is an underestimation, since data concerning COD loads from skin and dirt in clothes were not determined. Thus, the sum of COD loads including data from skin and dirt would most likely exceed reference data.

Possible reasons for the high result are:

- Uncertainty in data: the average COD of laundry detergents is based on highly variable data.
- Change of user behavior: considering that the use of compact forms of laundry detergents is increasing (being accompanied by lower dosage demand), while the per capita consumption of detergents stayed stable over the last years (IKW, 2011), either the dosage of detergents has not been adjusted to the kind of detergents used or more laundry is washed. In either case, greywater characteristics of laundry effluent would be different from the data from 2001 (Mehlhart, 2005). This hypothesis is supported when the measured COD concentrations of 1541.5 mg COD/L (Table 4.10) is compared to the theoretical COD concentration of 976.5 mg COD/L (without skin/dirt) in laundry greywater.

The empirical reference data were collected over a decade ago. The results in this research indicate a shift to higher concentrated laundry greywater. More detailed data concerning detergent consumption and absorption of skin segregation and dirt by clothes would be needed to support this conclusion.

4.5.4 Results – Nitrogen and Phosphate-P

Nitrogen (as TNb) originating from skin constitutes 3.88 mg N/L in bathroom greywater (Table 4.21). Tap water quality at specific sites has to be considered (Chapter 4.4.1) to get total nitrogen loads. To estimate nitrogen loads in laundry greywater, more information concerning the impact of skin and dirt would be needed.

Phosphate levels in skin were low (Table 4.21). To calculate total Phosphate-loads, the tap water at specific sites has to be considered. Concerning Phosphate and other phosphorus forms in laundry detergents, the European Union is actually realizing new restrictions (Regulation (EU) No 259/2012). Thus, decreasing P concentrations in greywater have to be expected in Germany.

4.5.5 Conclusion

Statistical market data concerning the consumption of personal care products and detergents is a practicable tool to estimate greywater compositions. By supplementing empirical sampling, this method helps to reduce the effort to characterize greywater. Changes in general user behavior over time can be recognized. In the case of washing machine effluents, the statistical data indicate a shift in user behavior that should be object of further analysis to be verified.

More extensive statistical data would offer the opportunity to distinguish different socio-economic groups, which could support system design processes for socio economic niches, e. g. in multi-family homes, student residences or nursing homes.

Furthermore, the method of using statistical data and average COD loads of products could be extended to cover further parameters of interest, e. g. on surfactants.

Especially regions lacking experiences with greywater reuse can benefit from the use of statistical market research data to estimate greywater characteristics.

Market research and the determination of user behavior are in the focus of the large companies that deal with consumer goods like personal care products and detergents.

Detailed consumption data exist. The support of these enterprises for future research would be desirable to facilitate the estimation of greywater composition.

5 Zahn-Wellens-Test

5.1 Background

The greywater components from care products and laundry detergents are regularly present in greywater. Both substance groups are a source of surfactants and xenobiotics (cf. Chapter 2.5.1; Chapter 4.4.2 and 4.4.3), coming with potentially low biodegradabilities.

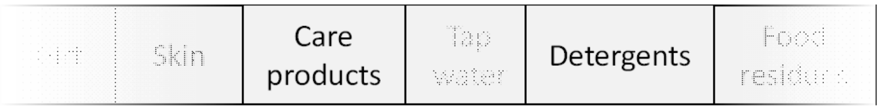


Figure 5.1: Greywater components focused by Zahn-Wellens-Test: Care products and (laundry) detergents

The Zahn-Wellens-Test is a standardized test method to determine the biodegradability of an organic substance in an aerobic aqueous medium. In Germany, the Zahn-Wellens-Test is described in the standard DIN EN ISO 9888 (1999). In this work, it was used to determine the biodegradability of single representative products that are components of greywater. Since the composition of greywater is highly variable, exemplary single products were used instead of a mixture to keep the quantity of possible influences low. The aim of the Zahn-Wellens-Test was not to simulate real degradation conditions, but to create comparable and transferable results concerning the biodegradaibility of different products.

5.2 Test Procedure

The Zahn-Wellens-Test is a batch test with a standard duration of 28 days. The test substrate is degraded in an aqueous medium which is inoculated with activated sludge and enriched with mineral nutrients. The test mixture is continuously stirred and aerated. Oxygen concentrations as well as pH and temperature are controlled. COD is analyzed regularly to monitor the degradation process.

A control sample with a reference substrate and a blank sample without substrate are run in parallels.

5.3 Materials and methods

The substrates that were analyzed were typical personal care products and detergents used in households:

- Personal care: Shampoos, shower gel, conditioner, hair mask, shaving gel, toothpaste
- Laundry detergent and additive: powder and liquid, fabric softener

All tested substances were set up in duplicates and ethylene glycol served as reference substrate.

Table 5.1: Zahn-Wellens-Test experimental parameters

Parameter	Value
Initial sample volume	1 L
COD – originating from test substance/reference substrate	400 mg/L
TSS – originating from activated sludge	0.533 g/L
pH	7.0±5
Oxygen concentration	> 3.5 mg/L
Temperature	20±1 °C

For all test runs, setup parameters were identical as shown in Table 5.1.

A COD concentration of 400 mg/L originating from the test substance was chosen according to the standard requirements and in the range of typical greywater COD concentrations (Table 4.2).

Activated sludge was taken from the municipal wastewater treatment plant Berghausen, Germany. The activated sludge was washed twice with tap water and its SS was analyzed before it was used as inoculum.

If necessary, pH was adjusted by adding HCl or NaOH.

At the beginning of each run, solutions with nutrients were added to each sample (Table 5.2).

Table 5.2: Stock solutions for nutrient supply according to DIN EN ISO 9888:1999

	Solution a: 10 mL		**Solution b: 1 ml**		**Solution c: 1 mL**		**Solution d: 1 mL**	
Ingre-dients (g/L)	KH_2PO_4 K_2HPO_4 $Na_2HPO_4 \cdot 2H_2O$ NH_4Cl	8.5 21.75 33.4 0.5	$MgSO_4 \cdot 7H_2O$	22.5	$CaCl_2 \cdot 2\ H_2O$	36.4	$FeCl_3 \cdot 6H_2O$	0.25

During the test duration, evaporated water was replaced by deionized water to avoid concentration changes caused by water losses.

5.3.1 Sampling

Samples for degradation determination based on dissolved COD were taken according to DIN EN ISO 9888:1999. Thus, the samples for C_A and C_{BA} (Equation 5.1) were taken three hours after the beginning to account for adsorption of substrate to biomass.

Further samples were taken until degradation rates reached their plateaus or until 28 days of test duration were reached.

Dissolved COD was determined after the samples had been filtered (0.45 µm membrane filter).

5.3.2 Calculation

The degradation of dissolved COD was calculated according to Equation 5.1:

$$D_t = \left(1 - \frac{C_t - C_B}{C_A - C_{BA}}\right) \cdot 100 \tag{5.1}$$

D_t	Percentage degradation at time t
C_A	Concentration (mg/L) of dissolved COD in the test suspension measured after 3 h of incubation
C_t	Concentration (mg/L) of dissolved COD in the test suspension at time t
C_{BA}	Concentration (mg/L) of dissolved COD in the blank measured after 3 h of incubation time
C_B	Concentration (mg/L) of dissolved COD in the blank at time t

5.4 Results

In the following, the results of the Zahn-Wellens test according to the standard are presented.

5.4.1 Reference sample – Test validation

The Zahn-Wellens-Test is considered valid, when the reference sample shows a percentage degradation of >70 % after 14 days. All runs were valid with degradations of the reference sample reaching 98-100% within 14 days.

5.4.2 Substrates

The analyzed products reached degradations between 87.8 and 100 %.

Plateaus were normally reached within 10 days of test duration, except for shaving gel and fabric softener, which needed 17 and 15 days respectively. The biomass showed no adaption time (see example Figure 5.2).

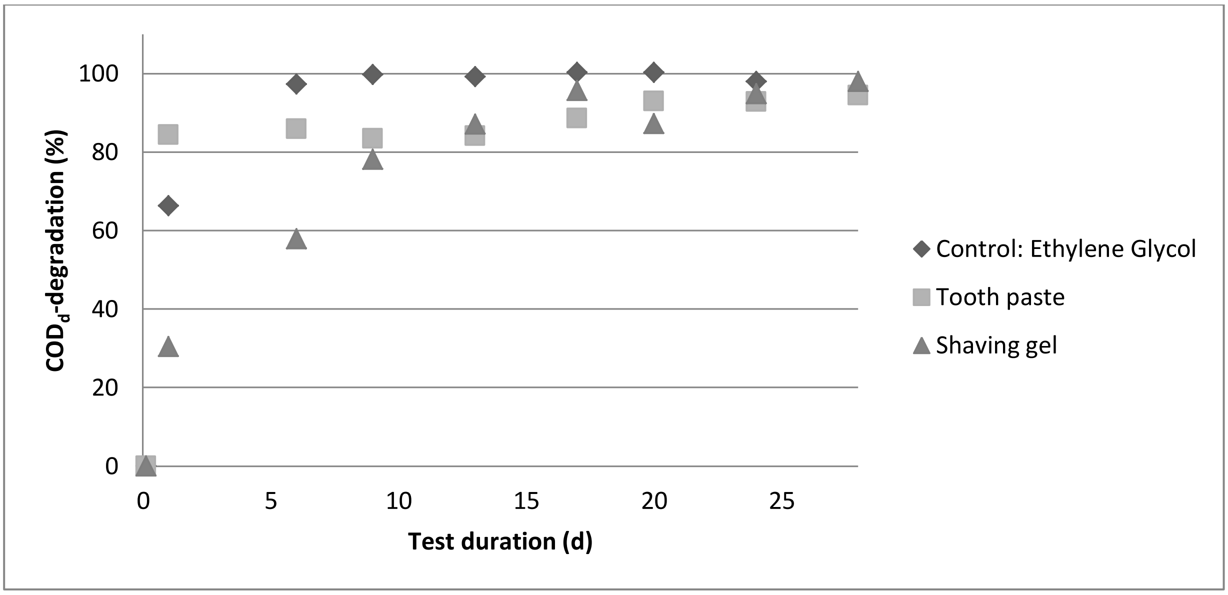


Figure 5.2: Examples of Zahn-Wellens degradation recordings

Personal Care Products: As shown in Figure 5.3, all tested shampoos reached high degradations between 96 and 100 %.

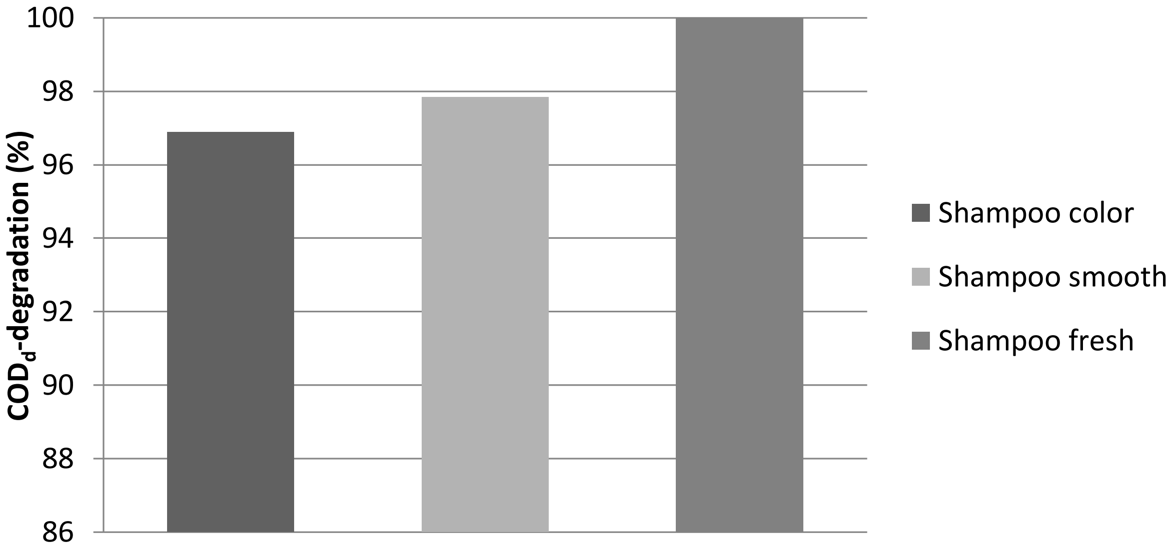


Figure 5.3: Percentage degradation of shampoosFigure 5.4 shows the degradations of further personal care products, which were in the range of 94 to 100 %.

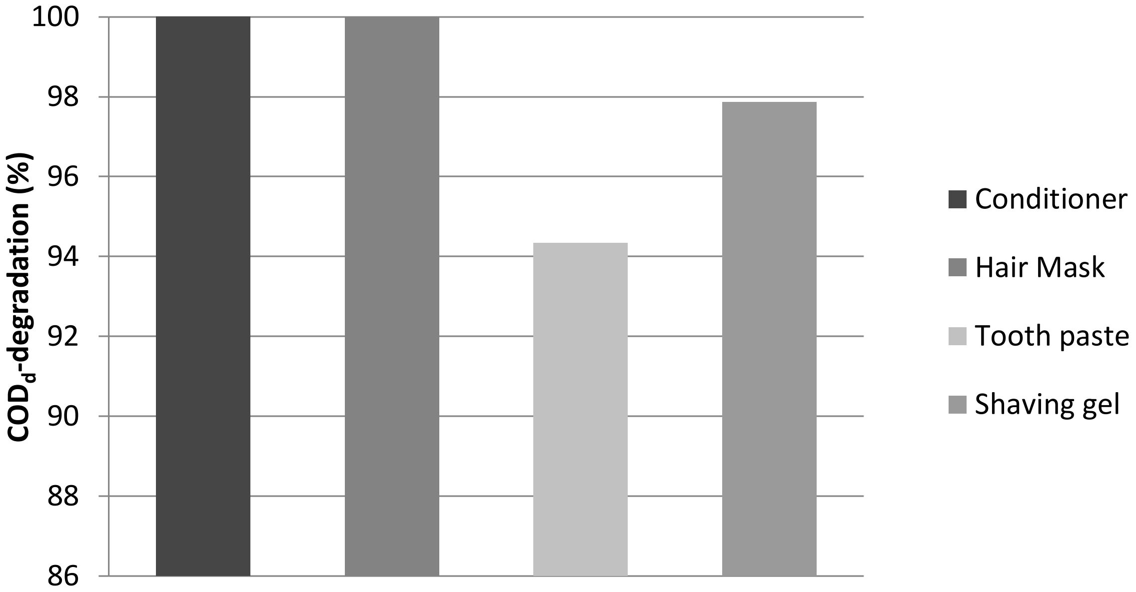


Figure 5.4: Percentage degradation of personal care products

Laundry products: The degradation of laundry detergents was between 87 and 91 % while the fabric softener was completely degraded (see Figure 5.5).

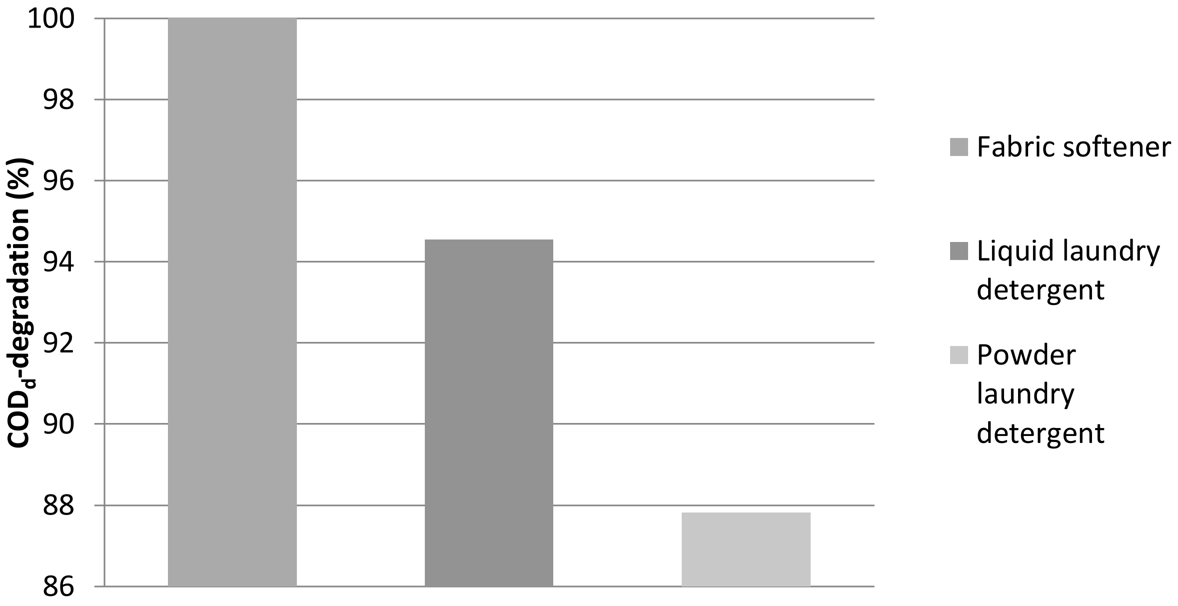


Figure 5.5: Percentage degradation of fabric softener and laundry detergents

Laundry detergents, which are a major COD source in greywater (Table 4.20), showed the lowest percentage degradations of the products that were analyzed.

5.5 Conclusion

According to the standard (DIN EN ISO 9888:1999), no single product or product group commonly used in households showed significantly low degradability.

Powder laundry detergents showed the lowest degradations but were clearly higher than the minimum degradation of 80 % demanded by law (Regulation (EC) No 648/2004).

It can be concluded that the tested personal care products and laundry detergents have high inherent biodegradability. No differences were found between German and international products.

5.6 Discussion

Since the conditions of the Zahn-Wellens-test are optimal for biological degradation, the results cannot be transferred to a real biological treatment system. In the case of greywater treatment, nutrient deficiency (Table 4.7) can negatively impact the degradation of COD.

Furthermore, the Zahn-Wellens-Test gives no information about the quality of COD which is not degraded within the 28 days of the test duration. This fraction of COD would not negatively affect the reusability of greywater as in-house service water, since no major degradation processes would take place in storage tanks or pipes with treated greywater. Yet, residual COD fractions should be analyzed in detail before it is used to irrigate soils. Otherwise, accumulation of harmful substances could occur.

For detailed interpretation of the test results, the following points should be considered:

- In accordance with the test standard, only dissolved COD was determined. For the determination of COD incorporation into biomass or adsorption processes, more detailed sampling including total COD would be needed.
- The calculation of the percentage degradation D_t (Equation 5.1) is based on samples of the test suspension and the blank. Thus, variations or disruptions in the blank can have high impacts on the results, especially when a high ratio of COD is adsorbed to the biomass in the first 3 h of the test resulting in a small C_A.

The range of products that were analyzed in the Zahn-Wellens-Test does not cover the range of products available on the market (cf. Chapter 4.5.1). Thus, for general conclusions concerning the inherent biodegradability of personal care and household products, a wider product range would need to be covered.

6 Impact of cleaning and special additives on greywater biodegradability

6.1 Background:

The relevance of cleaning agents can be estimated considering the consumption of detergents and cleaners in Germany (Table 6.1).

Table 6.1: Consumption cleaners Germany 2001 - Based on 82.44 mio inhabitants in Germany in 2001 (destatis) and usage data in Hauthal (2004)

Product group	**per-capita consumption per week in kg/(c*w)**	**Weekly COD load in g/(c*w)[1]**
All-purpose cleaners	0.0179	2.69
Abrasives	0.0056	0.84
Other cleaners (special cleaners for kitchen, bathroom, toilet etc.)	0.0028	0.42
Sum:	**0.0263**	**3.94**
[1]based on 150 mg COD/g (own sampling)		

The COD load contributed by cleaning products is very low compared to the contribution of personal care products, laundry detergents and skin (cf. Chapter 4.5.3). Yet, cleaning products can contain caustic substances potentially harming biological treatment systems. Thus, this research determines the effects of different representative cleaning agents from different product groups on biological greywater degradation (cf. Chapter 4.4.6). The aim was to identify agents that would have to be banned or limited in a greywater using household.

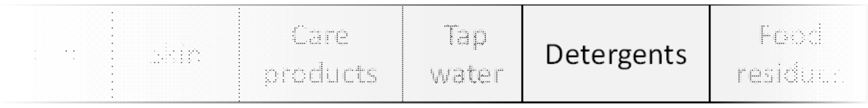


Figure 6.1: Greywater component ‘detergents’ - impact of cleaning agents

6.2 Methods and material

Material: Karlsruher flasks, stirrer, Oxygen, aerators, optical Oxy-meters, synthetic greywater (cf. Table 7.2), acclimated biomass, test substrate.

Tap water was used to generate synthetic greywater. Lose biofilm was taken from an RBC treating synthetic greywater (cf. Chapter 7). A mixture of biofilm and fresh synthetic greywater was shaken thoroughly to split and evenly disperse biofilm rags.

The mixture was aerated with pure Oxygen. When the Oxygen concentration reached approximately 20 mg/L, the flasks were closed by inserting the Oxygen sensors (see Figure 6.2). Oxygen concentration was recorded every 30 seconds. After stabilization of sensors, the Oxygen concentrations were at least recorded over 10 min to determine the undisturbed respiration (blank respiration). Then, test substrate was added to the flasks in three different concentrations (cf. Table 6.3). The dosages of agents were chosen in a small range to keep COD concentrations stable. COD increase was < 2 % to avoid impact due to shifts in COD to biomass ratio. The Oxygen concentration was recorded for at least 4 hours or until the Oxygen concentration fell below 2 mg/L.

The high Oxygen concentration in the flasks was chosen over standard saturation since prior testing showed interference of re-aeration (assuming volatile components of detergents as origin of this impact). By having a reservoir of 20 mg/L of Oxygen instead of 7.5 mg/l, which were achieved by aerating with atmospheric air, re-aeration was avoided.

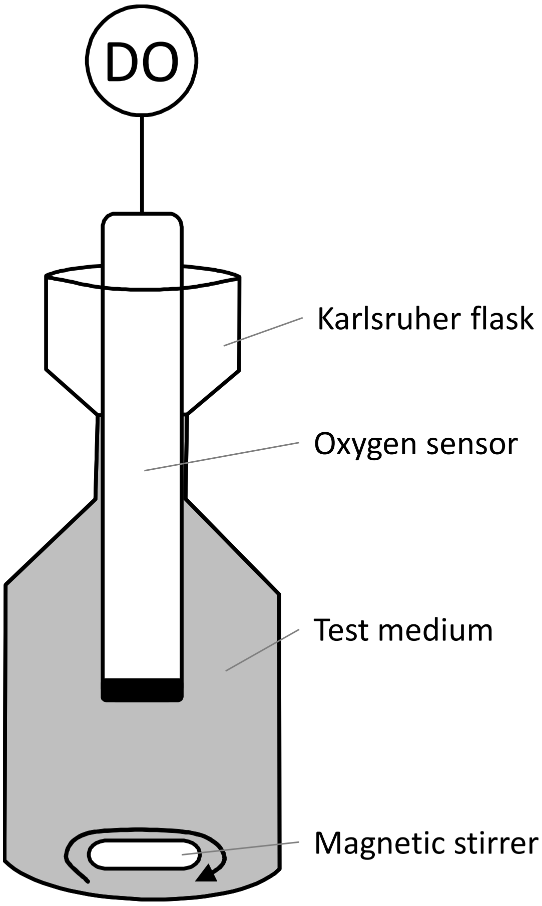


Figure 6.2: Test setup in Karlsruher flask for respirometry

The concentrations of suspended solids and organic suspended solids were determined in every sample to control test setups and COD to biomass ratios.

Table 6.2: Chosen cleaning agents/additives and specific characteristic

Substrate	Characteristic
All-purpose cleaner	Labeled as environmentally friendly
Abrasive	Liquid
Bathroom cleaner	Based on organic acid
Fabric whitener (laundry additive)	Based on enzymes

6.2.1 Analysis

The recorded data were processed according to Lineweaver-Burk to determine kinetic parameters and potential inhibition (Appendix A.3).

6.3 Results

6.3.1 General data characteristics

Over the whole test period, the Lineweaver-Burk diagrams showed no linear gradient (see Appendix Figure A 3) indicating that the organic fractions have different degradation characteristics. Therefore, to compare the impact of different cleaner dosages, only the first data after substrate dosage were regarded and compared, showing a linear characteristic.

6.3.2 Michaelis-Menten parameters

Table 6.3: Setup details and Michaelis-Menten-parameters of tested agents

	Dosage (ml/L)	v_{max} (mg O_2/(L*h))	k_m (ml/L)	R^2	COD/SS (mg/g)
All-purpose cleaner	0.03	7.36	3.45	0.72	0.22
	0.07	7.46	3.57	0.53	
	0.10	(11.81)*	(7.02)*	0.14	
Abrasive	0.02	6.64	2.22	0.81	0.25
	0.03	5.56	3.94	0.53	
	0.05	5.38	5.35	0.56	
Bathroom cleaner	0.03	12.09	12.82	0.65	0.22
	0.06	12.09	11.90	0.73	
	0.10	(6.84)*	(6.81)*	0.13	
Fabric whitener	0.006	6.98	3.36	0.74	0.26
	0.013	7.39	3.45	0.69	
	0.018	(6.55)*	(4.35)*	0.12	
	* high variation of recorded input data ($R^2 < 0.5$)				

Assuming, that changes of parameters < 10% are in the range of inaccuracy of the methodology, only the kinetic results of the liquid abrasive indicate inhibition impacts (see Figure 6.3). The other agents did not indicate inhibition effects.

The Lineweaver-Burk graphs of the abrasive are shown in Figure 6.3. The abrasive agent showed mixed inhibition effects, affecting both Michaelis-Menten-Parameters v_{max} and k (Equation 2.3). Yet, the approximate intersection of the Lineweaver-Burk graphs of the three different inhibition dosages is close to the y-axis. Thus, a competitive inhibition mechanism cannot be excluded from the presented data.

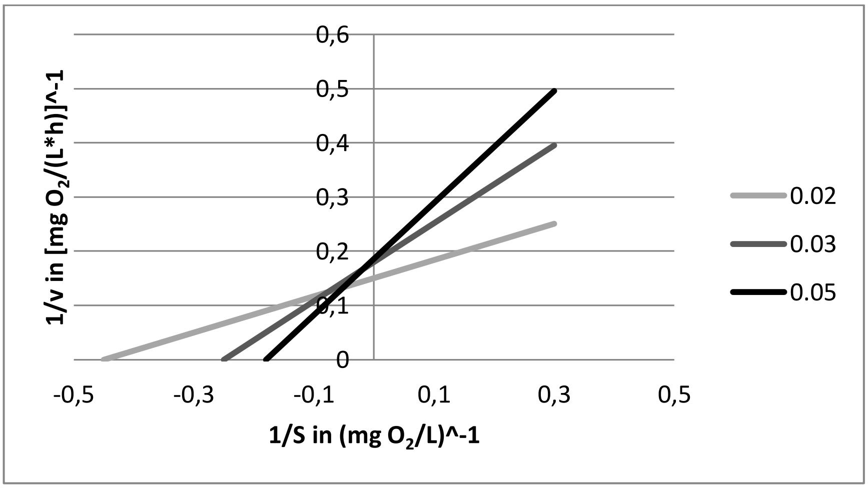


Figure 6.3: Lineweaver-Burk diagram of abrasive as inhibitor in dosages from 0.02-0.05 g/L

6.4 Conclusions

6.4.1 Abrasive

The ingredient list of the tested abrasive was analyzed for potential compound causing inhibition effects. No ingredient stood out specifically. Yet, the abrasive contained various sodium salts, surfactants and Benzisothiazolinone (preservative). Furthermore, the abrasive contained relatively high organic fractions (223 mg COD/g). Even though the inhibition effect of the abrasive cannot be related to a specific ingredient, hardly degradable organic fractions could serve as competitive substrate. Furthermore, salts could serve as inhibitor.

6.4.2 Potential impact on greywater treatment

Transferring the results for the abrasive cleaner on a model scenario for a small greywater treatment unit for one person with a volume of 53 L (cf. Chapter 4.2.4) , the concentrations (0.02 g/L, 0.03 g/L, 0.05 g/L) of the inhibition test would correspond to 1.06 g, 1.59 g, and 2.65 g respectively. These loads of abrasive causing inhibition are likely to be reached during cleaning, since the average weekly per-capita consumption of abrasives is 0.0056 kg = 5.6 g (Table 6.1). Thus, the biological treatment of greywater could be inhibited by the usage of abrasives as cleaners.

6.4.3 Quality of measurements

Though the density of data over time was good, the variation of data due to the (in-)stability of the data recording was high. This created some problems during data processing. The data needed mathematical smoothing and still often showed poor coefficients of determination R^2 (Table 6.3). Furthermore, the determination of Michaelis-Menten parameters using the linear regression of Lineweaver-Burk shows uncertainties since small substrate concentrations have a mathematically high impact.

However, the obtained results for v_{max} in this research lay in the range of research using respirometry with domestic wastewater sludge (Hagman and la Cour Jansen, 2007)

To eventually calculate dosage recommendations or limitations, the inhibition of greywater degradation should be determined more extensively, using a more precise test setup wich could be obtained e. g. by better control of stable COD/SS ratios. Furthermore, the reasons of the poor quality of recorded Oxygen concentrations should be identified. For example, the nature of the suspended biomass in the test setup coming in rags could have disturbed the optical Oxygen sensors. A better homogenization of biomass could lead to better results.

The results concerning the impact of abrasives should be interpreted carefully keeping the uncertainties discussed above in mind. Furthermore, only one specific abrasive was determined. To get further information, a wider range of products should be analyzed. However, reports from existing greywater treatment plants (Nolde, 2005) did not mention impacts of cleaning agents on greywater treatment. Yet, this issue has simply not been in focus before.

7 Biological treatment with Rotating Biological Contactors (RBC)

7.1 Introduction

A lab scale greywater treatment system was operated to draw conclusions regarding general treatment principles concerning greywater which were compared to those of conventional wastewater.

BL greywater was used according to the findings of Chapter 4.2.4. A synthetic greywater mimicking BL greywater was designed (Chapter 7.1.2 and 7.1.3)

Figure 7.1: Approach of biological greywater treatment in this work

7.1.1 General characteristics of RBCs

For the biological treatment process, a rotating biological contactor was chosen. RBCs have low demands concerning energy and space. Furthermore, they are easy to maintain (Waskar et al., 2012). Thus, RBCs are ideal for semi- or decentral applications like greywater treatment. Since RBCs are based on sessile biomass with high sludge ages, the biocenosis in such systems can adapt to substrates that show low biodegradabilities. As greywater has higher concentrations of those substrates while it shows nutrient deficiencies (Table 4.7), RBCs were assessed as a suitable treatment solution. Furthermore, earlier experiences with RBCs in greywater treatment showed good results (Eriksson et al., 2009, Friedler et al., 2005).

7.1.2 Description of synthetic greywater recipe

To determine biodegradation parameters of greywater, a synthetic greywater recipe was developed.

Synthetic greywater guaranteed constant and controllable composition, which is not given in real greywater sources where volume and loads show high variability (Eriksson et al., 2009). Thus, the impact of high inflow variations was excluded from the test setup.

The recipe was developed based on data of water volumes of different sources and orientation values for COD concentrations (Mehlhart, 2005). Thus, the COD-loads of different sources were determined (Table 7.1).

Table 7.1: COD-assumptions for greywater recipe design based on literature data (Table 4.2 and Figure 4.2 right)

Source	**Water volume in L/(c·d)**	**COD concentration in mg COD/L**	**Load in g COD/(c·d)**
Bathroom	40 L	∅ 225 mg COD/L	9.00
Bathroom + Laundry	53 L	250-430 mg COD/L (chosen for further calculation: 350 mg COD/L)	18.55
Difference: only Laundry	13 L		**9.55**

Ingredients for the synthetic greywater were chosen from different brands and a low to medium price range. Furthermore, the chosen products were available in normal supermarkets.

Ingredients of the synthetic greywater

The ingredients of the synthetic greywater were combined to match the COD loads (Table 7.1). Statistically representative data concerning the consumption of personal care products was not available at the time of the development of the recipe. Thus, the ratios of the ingredients had to be assumed.

Personal care products were combined including deodorant, which comes with antimicrobial ingredients and moisturizer to mimic biochemical skin constituents. The sum of personal care products represents the COD in bathroom greywater. Additionally, laundry detergent was added to represent the COD originating from washing machines.

Table 7.2: Synthetic greywater recipe for 50 L of tap water

Ingredient	Mass (g)	COD load (g)
Toothpaste	0.5	0.26
Deodorant	0.25	0.06
Moisturizer	3.75	1.56
Shampoo	5	2.65
Shower gel	5	3.18
Conditioner	3.75	0.86
Washing powder (concentrate)	9.5	8.88

7.1.3 Characteristic parameters of the synthetic greywater

Table 7.3 shows the wastewater parameters which resulted from the recipe design.

Table 7.3: Wastewater parameters synthetic greywater

Parameter	Unit	Value
COD	mg/L	350
BOD_5	mg /L	157
Total nitrogen bound, TNb*	mg/L	1.06
Ammonium-N, NH_4^+-N*	mg/L	0.02
Nitrate-N, NO_3^--N*	mg/L	0.47
Phosphate-P, PO_4^{3-}-P*	mg/L	0.14
Anionic Surfactants	mg/L	33.1
Electric conductivity, EC*	mS/cm	0.876
pH	(-)	7.9
*) high influence of tap water quality		

Comparison of the synthetic greywater with literature data and test household

Based on COD as start parameter, the concentration of BOD_5 turned out to be in the same range as suggested by literature (Table 4.2). Since the literature data used as reference did not include information on nutrient concentrations, the data of the synthetic greywater cannot be compared directly. Yet, the very low values in comparison to both B-greywater (Table 4.1), and L-greywater from the test household (Table 4.10) and, moreover, the information of nitrogen loads from skin (Chapter 4.4.4) indicate a substantial nutrient under-representation (COD/N/P=100/0.3/0.04) in the synthetic greywater (cf. Chapter 2.5.2). Neither the data from the test household nor the information on the impact of skin segregation were determined at the time the synthetic greywater recipe was designed. For future research, the addition of nitrogen, e. g. in form of urea (cf. Chapter 4.4.4) should be considered.

Eventually, the determined biodegradation of synthetic greywater is assumed to underestimate the treatability of real greywater. Yet, the results should consequently be on the safe side and underestimation of the treatment potential is indicated.

7.2 Description of the RBC treatment system

A RBC with three stages was used to treat the synthetic greywater. The RBC was designed according to the guideline ATV-DVWK-A 281 (2004) for municipal wastewater. Due to the low nitrogen loads of greywater, Nitrification was not considered for the RBC design.

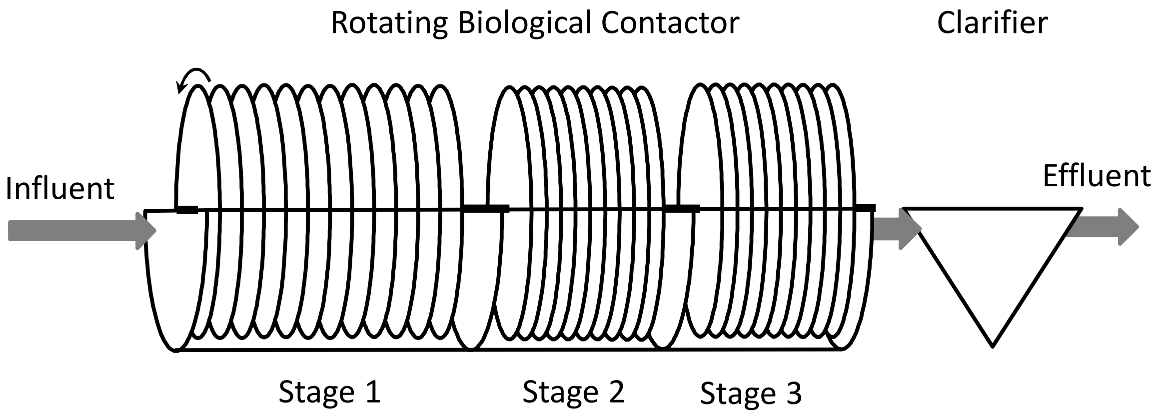


Figure 7.2: Scheme of rotating biological contactor used for greywater treatment

Table 7.4: Characteristic parameters of the RBC used to treat greywater

	Volume (L)	Active disk area (m^2)	Disk distance (mm)
Stage 1	6.1	1.18	18
Stage 2	4.5	0.98	15
Stage 3	4.5	0.98	15
Total (all stages)	15.1	3.14	-
Disk diameter (m)		0.25	
Water level (m)		0.108	
Immersion level (%)		33	
Total volume/total area (L/m^2)		4.82	
Rotation velocity (rpm)		2.5	
Temperature (°C)		20±1	

To determine the degradability of greywater in a real treatment system, the RBC was tested with three different organic load configurations summarized in Table 7.5.

Table 7.5: Overview - runs and respective organic loads

Run	1	2	3
Organic load (g BOD_5/m^2*d)	5.01	2.50	1.43
Organic load (g COD/m^2*d)	11.15	5.57	3.18

BOD_5/COD-ratio was known for the synthetic greywater (Table 2.5). COD was chosen to monitor the RBC removal efficiencies. When the effluent of the RBC showed stable COD values after acclimatization, BOD_5 was tested additionally to enable comparability of removal efficiencies to reference literature.

7.3 Results

pH and Oxygen concentrations

pH was in the range of 8.1 ± 0.3, thus, the greywater system was in a slightly basic range that was not restricting the biological treatment process.

Oxygen concentrations in the water (Figure 7.3) were always > 2 mg/L, indicating no Oxygen limitation in the liquid phase. The Oxygen concentrations in the first stage were the lowest. They indicating the highest COD degradation rates but were also influenced by the initially low Oxygen concentrations of the influent.

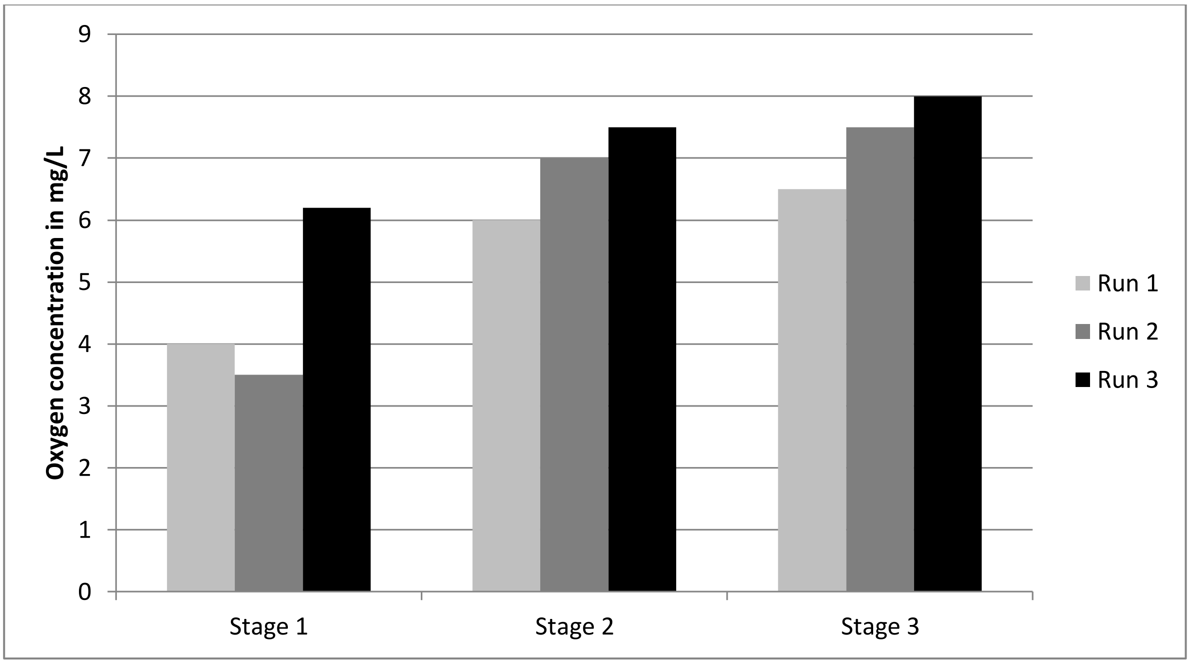


Figure 7.3: Oxygen concentrations in the water phase

The Oxygen concentrations increased during the second and third stage, indicating slower degradation rates.

The higher the organic load, the lower the Oxygen concentration was in the stages. Thus, as expected, degradation rates increased with higher organic loads. Since the organic load was decreased with each run (cf. Table 7.5), the Oxygen consumption decreased, too, causing higher Oxygen concentrations in each respective stage.

Even though Oxygen concentrations in the water phase were aerobic, the sloughed biofilm showed black areas in deeper zones, indicating anaerobic degradation processes. However, the trends of the Oxygen concentrations in the different stages and runs comply well with the trend expected for a functioning RBC.

Removal efficiencies

Figure 7.4 shows the COD and BOD_5 effluent quality of the RBC under the different load conditions (cf. Table 7.5).

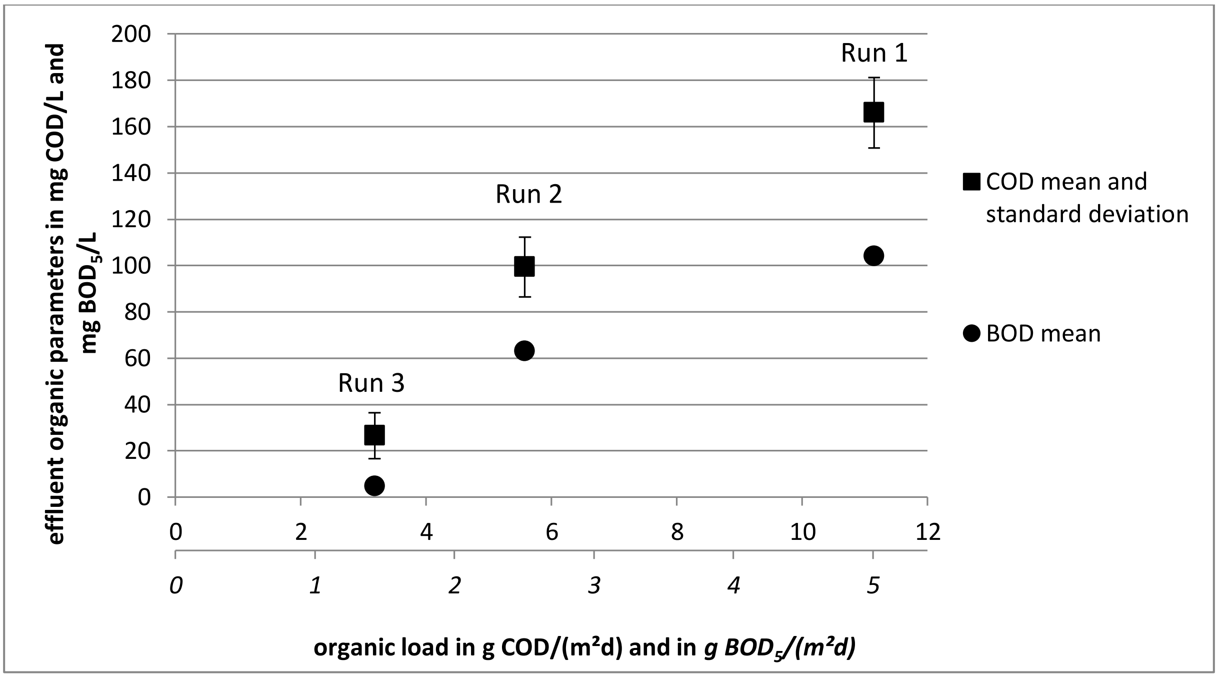


Figure 7.4: COD and BOD_5 under the different organic loads

As expected, the effluent quality rises with lower organic loads.

Nutrients

Nitrogen and phosphorus were deficient in the treated greywater. The concentrations were in the range of the detection limits.

General observations

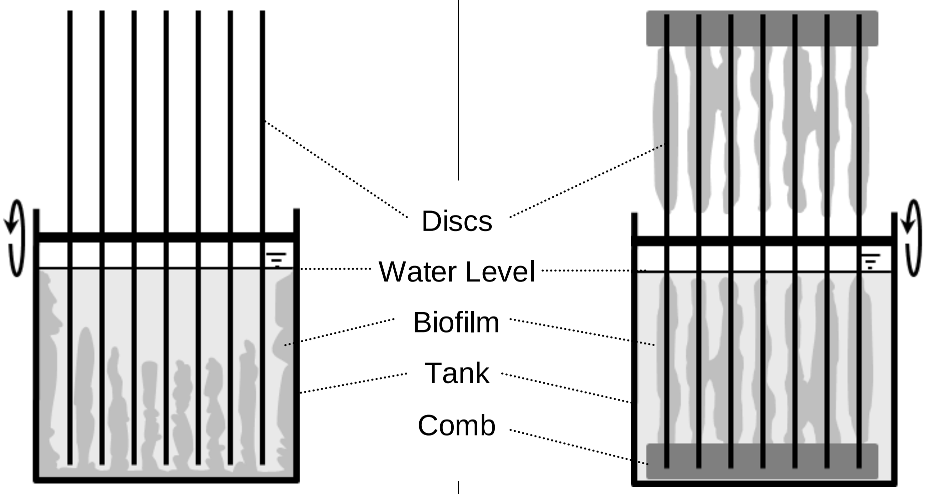
Though the RBC was inoculated with wastewater microorganisms, the initial establishment of the biofilm needed about eight weeks.

The biofilm showed a grey to beige color, which is reported to indicate unhealthy biofilm but also filamentous bacteria (Zickefoose, 1984). The biofilm was thick and slimy, indicating high levels of EPS (extracellular polymeric substances). Microscopic observation confirmed the dominance of filamentous bacteria, but also showed other microorganisms as well as higher organisms like nematodes. The occurrence of filamentous bacteria and high amounts of EPS can be caused by nutrient deficiency (Liu and Liu, 2006). These findings are coherent with the characteristics of greywater.

The slimy and filamentous structure caused problems in the RBC, which had been designed according to the standards of conventional household wastewater.

- Filamentous microorganisms led to formation of tissue between the discs, causing hydraulic dead zones. Thus, combs were installed at the discs, preventing tissue formation.
- The distance between the disks was too narrow, thus, biofilm merged occasionally and had to be separated by the operator. To prevent the risk of merging biofilm, it is recommended to extend the minimal distance between disks of 15 mm and 18 mm (ATV-DVWK-A 281, 2004) about 20 %, resulting in a minimal distance of 18 mm and 22 mm, respectively.

Table 7.6: Operational problems of greywater treatment

Problem	**Formation of tissue in water**	**Merging of biofilm**
Description	Due to filamentous miccro-organisms, tissue forms in water between the discs.	Thick biofilm merges.
Consequence	Hydraulic dead zones.	Active surface is reduced.
Figure		
Solution	Installation of combs (see right figure, dark grey and in Figure 7.5)	Higher distance between disks.

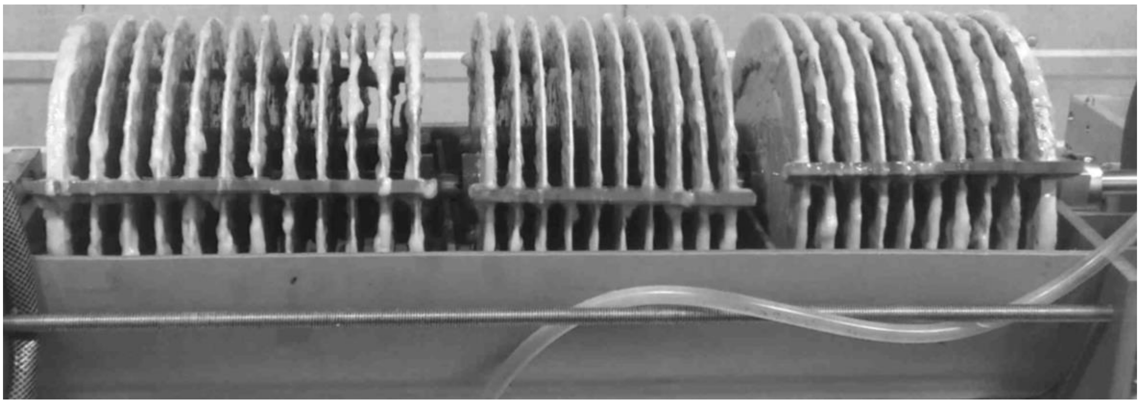


Figure 7.5: Picture of RBC in operation, with combs

Even though the biofilm was dominated by filamentous microorganisms, the excess biomass showed excellent settling properties as expected for a RBC (e.g. Waskar et al., 2012).

7.4 Conclusions

7.4.1 Comparison to other studies

Although some RBCs treating greywater have been studied before, the results are hardly directly comparable due to unspecified process configurations in the reference plants (e. g. temperature, disc surface areas) or very different greywater composition (e. g. including kitchen wastewater or substantially higher nutrient levels). However, reported removal efficiencies were generally better than in this study (Abdel-Kader, 2012; Enayathali and Kumar, 2012). The reason for this is most likely the high nutrient deficiency in the synthetic greywater.

7.4.2 Organic load

The best effluent quality obtained in Run 3 with the lowest organic load was 4.7 mg BOD_5/L. This would correspond to 5.4 mg BOD_7/L (based on the assumption that $BOD_7/BOD_5 = 1.15$ according to Henze and Cumeau, 2008). Thus, the quality recommendations for toilet flushing and washing machines with a $BOD_7 = 5$ mg/L (Table 3.1) would not be fulfilled.

7.4.3 Comparison to conventional RBC

RBCs for conventional domestic wastewater have, depending on the number of stages and the number of connected inhabitants, an organic load of 4 – 10 g BOD/(m^2*d) (design parameters, ATV-DVWK-A 281, 2004).

Thus, a RBC treating greywater would need an active surface area 2.8 to 7 times larger than that of a conventional RBC.

7.4.4 Recommendations

Design parameters:

- Active surface: Since the synthetic greywater used in this research was extremely nutrient deficient, the design parameters concerning the organic load concluded from the comparison to a conventional RBC should be considered carefully.
- Disk distance: the disk distance should be enlarged by approximately 20 %.
- Combs should be installed on the disks to control tissue formation.

System integration:

The RBC is only the biological degradation unit for greywater treatment. For the whole greywater treatment system, further units would be needed (cf. Chapter 2.6).

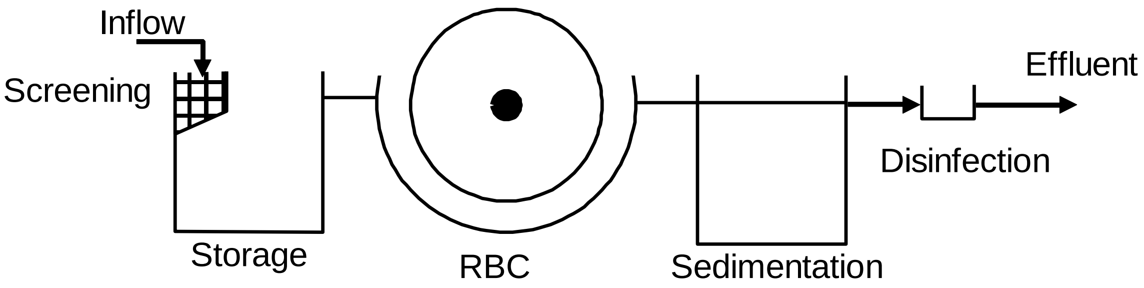


Figure 7.6: Suggestion for greywater treatment system based on RBC

Facing the increased space demand for an RBC concluded from the presented results, e. g. the combination of a RBC as first biological stage with a sand filter as second stage should also be considered. Yet, the decision for a system combination should be based on an evaluation of the available space. E. g. the installation of a membrane instead of a sedimentation tank for the separation of excess sludge would require less space (but more energy).

8 Summary process related results

The different greywater streams were determined considering their volumes and pollutions. Thus, kitchen greywater and its components were excluded from greywater under consideration of its pollution characteristics.

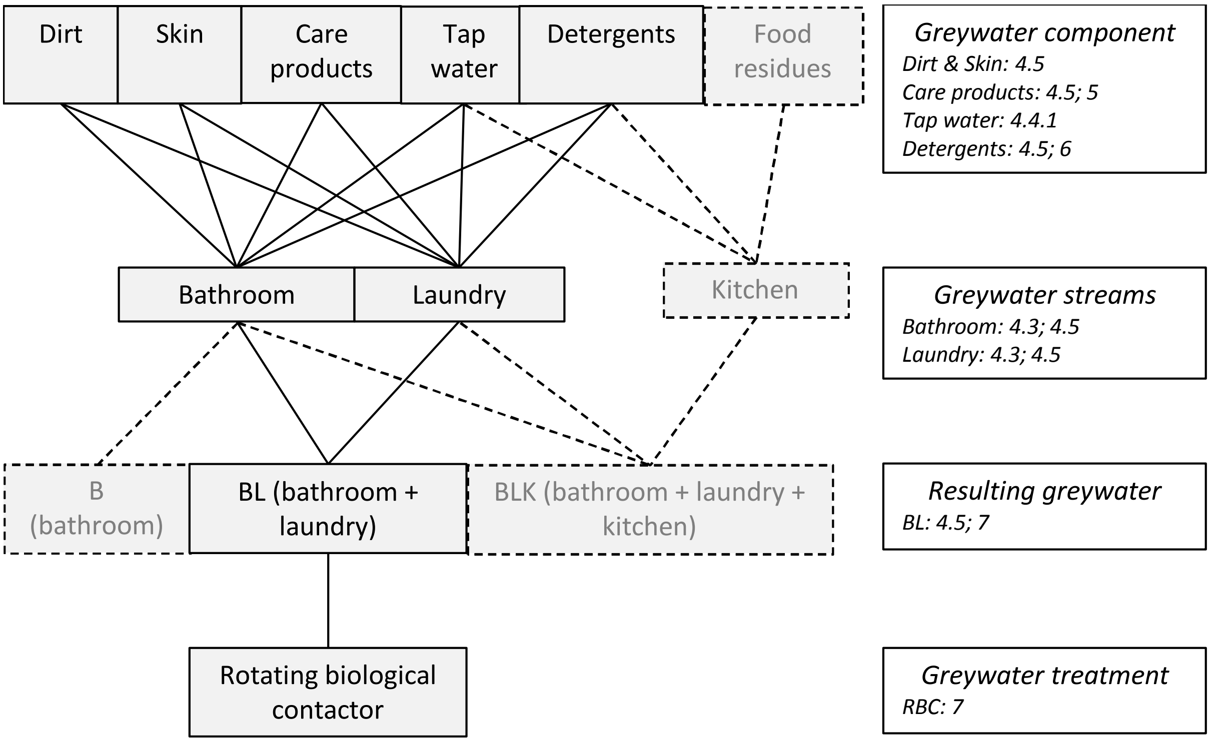


Figure 8.1: Overview of analyzed greywater composition aspects and reference to addressing chapters

The substances in bathroom and laundry greywater streams were determined closer by quantifying component groups. Thus, an alternative approach to estimate greywater compositions based on statistical consumption data was introduced. This approach was applied and revealed the demand of a closer evaluation of washing machine greywater due to likely changes in laundry detergent composition and use. Furthermore, it showed that the impact of skin segregation has been underestimated in the past. Eventually, using statistical data for the estimation of greywater characteristics is a convenient tool. It has the potential to be applied to specific demographic user groups or substances as far as consumption data are available.

Two specific product groups, personal care products and detergents, were determined closer due to their potential impacts on biological greywater treatment. The general biodegradability of personal care products was controlled using the Zahn-Wellens-Test. Detergents were tested for potential inhibition effects on biological greywater treatment.

To finally determine greywater treatability, a rotating biological contactor was used to treat synthetic greywater. From the results, design parameters were modified to be suitable to treat greywater.

However, to realize and establish greywater reuse in Germany, further steps that exceed process related consideration have to be taken.

9 Implementation of greywater reuse in Germany

9.1 Introduction

Greywater reuse is not very common in Germany even though first experiences go back to the 1980s (according to Nolde, 1999).

Specific laws and guidelines for the implementation of greywater systems are missing. Thus, implementation procedures are unclear, liabilities are not defined and future developments cannot be estimated. Furthermore, authorities handle the approval of greywater systems differently, with some states and local authorities generally rejecting greywater recycling (Nolde, 2005) while others, like the cities of Berlin (SenBer, 2007) and Hamburg (Hamburg, 2007), support it.

To develop possible strategies to implement greywater reuse in Germany, the practice of greywater reclamation in Australia was studied. In Australia, greywater reclamation is far more established than in Germany. In Australia, 55 % of households report greywater as a water source (ABS, 2007). Thus, the conditions concerning greywater reclamation in Australia were determined using a stakeholder analysis. Literature including legislation, statistical data and research publications were analyzed. The literature research was supplemented by individual interviews.

9.2 Method: Comparative stakeholder analysis Australia – Germany

The main stakeholders influencing greywater implementation were identified and described. Subsequently, the German conditions were determined and compared to the conditions in Australia. Finally, conclusions for the greywater implementation in Germany were drawn.

9.2.1 Definitions

Stakeholder

Here, stakeholders are persons or institutions that influence the implementation of greywater reclamation.

Action theory

It is assumed that the decision for or against the implementation of greywater treatment is a rational action driven by motivation or objections to reclaim greywater. Motivations and objections can be based on idealistic or objective considerations (Gröbl-Steinbach, 2004).

Approach

To understand the conditions of greywater reclamation in Australia, literature, including statistical data and guidelines, were researched. This information was supplemented by insights from individual interviews (n=7) with professional engineers working with greywater, manufacturers and users. The interviews were held in meetings, via telephone or email. A question catalogue (Appendix Chapter A.5), which covered different aspects of greywater reuse, was used adjusted to the type of interviewee. The research was conducted in Sidney, New South Wales (NSW). Therefore, the findings focus mainly on this region, especially concerning the legislative aspects.

9.3 Results - Greywater reuse in Australia – New South Wales

According to statistical data obtained by the Australian Bureau of Statistics (ABS) in 2010, 20 % of households in New South Wales reported greywater as a source of water. In 12.7 % of all households, greywater was used for irrigation in the garden. More extensive questioning in 2007 showed that 1.6 % of households used greywater for toilet flushing (ABS, 2007).

9.3.1 Legislative background of greywater reclamation in New South Wales (NSW), Australia

In Australia, the “Australian guidelines for water recycling: Managing health and environmental risks (phase 1)” (NRMMC-EPHC-AHMC, 2006) define the standard that is realized by the different states. According to this, NSW developed a guideline addressing “greywater reuse in sewered, single household residential premises” (NSW, 2008). In these private recycling schemes, the maximum size of a treatment system is designed for a maximum estimated greywater volume of ten persons (NSW, 2005).

For single households, the NSW-guideline differentiates between the reclamation of untreated and treated greywater. Table 9.1 shows the reclamation conditions for both types of greywater.

Table 9.1: Summary of main aspects of reclamation of untreated and treated greywater in New South Wales (NSW, 2008)

	Untreated greywater	Treated greywater
Sources	Washing machines, laundry tubs, showers, hand basins, baths	Washing machines, laundry tubs, showers, hand basins, baths AND kitchens
Reuse options	Irrigation via bucketing Sub-surface irrigation via diversion device	Irrigation Toilet flushing Washing machines
Approval requirement	Bucketing: no approval needed Diversion device: Certified device needs to be installed by licensed plumber, notification of local water utility	Prior approval of local council Notification of local water utility Greywater treatment system has to be accredited

Only greywater treatment systems that passed the accreditation process (NSW, 2005) can be installed in private households. During accreditation, a system has to comply with the effluent quality criteria (Appendix Table A 2 and Table A 3) over a testing period of 26 weeks.

For the implementation of a greywater treatment system for more than ten persons, the “interim NSW guidelines for management of private recycled water schemes” (NSW, 2008a) apply. Approval conditions are more complex than for single households. Systems have to undergo a general validation process, a verification process at each site and regular monitoring of E.coli, turbidity, pH and disinfection residues.

9.3.2 Greywater reuse practice in Australia

Pinto and Maheshwari (2010) surveyed the use of greywater for garden irrigation in the region of Sydney, New South Wales, (Pinto, 2010). The results showed that greywater users were very motivated to reuse greywater because of environmental reasons: respondents named helping the environment (37.1 %) and coping with the current water crisis (37.6 %) as their main motivation to reuse greywater.

An earlier Australia-wide study conducted by the Alternative Technology Association (ATA, 2005) showed similar results with 88 % of respondents naming water conservation, followed by 56 % naming the irrigation of garden/lawn as a main reason to reuse greywater.

In this context, the application of water restrictions concerning garden irrigations has to be considered. During times of droughts, the use of tap water for garden irrigation is restricted. It is allowed to use greywater as an alternative water source (NSW, 2011). The water restrictions are managed by the water agencies according to the orders of the legislation.

Even though the reuse of untreated greywater for irrigation is allowed, 23 % of participants in the study of Pinto and Maheshwari (2010) practicing greywater reuse reported using a greywater treatment system (not defined in terms of technical or legal aspects). In the survey conducted by the ATA (2005), which also considered indoor reuse applications, 42 % of greywater users used a do-it-yourself-system (consequently not accredited), and 5 % had a commercial system.

According to the ATA, 13 % used greywater for toilet flushing. Greywater was also used in the laundry but no quantification was given.

Hygienic and environmental safety

Users of greywater systems chose environmentally friendly detergents, which, in Australia, are available in normal supermarkets. This indicates that greywater users were generally willing to adjust their behavior, and environmental aspects were of concern to them.

Yet, where knowledge about safe handling of greywater is not present, mishandling is observed.

The guidelines (NSW, 2008) as well as other publically accessible material give extensive information in regard to safe handling of greywater. Yet, while the majority had no problems accessing information, considerable 28 % of greywater users had not looked for information and 23 % considered it inadequate.

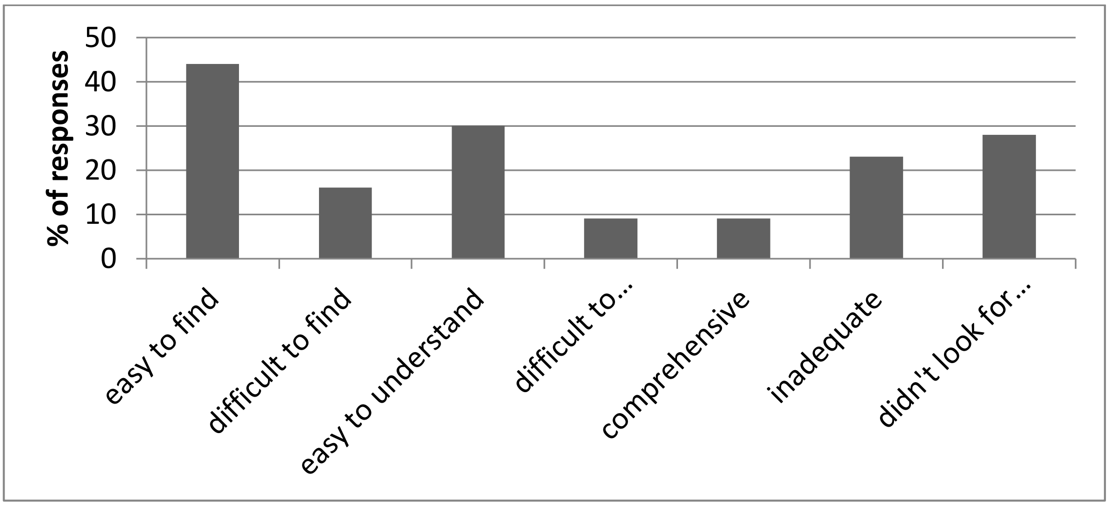


Figure 9.1: Access to information on greywater (ATA, 2005)

The individual interviews confirmed the lack of information about greywater as a major issue. Professionals stressed that ignorance had resulted in mishandling of treatment system and greywater.

For example, not being aware of hygienic risks, users switched off UV disinfection units to save energy as long as the effluent of a treatment system was clear. Yet, unclear effluent of a treatment system was not interpreted as an indicator of a process problem in the treatment system, but UV disinfection was switched on.

Issues like these were avoided when a maintenance plan with the manufacturer of a treatment system was in place.

Even though environmental consciousness was a major motivation to reuse greywater, many users were not aware of potential environmental impacts when applying greywater on soils, plants or letting it run-off the property.

Thus, the need for water related education was emphasized by interviewees. Since the provided information does not effectively reach greywater users, active education tools are needed.

Economic aspects

At the current state, the likelihood of a greywater treatment system to be economically viable is low. Since the factors influencing economic viability are highly variable, economic viability has to be determined for every single case.

The investment and operational costs for greywater treatment systems are relatively high, since the majority of systems accredited in New South Wales are technically advanced[6]. Thus, not only do high investment costs have to be considered, but also the high costs for energy demand and wear parts.

The financial savings resulting by lower tap water demand and reduced wastewater discharge were normally not high enough to cover the costs for a greywater treatment system (Pinto and Maheshwari, 2010). 2.13 \$/m³ were the potential savings[7] (July 2012).

According to interviewees, greywater treatment systems in units larger than a single household, e.g. in a hotel or other commercial buildings, would have further monetary benefits: when a conventional water system would cause high rehabilitation or investment costs for the sewer system or when more customers can be expected due to an improved ecological image. Furthermore, the specific costs of a greywater treatment system would decrease with increasing size (Friedler and Hadari, 2006).

9.3.3 Stakeholder: Summary

For the current conditions concerning greywater reclamation, the following stakeholders were identified in NSW:

Legislative

Function: provides legal framework for greywater reclamation

For small systems in single households, the guidelines offer detailed orientation for users and approving authorities. Yet, the approval processes for larger systems (> ten persons) is very complex.

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[6] An actual list of accredited systems is published on http://www0.health.nsw.gov.au/ publichealth/environment/water/accreditations/gts.asp, accessed 04.01.2013.

[7] http://www.sydneywater.com.au/YourAccount/PricingInformation/, accessed 03.09.2012; \$=Australian Dollar; 2.13 \$ = 1.73 € according to exchange rate of 04.09.2012

Water agencies

Function: manage water pricing and water restrictions (execute legislative orders)

The water and wastewater tariff structure is affecting the extent of financial benefits due to lower tap water demand.

The restrictions concerning the use of tap water for irrigation are a major motivation for users to reclaim greywater as an alternative water source.

Manufacturers

Function: offer greywater treatment systems and service plans

Since most of the accredited systems are based on technically advanced processes (e.g. membrane filtration) as well as measurement and control technologies, the investment and operational costs of greywater recycling are high.

Regular operation and maintenance by manufacturers guarantees a safe operation of a system, while the operation and maintenance by the owner of the systems, mostly private persons, is often unreliable.

Users

Function: Apply greywater reclamation and are responsible for hygienic and environmental safety.

Users are mainly private persons in single-dwellings. They can be characterized as environmentally conscious. The main motivation to reclaim greywater is to irrigate gardens during water restrictions. Economic aspects play a minor role. Due to missing knowledge, mishandling of greywater is reported. Furthermore, maintenance and operation safety of treatment systems is often neglected by users.

9.4 Comparison Germany – Australia: general background

The main difference between Australia and Germany concerning water management is the climatic background. Australia is afflicted by frequent droughts and New South Wales suffers from physical water scarcity (fao, 2007).

In Germany, only 19 % of the available water resources are used (UBA, 2007). Even though there are regional disparities (Nolde, 2000), water availability is not considered at risk.

However, both countries have a very high human development index (hdr, 2011) indicating a similar potential for technical investments and a high education level.

Furthermore, the legislative structure in both countries is based on federal structures.

9.4.1 German conditions in regard of greywater recycling

In Germany, practical experiences with greywater recycling are limited. The majority of people are not familiar with the term “greywater” and the opportunity to reuse it. The existing sites are mainly in scales of apartment buildings, hotels etc. The main reuse application is indoors for toilet flushing. Irrigation with greywater is optional, but plays a minor role (cf. fbr, 2009)

Legislative background of greywater reclamation in Germany

In Germany, the reuse of greywater has not been directly addressed by any law or guideline. Yet, actual information and recommendations were derived from general guidelines concerning water and wastewater. The first recommendations concerning greywater quality criteria (Table 3.1) were introduced by the Senate of Berlin in cooperation with the federal bureau of health in 1995 (Nolde, 2000) and since then have been used as a reference – not only in Berlin but also in the rest of Germany.

Furthermore, the Berlin Senate published the brochure “Innovative Water Concepts – Service Water Utilisation in Buildings” (SenBer, 2007). The brochure gives recommendations concerning rainwater and greywater use. Furthermore, approval and notification requirements are specified:

- Building permission: Only for systems with capacities > 20 m^3/d
- Notification of local water company
- Notification of local public health department.

Since Berlin has no greywater specific legislation, the approval and notification requirements were derived from other federal and national laws. Thus, these requirements cannot be transferred to other federal states.

Conclusions concerning legislation in Germany

Only first steps have been taken to define legal requirements for greywater reuse. Even though the demand of orientation and legal certainty is high, Berlin is one of the few regions in Germany that has published approval information (SenBer, 2007).

The development of official guidelines for greywater reuse should be enhanced in Germany. Following the example of New South Wales, these topics should be considered

- Approval conditions have to be specified
- Effluent quality criteria need to be revised and its control requirements need to be defined
- Liability/responsibility for the safe operation of greywater treatment systems should be defined
- Quality standards for greywater treatment systems could be guaranteed by a certification system (according to accreditation system in NSW).

Water agencies

By managing water supply, wastewater collection and treatment, the water agencies in Germany have similar functions as in Australia.

The water pricing structure in Germany is based on the consumed water volume (supply and sanitation), ranging from 1.99 to 7.10 € per m^3, (mean = 3.79 €), (Schleich and Hillenbrand, 2009)[8], defining the financial benefit potential of greywater recycling due to water savings.

Some plants in Germany are reported to be economically viable (Sellner and Schildhorn, 2009 in fbr). According to Kerpen and Zapf (2005), at least 150 persons should be connected to a greywater treatment system to be economically feasible (based on water and wastewater costs of 4.50 €/m^3). Yet, in regions with high water prices, smaller systems would also have reasonable periods of amortization.

However, from an economic point of view, investing in a greywater treatment system in Germany is more likely to be profitable than in Australia.

Manufacturers

Several manufacturers of wastewater treatment components offer greywater treatment systems in Germany. Most of the systems are based on MBR-technology, but other

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[8] data from 2003-2007

biological processes are in use, too. UV stages are used to disinfect the effluent. Normally, plants are maintained by the manufacturer and equipped with remote monitoring.

In comparison to New South Wales, the technological standard covers a wider range, not only focusing on very advanced systems. Furthermore, the practice of contracting operators for maintenance and control of systems secures the safe operation of systems.

Users

The function of users in Germany has to be modified: people that use recycled greywater at home, at work, etc., are normally not responsible for maintenance (done by external contractors), and they can decide for housing concept (e.g. “green living”, resource efficient buidlungs).

In Germany, many people are not familiar with the term “greywater” or other water recycling schemes. From the author’s experience, people have not formed an attitude towards greywater recycling yet. The user perception of greywater recycling in the few existing sites has not been directly determined yet. However, reports indicate that users are satisfied with greywater recycling and are even willing to adjust their household product choices (Oldenburg, 2005), whereas negative experiences with unreliable systems had led to total rejection in the early stages of greywater recycling in Germany (Nolde, 2009).

While in New South Wales, homeowners become greywater users by deciding to install a greywater treatment system, in Germany, people rather become greywater users by deciding for a housing concept (“ecological living”). Thus, construction companies, investors or city planners are the initializing stakeholder by offering housing concepts with greywater recycling. Yet, potential residents only choose to live in such a dwelling if their perception towards greywater is positive. This perception can be positively influenced by promoting greywater recycling, especially with reference to already well-established projects. Concerns of users in regard to aesthetics or comfort as well as hygienic aspects of greywater have to be taken seriously and have to be addressed.

9.5 Conclusion

The legal basis for greywater recycling in Germany has not been clearly determined yet. This should be addressed by the authorities. The responsibilities of operators, owners and users of greywater treatment systems should be clearly defined by legislature. Furthermore, effluent quality criteria have to be established mandatorily (cf. Chapter 3).

The comparison of greywater reclamation in New South Wales and Germany shows that the focus in Germany is on commercial systems rather than on private household level. Thus, city planners, investors or constructing companies are important stakeholders in Germany that are needed to enhance the implementation of greywater recycling. For these decision makers, a legislative background is important to estimate the safety and outcome of their investments. The economic feasibility of a specific greywater treatment system has to be calculated for every single case due to the high impacts of system design, size and localization. Yet, the economic feasibility of greywater treatment in Germany is in all probability better than in New South Wales since the focus is on larger systems and water savings result in higher financial savings.

Table 9.2: Economic conditions for greywater reclamation in Australia and Germany

	Economic frame conditions		**Economic system balance**	
	GNI 2010 (US $)	**Costs of living**	**System costs**	**System benefits**
Comparison: Australia (AUS) Germany (GER)	43,740 (AUS), 43,330 (GER) → similar	similar	Depending on: - chosen treatment technology - system size	- Impact of (waste-) water charges: AUS (1.78 €/ m^3) < GER (3.79 €/m^3)[1] - Financial Incentives[2]
References	World Bank, 2011	daad.de, 2013	Kerpen and Zapf, 2005	[1] cf. p. 94 and 97 [2] depending on local conditions

It is already common practice in Germany that the operation of treatment systems is done by the manufacturer of the system or by external operators. Consequently, the risk of operational mishandling is reduced compared to systems operated by private users in New South Wales. Thus, the practice of contracting operators in Germany should be maintained.

Furthermore, environmental aspects play a minor role in Germany, because greywater is mainly reused indoors and thus being disposed in the conventional sewer system (after reuse) instead of being used for irrigation and thus disposed into the environment. Yet, users should be educated to prevent mishandling of greywater. Furthermore, a certain understanding of the treatment process and its context motivates users to adjust their behavior, e. g. not to bring dye or highly toxic substances into the greywater system (cf. Chapter 4.4.7).

However, a wider successful implementation of greywater treatment will depend on the user acceptance, whether or not greywater recycling is seen as a desirable part of ecological housing and thus would become an attractive investment option.

10 Implementation of greywater reuse in Germany

In this work, the frame conditions of greywater reuse in Germany were assessed based on process related socio-economic aspects. In the following, the main results are summarized and conclusions are presented.

10.1 Summary and conclusions

1. Greywater was characterized concerning quantity and quality of single greywater streams (Chapter 4.2.4). Thus, kitchen greywater should preferably be excluded from the greywater collection.
2. The components of bathroom and laundry greywater were analyzed (Chapter 4.4) and quantified focusing on COD loads and nitrogen contribution. The usage of statistical consumption data was introduced as a practicable tool to quantify and monitor the impact of personal care substances and laundry detergents on greywater characteristics (Chapter 4.5). Furthermore, the relevance of skin as an important source of nitrogen in greywater was pointed out (Chapter 4.4.4, Table 4.21).
3. The impact of personal care products and detergents on greywater biodegradability was assessed. The Zahn-Wellens-Test (Chapter 5) was used to determine the biodegradability of personal care products and laundry detergents. Results showed good biodegradabilities of 87-100% in context of the test procedure, which demands 80 % degradation of dissolved COD within 28 days. Yet, COD was not degraded totally, which poses a potential risk for soils when greywater is reclaimed for irrigation. For detailed determination of the fate of COD compounds, e. g. originating from surfactants, the test procedure should be modified: The nature of undegraded COD, dissolved and suspended should be analyzed in terms of impacts on plants and soil degradation.
4. Household cleaning detergents were analyzed focusing on potential inhibition of greywater biodegradation (Chapter 6). Respirometry showed mixed inhibition effects of an abrasive. To reliably quantify inhibition, the used test procedure would need more precise data recording. Yet, the inhibition effect of the abrasive is obvious in concentration ranges that are caused by average cleaner consumption.
5. Synthetic greywater (BL) was treated with a Rotating Biological Contactor (RBC), (Chapter 7). Even though the synthetic greywater was extremely nutrient deficient, conclusions concerning design parameters of RBCs treating greywater were drawn: based on the design parameters for conventional wastewater (ATV-DVWK-A 281, 2004), a 20 % larger distance between the disks of an RBC treating greywater should be chosen. Furthermore, combs need to be installed to prevent unwanted tissue

formation. The organic load of greywater in an RBC needs to be reduced. The lowest organic load of 1.43 g $BOD_5/(m^2*d)$ did not meet the current recommendation for reuse water quality. This could be due to the usage of a synthetic greywater lacking nutrients. Thus, further analysis would be needed to get transferable results.

6. For the implementation of greywater reuse in Germany, socioeconomic and legal frame conditions were determined based on experiences with greywater in New South Wales, Australia. A stakeholder analysis (Chapter 9) showed that a likely realization of greywater reclamation in Germany is on commercial levels (e.g. multi-dwelling houses) with indoor reuse. Yet, the opportunities, responsibilities, and liabilities of different stakeholders like operators, owners and users of greywater treatment require legal definitions, including service water quality criteria, to guarantee a stable operation and safe investment conditions. Thus, the development of legal and technical guidelines needs to be pursued.

Table 10.1 summarizes the conclusions from this research according to the stakeholders that benefit from the findings.

Table 10.1: Summary of recommendations concluded directly from the results in this work

Practice of greywater reuse	Kitchen greywater should preferably be excluded from greywater collection (Chapter 4.2.4). From statistical consumption data, COD-loads in greywater can be estimated (Chapter 4.5). This methodology not only enables general estimations of greywater compositions without extensive sampling, but could also be applied for specific socio-economic user groups (e. g. students, families) living in potential sites for greywater treatment systems. Furthermore, changes of greywater composition over time caused by shifts in user behavior can be monitored. For greywater treatment with Rotating Biological Contactors, design parameters have to be modified (Chapter 7.4.4).
Research	Characteristics and impact on soils of residual COD in treated greywater used for irrigation processes require determination (Chapter 5.6) The impact of specific cleaning agents on biodegradation of greywater needs to be analyzed more deeply since this work proved inhibition effects of an exemplary cleaning agent (Chapter 6). The methodology of using statistical consumption data (Chapter 4.5) could be applied for other questions beyond greywater related topics: e. g. for the estimation of substance quantities, like specific pharmaceuticals, in wastewater.
Combined committees (including legislation)	The development of guidelines and specification of a legal basis for greywater reuse systems is needed. This concerns the definition of approval conditions, the discussion of effluent quality criteria and the respective control mechanisms, as well as the liabilities and responsibilities for the safe operation of greywater systems. A defined legislative and normative background would enable investors to plan and calculate based on reliable conditions.

10.2 Outlook

This work did not consider the option of supplementing greywater systems with heat recovery. However, recent studies indicate high energy savings (Ni et al., 2012, Nolde 2012). In the face of the increasing energy prices in Germany, greywater systems including heat recovery have a high economic potential: The preliminary results of a pilot plant with combined greywater and heat recycling presented in Nolde (2012) showed an energy demand of 5 kWh while producing 16.1 kWh (summer) to 45 kWh (winter).

Currently, first general guidelines for alternative sanitation, including greywater reuse systems, are developed in Germany (DWA-A 272 draft version, 2013). The relevance of this upcoming development has been addressed in this work. The future trend – covering potential modifications of legal and administrative conditions towards a clearer basis for alternative sanitation – will impact the implementation of greywater reuse.

In addition to this work, further research should focus on more detailed quantification of greywater biodegradability to enable efficient and appropriate design standards for greywater treatment systems. Concerning reused water for irrigation purposes, the current legal definition of biodegradability (c. f. Chapter 5.5) has to be reconsidered. While the application of greywater for irrigation currently plays a minor role in Germany, countries with more widespread application could face long term damages of soils (Chapter 3.1). Thus, research should address the use of treated greywater for irrigation purposes determining the impact of residual substances on soils.

On an international level, greywater as a means of efficient water management will presumably gain in importance. The methodology of estimating greywater composition based on statistical consumption data, which was introduced in this work, is a convenient tool that should be used to assess greywater in specific regions.

Appendix

A.1. Addendum to Chapter 2.6.2

Table A 1: Assessment of conditions impacting economic aspects (direct impacts and externalities) of greywater systems in Germany, extract of DWA-A 272 (draft version, 2013)

	Positive conditions	**Negative conditions**
Technical and operational aspects		
Wastewater infrastructure	High constructional or hydraulic need for rehabilitation Low depreciated costs	Recent high investments (high depreciated costs)
Functionality	Existing system has reached highest or lowest capacity limit	Recent optimization of system
Operational costs	Increasing energy prices	
Replanning/expansion/rehabilitation		
Site development	High distance to existing wastewater-infrastructure High capacity load of existing systems	Free capacity in existing system Already advanced planning process
Population densification	High capacity load of existing systems	Free capacity in existing system
Land recycling	Infrastructure in need of rehabilitation	Existing functioning infrastructure
Rehabilitation/conversion	High need for rehabilitation of existing buildings	High realization effort (e. g. city center) Grandfathering of existing buildings High number of owners
Synergies with existing infrastructure	Existing source separation systems	
Impact of changes of design affecting conditions		
Climate	Changes in raw water quality (higher treatment effort) Shortage of drinking water Need of higher flexibility of sewer system (concerning extreme rainfalls)	

	Positive conditions	Negative conditions
Demographic change	Strongly decreasing water demand and wastewater production	Growing population in region with free capacities in existing system
	High vacancies in buildings (deconstruction) Demand of systems with higher flexibility	
Resource scarcity	Increased demand for water recycling Increased demand for service water Increased demand for alternative energy sources	Missing acceptance Low quality of resulting service water
Economic aspects		
Cost assignment	Request for cost system based on cost-by-cause principle Request for cost transparent systems	Shift of investment costs on private households
Economic feasibility	Uncertainties of long-term financing of infrastructure facing long amortization	Restricted options due to deficient communal budgets
Global market for water related companies concerning alternative sanitation system	International market potential for alternative sanitation systems	Only few demonstration plants and sites in Germany
Social aspects		
Environmental and health awareness	Increasing environmental consciousness	Concerns about hygienic safety of new systems
Attitude towards water saving	Efficient water usage Operational problems of existing water infrastructure caused by decreasing water demand (overlapping with effects of demographic changes)	
Want for safety	Concerns regarding reactions of centralized systems on extreme events or attacks	Concerns regarding operational safety of alternative systems
User comfort	Opportunity to regard specific needs or concerns of potential end users	No/low acceptance of new technologies

	Positive conditions	**Negative conditions**
Cultural diversity	Positive attitude towards alternative sanitation (e. g. China, South Africa)	Cultural constraints concerning wastewater streams
Organizational and institutional aspects		
Organization structure	Opportunity of cooperation and concentration of different supply and disposal institutions	Existing established organization structures (centralized systems, separate responsibilities)
Compulsion to use supply/sewer system	Opportunity to apply compulsion to use new technology	Stabilization of existing system based on current extent of compulsion
Classification of products	Consistent requirements independent from origin Existing legal frame allows individual solutions	Existing legal uncertainties

A.2. Equations for Chapter 4.5.1

Average unit size of personal care products:

$$V_P = \frac{1}{n}\sum_{i=1}^{n} V_i \qquad \text{A.2.1}$$

VP	average unit size of personal care products of one product group (g)
Vi	Unit size of single product i (g)
n	Number of products in one product group (-)

Per-capita COD load from personal care products:

$$L_{COD,P} = \frac{n_s \cdot V_P \cdot COD_P}{I \cdot 365\, {}^{d}/_{y}} \qquad \text{A.2.2}$$

$L_{COD,P}$	per-capita COD load of product group (mg COD/[L·c·d])

n_S	Number of units sold per year (y^{-1})
I	Number of Inhabitants (-)
COD_P	average COD of products of one product group (mg COD/g)

A.3. Impact of cleaning agents and additives: Data processing

The data processing of respirometry is illustrated using the example of "*fabric whitener*" *with a dosage of 0.006 mL.*

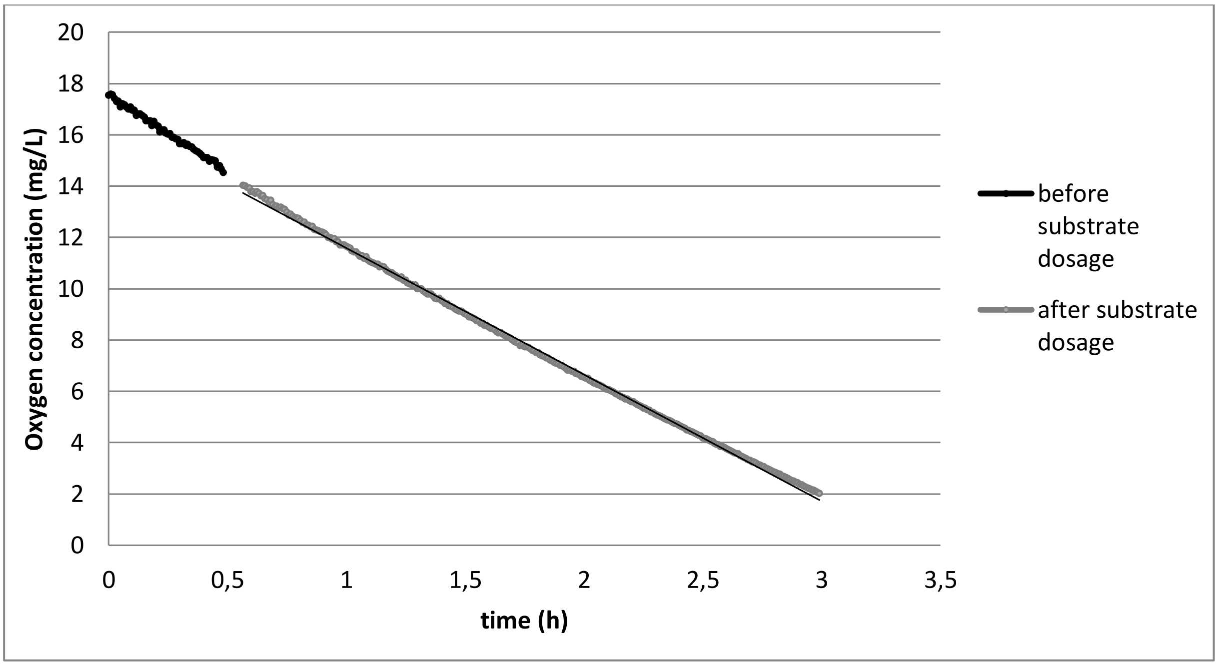

Figure A 1: original recorded oxygen concentrations

Figure A 1 shows the Oxygen concentrations over time of a respirometry sample. The test substrate was added after 30 min. The oxygen usage after substrate dosage (grey) is not linear (black line was added as linear reference).

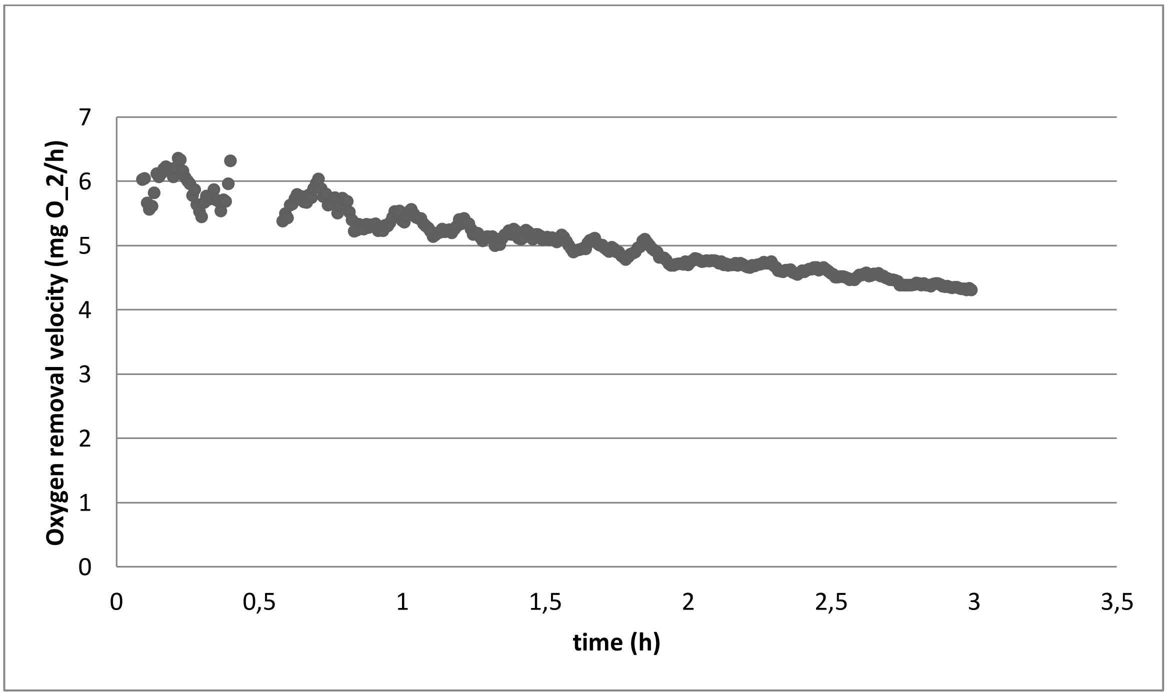

Figure A 2: Velocity of oxygen removal over time

Figure A 2 shows the velocity of Oxygen removal decreasing over time. The data in this figure are smoothed over 10 min.

Lineveawer-Burk

The data conversion according to Lineweaver-Burk (Equation 2.6) results in Figure A 3.

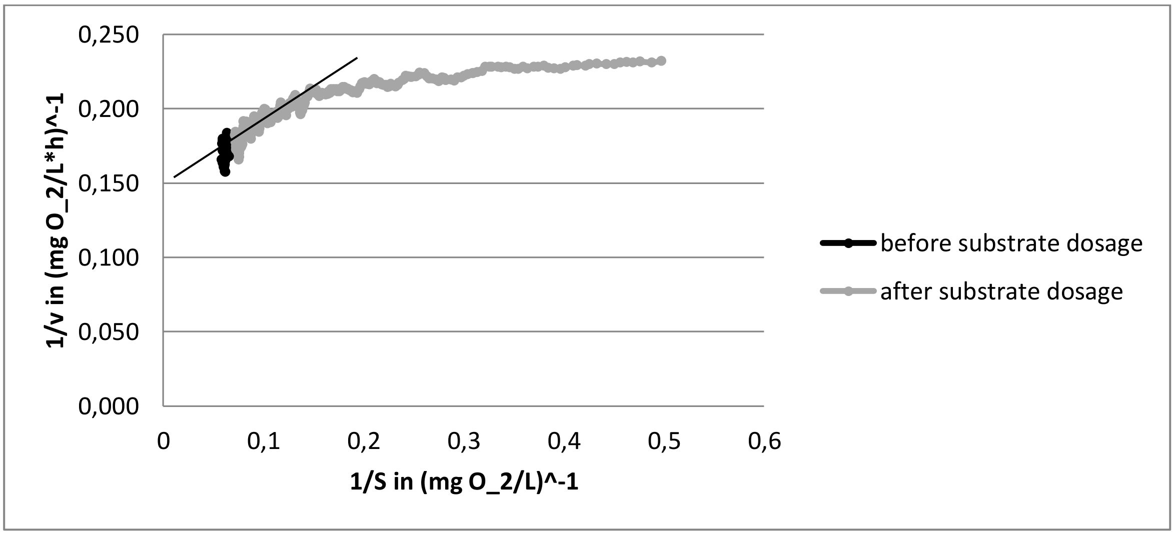

Figure A 3: Lineweaver-Burk conversion of data, initial phase of substrate removal is marked with linear reference

From the processing according to Lineweaver-Burk, an initial phase with fast degradation rates following a linear trend can be distinguished from a later phase with decreasing degradation rates. For the comparison of kinetic parameters, only the linear initial degradation phase is considered, which is illustrated in Figure A 4.

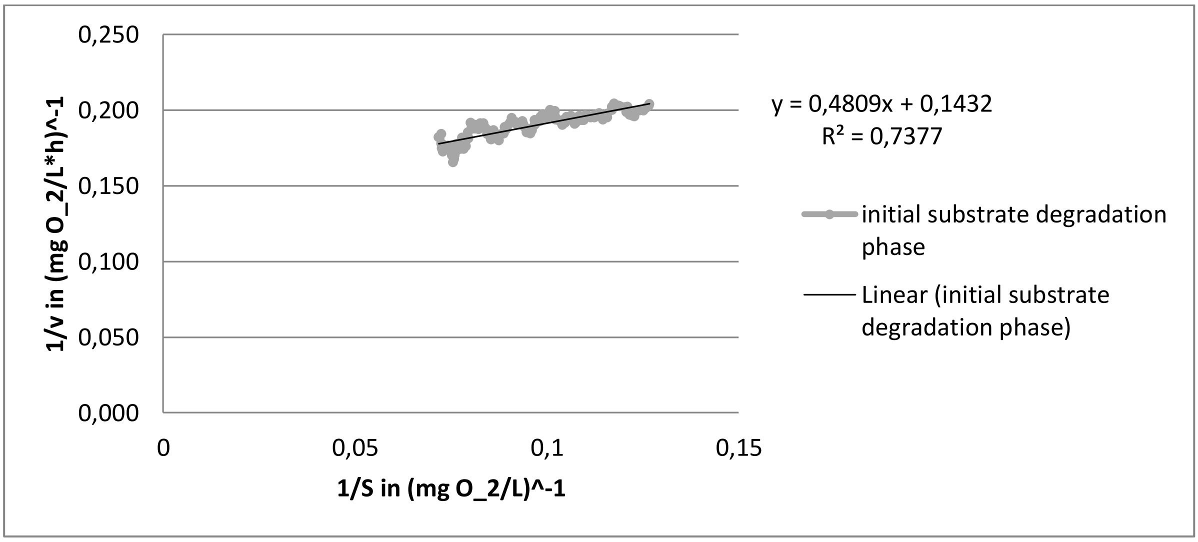

Figure A 4: Lineweaver-Burk of initial substrate degradation phase with linear regression resulting in 1/v_{max}=0.1432 →v_{max}=6.9832 mg O_2/(L*h); -(1/k_m)=-(0.1432/0.4809)=-0.2978 →k_m=3.36 mg O_2/L

A.4. Effluent quality criteria of treated greywater in New South Wales

Table A 2: Effluent quality criteria for different greywater reuse applications according to (NSW, 2005)

Application	**BOD_5 (mg/L)**	**SS (mg/L)**	**Thermotolerant coliforms (cfu/100mL)**	**Free Cl_2* (mg/L)**
Sub-surface irrigation				
90% of samples	< 20	< 30		
Maximum threshold	< 30	< 45		
Surface irrigation				
90% of samples	< 20	< 30	< 30	> 0.2 to < 2.0
Maximum threshold	< 30	< 45	< 100	< 2.0
Toilet/washing machine				
90% of samples	< 10	< 10	< 10	> 0.5 to < 2.0
Maximum threshold	< 20	< 20	< 30	< 2.0
* where chlorine is the disinfectant				

Table A 3: Effluent quality parameters for validation/verification of greywater treatment systems > 10 persons (NSW, 2008a)

Parameter	**Effluent Quality**
E. coli	< 1 cfu/100 mL
BOD5	< 10 mg/L
SS	< 10 mg/L
pH	6.5-8.5
Turbidity	< 2 NTU (95%ile) < 5 NTU (maximum)
Disinfection	Cl: 0.2-2.0 mg/L residual UV: TBA Ozone: TBA
Coliphages	< 1 pfu/100 mL
Clostridia	<1 cfu/100 mL

A.5. Question catalogue for individual interviews

For specific greywater treatment units:

- What was the motivation for the decision to use greywater recycling?
- Who initiated the idea of using greywater recycling?
- Who paid the investment costs?
- Where there any hindrances to realize the project? How were they taken?
- How many persons are connected to the plant (how many adults, jobholder and children (age of children))?
- In what kind of building is the greywater system installed (single dwelling, office building…)?
- Is there a combination with other alternative water saving systems?
- What are the sources of treated greywater (bathroom, washing machine, kitchen sink…)?
- Which processes are used in the treatment system?
- How high is the volume of treated greywater (e. g. l/day or l/year)?
- Do you have data of the water flow (variation)?
- How is the greywater quality (COD (mean and standard deviation if possible) and other parameters)?
- How are of solid waste (screening/sludge) disposed?

- During the operation of the system, where there any modifications were needed to keep it running/to optimize it?
- What is the reuse application for treated wastewater (if irrigation: technique)? Any problems occurred?
- Are there any restrictions concerning the use of certain detergents or other products?
- How high are the energy consumption/costs?
- How long is the return period?
- Were subsidies for the greywater treatment system received?
- Is there a maintenance plan for system? What has the owner/operator/external service for the system to do?
- Did any failures occurred (what kind of failures/how often) during the operation?
- Did any odor occur caused by greywater recycling (treatment system, storage, reuse application)?
- Is there any biofilm growth in the system/pipes?
- What is the most vulnerable part of the treatment system?

General questions:

- What new knowledge can be drawn out of the experiences with the system?
- How is the user acceptance? Are there any problems? Did you receive feedback from the users?
- How are the legislative regulations concerning the permission to run treatment system or to reuse water?

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