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Environmental Impacts of Various Disinfection Procedures during Laundering

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Abstract

The laundering procedures for health institutions and the food-processing industry must ensure the elimination of impurities and appropriate levels of hygiene. In addition to the classical combination of chemo-thermal disinfection procedures, the laundering procedure based on the liquid carbon dioxide (LCO) technology is becoming more and more assertive. In the previous studies on laundry care processes, the evaluations of disinfection effects have become prominent, while sadly the environmental impacts have remained in the background.

The research focused on comparing the environment impacts caused by chemical-thermal and CO_2 *laundering procedures regarding medical textiles. Bioindicators, classical and prototype* LCO_2 *equipment for the textile laundry, detergents, disinfectants and auxiliary agents, as well as the sampling equipment and sampling methods were used for the evaluation of disinfection effects.*

This paper introduces performed wastewater ecological analyses using a chemo-thermal procedure in accordance with the Slovenian regulation on the substance emission during the removal of wastewater from laundries and dry-

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Okoljski vplivi različnih razkuževalnih postopkov nege tekstilij

Izvirni znanstveni članek

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Izvleček

Od postopkov nege tekstilij za zdravstvene ustanove in živilsko industrijo se zahteva razen odstranjevanja nečistoč tudi zagotavljanje ustrezne stopnje higiene. Ob klasičnem kombiniranem kemijsko-termičnem postopku razkuževanja se čedalje bolj uveljavlja tudi postopek nege tekstilij, ki ima osnovo v tehnologiji tekočega CO_2 (LCO_2). V dosedanjih raziskavah postopkov nege je bilo v središču zanimanja predvsem vrednotenje razkuževalnih učinkov, medtem ko so bili vplivi na okolje nekoliko potisnjeni v ozadje.

Raziskava je bila osredotočena na primerjavo okoljskih vplivov, ki jih povzročata kemijsko-termičen in CO_2 postopek nege medicinskih tekstilij. Za vrednotenje razkuževalnega učinka so bili uporabljeni bioindikatorji, klasična in prototipna LCO_2 oprema za nego tekstilij, pralna, razkuževalna in pomožna sredstva ter oprema in metode za preskušanje. Opravljene so bile ekološke analize odpadnih pralnih vod kemijsko-termičnega razkuževalnega procesa v skladu z Uredbo o emisiji snovi pri odvajanju odpadne vode iz naprav za pranje in kemično čiščenje tekstilij (UL RS 41/2007).

Izdelane so bile energetske in okoljske bilance za oba negovalna postopka, pri čemer je bila upoštevana metodologija ocene življenjskega cikla izdelka/storitve LCA, popisa stanja LCI ter ocena vplivov na okolje v času življenjskega cikla LCIA. Rezultati raziskave kažejo, da je porabljena energija za 1 kg opranih tekstilij pri enokopelnem postopku LCO_2 za 2800 kJ manjša kot pri kemijsko-termičnem. Ugotovljeno je bilo tudi, da klasičen kemijsko-termični postopek daje štirikrat višji indeks globalnega segrevanja (GWP_{100}) in indeks zakisljevanja (AP), torej sprošča tudi štirikrat več emisij toplogrednih plinov in plinov zakisljevanja kot enokopelni LCO_2 razkuževalni postopek nege tekstilij.

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cleaner's (Slovenian Official Gazette 41/2007). Energy and environmental balances for both laundering procedures were prepared. Life cycle assessment (LCA), life cycle inventories (LCI) and life cycle impact assessment (LCIA) methodologies were taken into account.

The results of our investigation point to the fact that the energy used for 1 kg of textiles during one-bath LCO_2 procedure is in comparison with the chemo-thermal procedure lower by 2,800 kJ. It was also discovered that a classical chemo-thermal procedure has four times higher global warming potential (GWP_{TGP}) and acidification potential (AP) than the one-bath LCO_2 laundering procedure, regarding disinfection.

Keywords: textile care, LCO_2 procedure, wastewaters, LCA, ecology.

1 Introduction

Laundering is a complex process where the synergy of temperature, time, detergent and kinetic energy combines within an aqueous medium in order to ensure the elimination of impurities, thus providing the required quality of textile care. Water plays a significant and predominant role during the laundering process. It enables the wetting of textiles by superseding the air within fibres, it is a transportation system which supplies the heat and kinetic energy, it acts as a dispersing agent, which with the help of a detergent, absorbs inorganic and organic impurities and microorganisms, and prevents their redeposition onto a textile surface or onto the parts of a washing machine. It is well known that laundries consume large amounts of water and at the same time produce large quantities of laundering wastewater of heterogeneous impurities [1, 2]. The types and quantities of textiles, as well as the laundering procedure have an important influence on the degree and composition of laundering wastewater. When talking about wastewaters, laundries are torn between the economical and legislative demands. As stated by Simonič et al [3], large laundries that consume large quantities of fresh water during their daily operations require higher investment and operating costs regarding the wastewater treatment. Therefore,

Ključne besede: nega tekstilij, obdelava LCO_2, odpadne vode, LCA, ekologija

1 Uvod

Pranje tekstilij je kompleksen proces, pri katerem se s pomočjo sinergije temperature, časa, pralnega sredstva in kinetične energije mencanja v vodnem mediju odstranjujejo nečistoče, s čimer se zagotavlja ustrezna kakovost nege. Pri pranju ima voda izjemno pomembno vlogo, saj omogoča omakanje tekstilij z izrivanjem zraka iz vlaken, je transportno sredstvo, ki dovaja toplotno in kinetično energijo, zadržuje v sebi s pomočjo pralnega sredstva dispergirane nečistoče in mikroorganizme ter preprečuje njihovo posedanje na tekstilijo ali površine strojne opreme. Znano je, da so pralnice velik porabnik vode ter hkrati povzročajo velike količine odpadnih pralnih vod raznolikih onesnaženosti [1, 2]. Na stopnjo in sestavo odpadnih pralnih vod pomembno vplivata vrsta in količina negovanih tekstilij ter nečistoče in postopek pranja. Pralnice so tako glede pralnih vod razpete med ekonomskimi in zakonodajnimi zahtevami. Kot ugotavlja Simonič s sodelavci [3], so za večje pralnice, ki porabijo velike količine sveže vode pri dnevnem obratovanju, investicijski in obratovalni stroški čiščenja odpadne vode previsoki, da bi bila njihova ponovna uporaba ekonomsko upravičena. In na drugi strani, slovenska [4] in evropska okoljska zakonodaja zahtevata od pralnic, da nenehno zmanjšujejo količine porabljenih in odpadnih pralnih vod [5] ter energije, na čemer temelji Evropska okoljska zaveza in strategija trajnostnega razvoja do leta 2020 (povečanje energetske učinkovitosti za 20 %, zmanjšanje emisij toplogrednih plinov *za* 20 %) [6].

Bolnišnične tekstilije lahko vsebujejo različne vrste mikroorganizmov ter s tem pomenijo potencialno nevarnost za zdravje bolnikov, kot tudi za zaposlene v zdravstvenih ustanovah [7, 8]. Od postopkov nege se upravičeno pričakuje, da zagotovijo razen odstranjevanja nečistoč tudi ustrezno stopnjo higiene tekstilij, kot jih navajajo priporočila RKI (*nem. Robert Koch Institute Berlin*) [9] ali DGHM (*nem. Deutsche Gesellschaft für Hygiene und Mikrobiologie Hannover)* [10]. Že Jaska in Fredell [11] sta ugotovila, da med procesoma odstranjevanja nečistoč in mikroorganizmov iz tekstilij ni bistvenih razlik. Na odstranjevanje bakterij, gliv in virusov iz tekstilij v procesu nege odločilno vplivajo temperatura pranja, kopelno razmerje, dodatek belilnih sredstev, čas pranja ter z njimi povezani mehansko-kemijski mehanizmi. Prav tako sta Jaska in Fredell dokazala, da zviševanje temperature pralne kopeli nad 60 °C povečuje učinkovitost odstranjevanja mikroorganizmov. Pomembna je tudi ugotovitev, da se pri temperaturah pralnih kopeli, nižjih od 50 °C, odstrani iz tekstilije v kopel 95 odstotkov mikroorganizmov, vendar ti preživijo proces pranja [12, 13] ter pomenijo nevarnost širjenja okužb. Danes lahko antimikrobne učinke pri negi bolnišničnih tekstilij ali tekstilij za živilsko industrijo pralnice dosežejo *the recycling and reuse is economically unjustified. On the other hand, the Slovenian [4] and European environmental legislation demand from laundries a continuous reduction in the amount of fresh water and wastewater, plus the consumed energy during the laundering process. This is based on "The commitment, obligation and strategy for sustainable development in the European Union" (an increase in the energy efficiency of 20%, a reduction in the greenhouse gas (GHG) of 20%) [6].*

Hospital textiles may contain various types of microorganisms, thus posing a potential risk for the health of patients and staff in health facilities and institutes [7, 8]. The laundering procedures must ensure the cleansing of impurities and also an appropriate level of textile hygiene, as indicated by the recommendations of RKI (Robert Koch Institute, Berlin) [9] or DGHM (Deutsche Gesellschaft für Hygiene und Mikrobiologie, Hannover) [10]. Jaska and Fredell already found significant differences between the processes of eliminating impurities and microorganisms from textiles [11]. During the laundering process, the temperature, bath ratio and mechanochemical mechanisms play a significant role in the elimination of bacteria, fungi and viruses from textiles. Jaska and Fredell also proved that by increasing the laundering bath temperatures above 60 °C, the efficiencies of microorganism elimination increase as well. Moreover, it was also established that the laundering bath temperatures lower than 50 °C remove 95% of microorganisms from the textile into the bath. However, these microorganisms survive the laundering process [12, 13] and present a potential danger as they can spread infection. Nowadays, the disinfection effects on hospital textiles or textiles for the food industry can be achieved using conventional procedures, e.g. thermal, low temperature chemicals or by combining both procedures. More commonly used is the chemo-thermal disinfection laundering procedure, although the chemical and thermal procedures are being used less prevalently due to their large consumption of energy, water and high concentrations of chemicals. The latter could predominantly affect the length of the use-life of textiles or laundry equipment [14]. The classical disinfection laundering pro-

s konvencionalnimi postopki, kot so termični, nizkotemperaturni kemijski ali s kombinacijo obeh postopkov. Najpogosteje se uporablja kemijsko-termični postopek razkuževanja tekstilij, medtem ko sta kemijski in termični postopek manj razširjena zaradi velike porabe energije, vode in visokih koncentracij pralnih sredstev, ki lahko odločilno vplivajo na skrajšanje življenjske dobe tekstilij ali strojnih delov opreme za pranje [14].

Razen klasičnih postopkov razkuževanja tekstilij, katerih ekološke in energetske pomanjkljivosti omejujejo njihovo uporabo, se intenzivno raziskujejo in razvijajo tudi nove tehnologije in procesi nege tekstilij, ki so zasnovani na ozoniranju, UV-sevanju in mikrovalovih ter tehnologiji CO_2. Med njimi nedvomno izstopa tehnologija CO_2, ki se je že dodobra uveljavila v visokotlačnih separacijskih procesih in kemijskih sintezah [15]. Znano je, da je ogljikov dioksid negorljiv plin brez barve, vonja in okusa. Pridobiva se iz naravnih virov in deloma iz industrijskih odpadnih plinov [16, 17]. Uporaba tehnologije CO_2 na področju plemenitenja ni povsem neznana. V začetku devetdesetih let prejšnjega stoletja se je tehnologija nadkritičnega CO_2 uporabljala (120 barov) za barvanje PES vlaken [18, 19] ter pozneje skoraj docela zamrla, kar lahko pripišemo cenovno zahtevni in robustni strojni opremi, izrednim varnostnim zahtevam ter predvsem zaostrenim gospodarskim razmeram in modnim trendom, ki so se prevesili na stran naravnih vlaken.

Začetki razvoja nege tekstilij s tekočim CO_2 (LCO_2, *angl. Liquid Carbon Dioxide*), ki se uvršča med suhe postopke nege, segajo v sredino sedemdesetih let prejšnjega stoletja. Nega z LCO_2 poteka pri tlakih med 40 in 60 bari in temperaturah med 5 in 20 °C [20, 21]. Je tehnologija, ki naj bi v ZDA do leta 2020 nadomestila čiščenje tekstilij s perkloretilenom (PER) in ogljikovodikovimi topili (OVT) [17, 22]. Tudi EU se zaveda zdravstvenih in ekoloških vplivov kemičnega čiščenja s PER, katerega letna emisija v EU znaša 70.000 t [23], zato njene okoljske in energetske strategije vključujejo postopen prehod na „zelene" tehnologije pranja in čiščenja tekstilij [24].

Kot poroča Van Roosmalen [25], lahko LCO_2 učinkovito odstranjuje nečistoče brez segrevanja ali hlajenja pri sobni temperaturi. Relativno veliki delci (> 20 µm) se lahko odstranijo v LCO_2 z intenzivnim mehanskim delovanjem, medtem ko je delce nečistoč, manjše od 20 µm, mogoče iz tekstilije odstraniti le s kombinacijo mehanskega delovanja in površinsko aktivnega sredstva.

Primerjava učinkov različnih mokrih in suhih postopkov nege tekstilij [23, 26] je razkrila, da je čiščenje z LCO_2 ali OVT za 10 do 20 odstotkov učinkovitejše kot čiščenje s PER. Prav tako so učinki čiščenja z LCO_2 primerljivi ali nekoliko večji od učinkov pranja in mokrega čiščenja. Ugotovljeno je bilo, da suho čiščenje z LCO_2 ne povzroča dimenzijskih sprememb, sprememb barvnih karakteristik pigmentno barvanih in tiskanih ter kosmičenih tekstilij, zmanjšanje mase ploskih tekstilij in pilinga. Učinkovitost odstranjevanja madežev z LCO_2 se giblje med 60 in 100 odstotki v primerjavi s PER ter je odvisna od sestave madeža [21, 23].

cedures can be used; however, they are a subject to the environmental and energy restrictions regarding their usage.

Therefore, an intensive research and development are being performed on new textile care technologies and processes. These researches are based on ozone, UV radiation and microwaves, and CO_2 technology. The CO_2 technology clearly stands out from among these, as it is already well-established within the high-pressure separation processes and chemical syntheses [15]. CO_2 is a non-flammable colourless gas with no odour or taste. It is derived from natural sources and partly from industrial waste gases [16, 17]. The use of the CO_2 technology for textile finishing is not entirely unknown. In the early 1990s, a supercritical CO_2 technology (120 bar) was used in the dyeing of PES fibres [18, 19], which later almost completely disappeared. This was attributed to the expensive and robust equipment, special security requirements and a tougher economic situation, as well as to the fashion trends that have turned towards natural fibres.

Pioneering the treatment of textiles using the liquid carbon dioxide (LCO_2) laundry development, which belongs to dry-cleaning laundry methods, dates back to the mid-1970s. The textile care using LCO_2 was performed under pressure between 40 and 60 bar, and within the temperature range between 5 and 20 °C [20, 21]. This is the technology that is to be replaced in the USA after 2020 with textile cleaning using perchloroethylene (PER) and hydrocarbon solvents (HCS) [17, 22]. The EU is also aware of the health and ecological impacts of dry-cleaning with PER, the annual emissions of which in the EU amounts to 70,000 t [23]. This is why the EU's environmental and energy strategies include a successive transition towards "green" laundry and cleaning technologies [24].

As reported by Van Roosmalen [25], LCO_2 can efficiently remove impurities at room temperature, without any heating or cooling. Relatively large particles (> 20 µm) can be removed during the LCO_2 procedure using intensive mechanical action, whilst impure particles smaller than 20 µm can be removed from textiles only with a combination of mechanical agitation and a surface-active agent.

Nedvomno so rezultati raziskav učinkov nege tekstilije pripomogli k intenzivnemu razvoju tehnologije LCO_2 in naraščajočemu številu LCO_2 strojev v industrijskih pralnicah v ZDA in EU [23, 27].

Tudi na področju higiene tekstilij in LCO_2 potekajo poglobljene raziskave, ki so pretežno usmerjene na področje pralnih in razkuževalnih sredstev, pogojev razkuževanja ter odpravljanja pomanjkljivosti klasičnih razkuževalnih postopkov nege. Znano je [28, 29], da difuzija razkuževalnih sredstev v vlakno poteka izjemno počasi, kar zahteva podaljšanje časa postopka nege in s tem kopičenje težav, povezanih z morfološkimi spremembami toplotno občutljivih tekstilij. Na drugi strani lahko preostanek razkuževala ogrozi zdravje uporabnika, posledica tega pa je, da večine materialov za oskrbo ran (sintezni biomateriali, ki aktivno posegajo v biokemični proces celjenja rane [30]) in vsadkov ni mogoče kemijsko razkuževati. Pomembno je tudi, da je večina obstoječih razkuževalnih sredstev lahko vnetljivih, potencialno toksičnih, s čimer ogrožajo varnost in zdravje zaposlenih v pralnici ter obremenjujejo okolje [31].

Visoki razkuževalni učinki so bili doseženi pri obdelavi okuženih tekstilij s CO_2 pri temperaturah med 32 in 120 °C ter tlakom od 70 do 300 barov, s hitrimi periodičnimi spremembami delovnih tlakov, kot tudi s hitrimi prehodi z delovnega tlaka CO_2 na atmosferski tlak [32, 33]. Raziskave so prav tako potrdile, da ima LCO_2 pri 20 °C in tlaku 70 barov razkuževalni učinek zaradi nastanka ogljikove kisline pri raztapljanju CO_2 v sproščeni vlagi iz bombažne tekstilije [34]. Za razvoj razkuževalnih postopkov nege tekstilij je pomembna tudi ugotovitev, da je mogoče doseči razkuževalni učinek s kombinacijo LCO_2 in vode (< 1 %) že pri temperaturah med 20 in 65 °C ter pri delovnem tlaku CO_2, ki je nižji od 50 barov [31].

V sklopu projekta FP7 „ACCEPT", ki se je končal konec leta 2010, so bili raziskani in razviti postopki nege tekstilij s tehnologijo LCO_2 [35]. V pripravo in definiranje projektnih nalog, kakor tudi v izvedbo projekta, so bili vključeni trije centri znanja ter osem podjetij, od izdelovalcev pralnih sredstev in razkužil, medicinske opreme in vsadkov, proizvajalcev pralne tehnike, do industrijskih pralnic iz različnih evropskih držav [36]. Izvedba projekta je bila razdeljena v dve fazi. V prvi so bile opravljene raziskave in razvoj pralnih in razkuževalnih sredstev, postopkov nizkotemperaturnega razkuževanja tekstilij, usnja ter medicinskih pripomočkov s tehnologijo LCO_2. V središču pozornosti druge faze projekta so bile analize in vrednotenje ekoloških vplivov, ki jih povzročajo različni postopki nege medicinskih tekstilij. Analizirani so bili klasični in tudi na novo razviti nizkotemperaturni LCO_2 razkuževalni postopki nege. Uporabljeni sta bili metodologiji vrednotenja ekoloških parametrov odpadnih vod ter ocene *življenjskega cikla izdelka/storitve* LCA *(angl. Life Cycle Assessment)*, popisa stanja LCI *(angl. Life Cycle Inventory)* in ocene vplivov na okolje LCIA *(angl. Life Cycle Impact Assessment)* na osnovi standardov [37]. V članku je predstavljena primerjava vplivov na okolje za dva razku-

Comparisons between different wet and dry-cleaning textile care procedures showed [23, 26] that the cleaning with LCO_2 or HCS provides by 10–20% higher cleaning effects than the cleaning with PER. The LCO_2 cleaning effects are comparable or even somewhat higher than the effects of laundering and wet cleaning. It was discovered that the LCO_2 dry-cleaning does not cause changes in the dimensional and colour characteristics of dyed, printed or flocked textiles, as well as no weight reduction of the fabric or pilling. The stain removal efficiency with LCO_2 depends on the stain composition and is between 60%–100% compared to the PER procedure [21, 23].

The results of the research where textile care effects were evaluated undoubtedly contributed to the intensive development of the LCO_2 technology and the increasing number of LCO_2 industrial washing machines in commercial laundries in the USA and EU [23, 27].

In-depth investigations have been conducted in the field of laundry hygiene and LCO_2, mainly focusing on the laundering and disinfection agents, disinfection conditions and the elimination of imperfections regarding classical disinfection processes. The diffusion of disinfection agent into the fibre is a slow process [28, 29], which reflects in the prolonging of laundering time and consequently, in an accumulation of difficulties concerning the morphological changes to heat-sensitive textiles. On the other hand, the residue of the disinfection agent could compromise the health of the user with the result that most of the wound-care materials (synthetic biomaterials which actively interfere in the biochemical wound healing process [30]*) and implants are impossible to disinfect. The fact cannot be neglected that most available disinfectants are flammable, potentially toxic, and thereby jeopardise the health and safety of employees in laundries. At the same time they present environmental stressors [31].*

High disinfection effects were achieved when contaminated textiles were CO_2 treated at the temperatures between 32–120 °C, at pressures from 70–300 bar and with rapid periodic changes in the working pressure, as well as rapid transmission from working to atmospheric pressure [32, 33]. The research also confirms

ževalna postopka nege tekstilij, za kemijsko-termičen in enokopelni LCO_2, ki zagotavljata identično stopnjo higiene.

2 Eksperimentalni del

Izvedena sta bila kemijsko-termičen in enokopelni LCO_2 postopek nege tekstilij s ciljem, da se ovrednoti stopnja redukcije mikroorganizmov in okoljskih vplivov. Razkuževalni učinek se je določil tako, da so se v laboratorijskih razmerah izvedli postopki pranja različnih bioindikatorjev, ki so bili izbrani na podlagi priporočil [8]. Uporabljena je bila klasična in prototipna LCO_2 oprema za nego tekstilij ter pralna, razkuževalna in pomožna sredstva. Fazi pranja in vrednotenju razkuževalnega učinka je sledila faza ugotavljanja in primerjave okoljskih vplivov postopkov nege ter popis stanja življenjskega cikla postopkov LCI, ki je bil podlaga za oceno vplivov na okolje LCIA.

2.1 Bioindikatorji

Za vrednotenje razkuževalne učinkovitosti postopkov nege so bili uporabljeni tekstilni bioindikatorji z naslednjimi bakterijskimi kulturami: *Enterococcus faecium ATCC 6057, Staphylococcus aureus ATCC 6538, Enterobacter aerogenes ATCC 13048* in *Candida albicans ATCC 2091*. Kot nosilec bakterijskih kultur je bila uporabljena bombažna tkanina z lastnostmi, ki so ustrezale standardu ISO2267 [38] ter so navedene v preglednici 1. Bioindikatorji so bili pripravljeni v zaporedju faz in v razmerah, navedenih v predhodnih raziskavah [7, 39].

2.2 Kemijsko-termični postopek nege

V laboratorijskih razmerah je bil izveden klasičen proces nege bolnišničnih tekstilij, sestavljen iz predpranja, glavnega pranja, izpiranj, nevtralizacije in ožemanja. Za izvedbo kemijsko-termičnega razkuževalnega postopka je bil uporabljen bobnasti pralni stroj Wascator Nyborg W365H MP Electrolux (Švedska) s polnilno zmogljivostjo 7,5 kg, prostornino bobna 75 l, z možnostjo programiranja procesa pranja in mikroprocesorsko regulacijo časa, temperature in mehanske obdelave. Pralna, razkuževalna in nevtralizirna sredstva so bila dozirana z napravo Ecobrite LLD-205 Henkel Ecolab GmbH (Avstrija). Za pripravo mehčane pralne vode je bila uporabljena mehčalna naprava WAK 10-KMN-1 (Hidrotehnični biro, Slovenija). Količine snovnega in energijskega toka, ki so vstopale ali izstopale iz procesa pranja, so bile spremljane z digitalnimi merilniki, nameščenimi na vstopno/izstopnih linijah. Količine vode in pralnih sredstev ter njihove temperature so bile merjene z digitalnimi merilniki (vodomer WFH36 DVN Qvedis GmbH (Nemčija)) na vstopnih linijah, medtem ko se je količina odpadne pralne kopeli merila na izstopni liniji. Za lažje vzorčenje odpadnih pralnih kopeli sta bila na izstopni liniji nameščena ventil in izpustna pipa. Poraba električne energije je bil *that the LCO_2 treatment at 20 °C and 70 bar pressure has a disinfection effect due to the present carbonic acid which occurs when the CO_2 loosens moisture from a cotton textile [34]. It is also important to note that for the development of textile disinfection processes, the disinfection effect can be achieved with a combination of LCO_2 and water (< 1%) at the temperatures between 20 and 65 °C, and working pressure lower than 50 bar [31].*

Within the context of the FP7 project "ACCEPT", which ended in 2010, the textile care procedures based on the LCO_2 technology were studied and developed [35]. The preparation and definition of the project tasks, as well as the project implementation included three university research institutes and eight companies, from the manufacturers of laundering and disinfection agents, medical equipment and implants, laundering equipment, to the commercial laundries from different EU countries [36]. The implementation was divided into two phases. The first phase included the research and development of laundering and disinfection agents, and low-temperature disinfection procedures for textile, leather and medical instruments performed with the help of the LCO_2 technology. The focus of the second research phase was the analysis and evaluation of the environmental impacts caused by various laundering procedures of medical textiles. The classical and newly developed low-temperature LCO_2 disinfection laundering procedures were analysed. The life cycle assessment (LCA), life cycle inventories (LCI) and life cycle impact assessment (LCIA) methodologies were used during the research [37]. This paper presents a comparison

merjena s trifaznim električnim števcem MT351 Iskra (Slovenija). Shema pralne linije kemijsko-termičnega procesa nege tekstilij je prikazana na sliki 1.

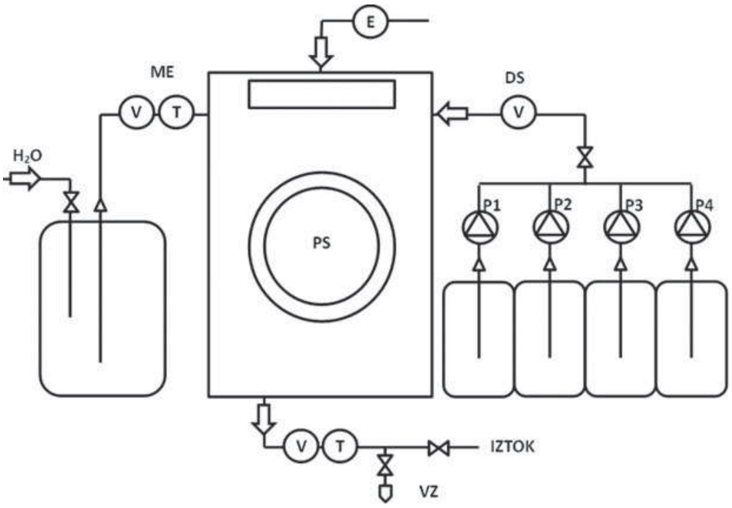

Figure 1: Scheme of chemo-thermal laundry unit
Used abbreviations: PS – drum washing machine; ME – water softening device; DS – automatic dosing device; P1–P4 – dosing pumps; V – flow meter for water/laundering agents; T – temperature measuring device; E – electricity meter; VZ – sampling of laundry wastewaters.

Kemijsko-termični proces pranja se je začel z vstavljanjem bioindikatorjev in balastne tkanine (preglednica 1) v boben pralnega stroja, doziranjem mehčane vode, pralnih sredstev in segrevanjem pralne kopeli do 35 °C. Sledila sta izpust kopeli predpranja in doziranje sveže mehčane vode, pralnih in razkuževalnega sredstva, segrevanje kopeli do 70 °C ter 9-minutno razkuževanje. Kemijsko-termični proces pranja se je končal s fazami izpiranja, nevtralizacije ter ožemanja s 550 vrt/min. Zaporedje faz in pogoji kemijsko-termičnega razkuževalnega postopka nege so prikazani v preglednici 2.

Table 1: Characteristics of used fabrics

Parameter	Bioindicator fabric	Ballast fabric
Producer	WFK GmbH (D)	MTT Maribor (SLO)
Product	ISO 2267:1986 cotton control fabric	Multipurpose fabric
Fibre composition	100% cotton	100% cotton
Density	Warp – 27 threads/cm, 295 dtex Weft – 27 threads/cm, 295 dtex	Warp – 28 threads/cm, 200 dtex Weft – 26 threads/cm, 200 dtex
Mass	170 g/m^2	120 g/m^2
Weave	Plain	Plain

Table 2: Structure and conditions of chemo-thermal laundering procedure

Phase	Temperature (°C)	Duration (min)	Laundering agent	Amount (ml/kg textile)
Pre-washing	35	9	Washing agent Builder Tensides	4.5 1.3 1.3
Main washing	70	9	Washing agent Builder Disinfection agent	4.5 1.3 1.3
Rinsing	–	11	–	–
Neutralisation	–	3.5	Neutralising agent	1.1

between the environmental impacts of two disinfection laundering procedures, namely the chemo-thermal and one-bath LCO$_2$ procedures, which provide identical levels of hygiene.

2 Experimental

The chemo-thermal and one-bath LCO$_2$ procedures were performed with the purpose of evaluating their degrees of microorganism reductions and environmental impacts. The disinfection effect was determined in such a way that different bioindicators, selected by recommendation, were laundered at laboratory conditions [8]. The classical and prototype LCO$_2$ textile laundry equipment and detergents, disinfectants and laundering agents were used.

The laundering phase and the evaluations of the disinfection effects were followed by further research and comparison between environmental impacts and LCI, which was the basis for the LCIA evaluation between different laundering procedures.

2.3 Postopek nege LCO$_2$

Uporabljena je bila laboratorijska visokotlačna naprava UHDE High Pressure Technologies GmbH Hagen (Nemčija). Njeni glavni sestavni deli so: zunanji in delovni rezervoar CO$_2$, hladilnik, visokotlačna črpalka, toplotni izmenjevalci, avtoklavirni posodi (500 ml, 5000 ml) in separator. Naprava UHDE uporablja t. i. zaprti sistem, saj vsakemu izpustu CO$_2$ iz avtoklavirne posode po obdelavi sledi še faza separacije oz. recikliranja, kjer se ločijo nečistoče in CO$_2$. Očiščen CO$_2$ se odvede v delovni rezervoar, s čimer je pripravljen za ponovno uporabo.

V laboratoriju je bila opravljena izvedba enokopelnega razkuževalnega LCO$_2$ postopka v razmerah, ki so enakim tistim pri razkuževanju s prototipno industrijsko napravo LCO$_2$ Gamma S35 Electrolux (Švedska), nameščeno pri raziskovalnem partnerju WFK Krefeld (Nemčija).

Vstavljanju bioindikatorjev in pralnega sredstva v separacijsko posodo prostornine 500 ml je sledilo polnjene CO$_2$ s čistostjo > 99,7 % [40]. Obdelavi biondikatorjev z LCO$_2$ pri delovnem tlaku 50 barov, temperaturi 50 °C v času 25 minut je sledila faza dekompresije, tj. počasnega zniževanja tlaka z delovnega na atmosferski tlak v času 15 minut. Zaporedje faz in pogoji obdelave LCO$_2$ so prikazani v preglednici 3, medtem ko je sestava uporabljene naprave LCO$_2$ prikazana na sliki 2.

Table 3: Structure and conditions of one-bath LCO$_2$ laundering procedure

Phase	**Temperature (°C)**	**Pressure (bar)**	**Duration (min)**	**Laundering agent**	**Amount (ml/l CO$_2$)**
Evacuation	–		1	–	–
LCO$_2$ preparation	50	50	1	–	–
Laundering	50	50	25	Washing agent	4.0
Depressurizing	–		15	–	–
Recycling	–		2	–	–

2.1 Bioindicators

Textile bioindicators were used in the evaluation of the disinfection efficiency using the following cultures of microorganisms: Enterococcus faecium ATCC 6057, Staphylococcus aureus ATCC 6538, Enterobacter aerogenes ATCC 13048 and Candida albicans ATCC 2091.

A cotton fabric was used as the substrate. Its characteristics met the ISO2267 standard [38] and are shown in Table 1. The sequences and conditions for the preparation of bioindicators were stated in previous research [7, 39].

2.2 Chemo-thermal laundering procedure

The classical laundering procedure for washing hospital textiles was performed at laboratory conditions, consisting of prewashing, main washing, rinsing, neutralisation and spinning. In order to realise the chemo-thermal disinfection laundering procedure, an Electrolux Wascator FOM 71 CLS-LAB (Sweden) drum washing machine was used with the capacity of 7.5 kg, drum volume 75 l, a programmable washing process and a microprocessor regulation of time, temperature and mechanical action. Soft laundering water was prepared using a WAK 10-KMN-1 (Hidrotehnični biro, Slovenia) softening device. The quantities of the input/output material and energy flux were monitored using digital measuring devices mounted on input/output lines.

The amounts of water and detergent, as well as their temperatures were measured using digital meters (meter WFH36 DVN Qvedis GmbH (Germany)) at the inlet pipes and similarly, the amount of the waste washing bath criteria at the outlet release pipe. A valve and an output tap were installed at the outlet opening for an easier sampling of the laundering wastewater. The power consumption was measured using a three-phase MT351 electricity metre (Iskra, Slovenia). The scheme for the used laboratory chemo-thermal laundry unit is shown in Figure 1.

The chemo-thermal process began with the insertion of bioindicators and ballast fabric (cf. Table 1) into the drum of the washing machine, followed by dosing with softened water and

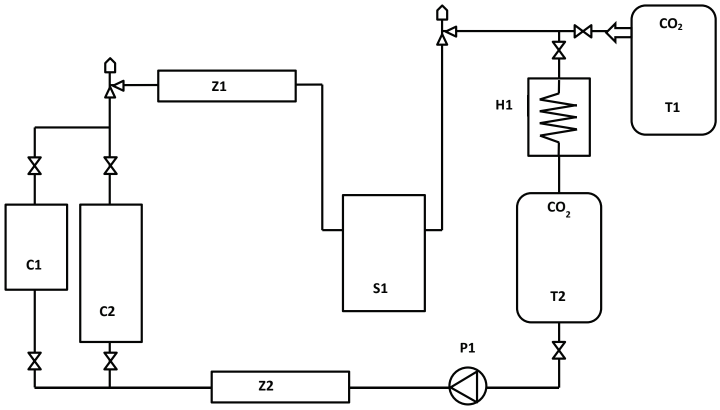

Figure 2: Scheme of high pressure UHDE HP Technologies GmbH Hagen (Germany) CO_2 device
Used abbreviations: T1 – CO_2 outdoor storage tank; H1 – condenser; T2 – CO_2 machine storage tank; P1 – compressor; Z1, Z2 – heat exchangers; C1, C2 – cleaning vessels (500 ml, 5,000 ml); S1 – distillation tank.

2.4 Pralna sredstva

V kemijsko-termičnem postopku nege je bilo uporabljeno industrijsko pralno sredstvo (tekoče, visoko koncentrirano, močno alkalno, sestavljeno iz natrijevega hidroksida, kalijevega hidroksida, glikolne kisline, neionogenih tenzidov, fosfonatov, optičnega belilnega sredstva), razkuževalno (vodikov peroksid, peroksiocetna kislina, ocetna kislina) in nevtralizirno sredstvo (raztopina ocetne kisline).

V razkuževalnem postopku nege LCO_2 je bilo LCO_2 dodano tekoče industrijsko pralno sredstvo, sestavljeno iz 2-(2-butoksi etoksi) etanola, alkoholov, neionskega tenzida, s topnostjo do 12 ml/l LCO_2 [41].

2.5 Vrednotenje ekoloških parametrov pralnih vod

Vzorčenju pralnih vod v posameznih fazah kemijsko-termičnega razkuževalnega procesa je sledilo vrednotenje parametrov odpadnih pralnih vod v skladu s predpisi [42, 43, 44]. Standardi in metode vrednotenja odpadnih pralnih vod so navedeni v preglednici 4.

2.6 Vrednotenje razkuževalnih učinkov

Postopek pranja mora zreducirati število bakterij za 5 logaritemskih stopenj in število gliv za 4 logaritemske stopnje, da je dosežen razkuževalni učinek glede na standarda SIST14065, NFXP07172 [45, 46]. Štetje števila kolonij mikroorganizmov *CFU (angl. Colony Forming Units)* na bioindikatorski tkanini pred izvedbo razkuževalnega postopka in po njej ter izračun stopnje redukcije mikroorganizmov Red_{CFU} je bilo izvedeno tako, kot predpisujejo standardi SIST20734, SIST20645, SIST6222 [47–49] in [7, 39].

Table 4: Parameters, concentration limits and methods for chemo-thermal laundry wastewaters [4]

Parameter	Unit	Concentration limit of emission into		Standard	Method
		water	sewage		
GENERAL PARAMETERS					
Temperature	°C	30	40	SIST DIN 38404-4	
pH		6.5–9	6.5–9.5	SIST ISO 10523	Electrometrical
Suspended substances	(mg/l)	80	(a)	SIST ISO 11923	Gravimetrical
Sedimented substances	(ml/l)	0.5	10	DIN 38409-9	Sedimentation
INORGANIC PARAMETERS					
Chlorine-free	(mg Cl_2/l)	0.2(b)	0.5	SIST ISO 7393-2	Colorimetric
Nitrogen ammonia	(mg N/l)	5	100; 200(c)	SIST EN 25663	Spectrophotometric
Total phosphorus	(mg P/l)	2[d]	–	SIST ISO 6878-1	Spectrophotometric
ORGANIC PARAMETERS					
COD	(mg O_2/l)	120	–	SIST ISO 6060	Titrimetric
BOD_5	(mg O_2/l)	25	–	SIST EN 1899-1	Dilution
AOX	(mg Cl/l)	1.0; 3.0 (d)	1.0; 3.0 (d)	SIST ISO 9562	Colorimetric
Sum of anionic and non-ionic surfactants	(mg/l)	3.0	(a)	SIST ISO 7875-1 SIST ISO 7875-2	Spectrophotometric Dragendorff's reagent

Legend of used abbr.:

(a) The limit concentration of suspended substances and surfactants in wastewater is determined with the value at which there is no influence on the sewage system or purifying plant.

(b) The limit value is not defined in the case of disinfection of laundry from health care.

(c) For wastewater flowing into a purifying plant with capacity less than 2,000 PE, the limit value is 100 mg/l; for wastewater flowing into a purifying plant with capacity of 2,000 PE or more, the limit value is 200 mg/l.

(d) The parameter limit value is valid for wastewater originating from washing laundry from health care.

laundering agents, the bath then being heated to 35 °C. This was followed by the release of the pre-wash bath, dosing of freshly softened water, the laundering and disinfection agents, the bath being heated to 70 °C and a 9-minute disinfection. The chemo-thermal washing process was completed by rinsing, neutralisation and the spinning phase at 550 RPM. The sequence of phases and conditions performed during the chemo-thermal laundering procedure is shown in Table 2.

2.3 LCO$_2$ laundering procedure

The laboratory's UHDE High Pressure Technologies GmbH Hagen (Germany) device was

2.7 Analize LCA, LCI

Kot najprimernejša metodologija za objektivno oceno vplivov na okolje se je izkazala metodologija LCA. Metodologija LCA vrednoti obremenitve okolja, povezane s posameznim izdelkom ali storitvijo z oceno morebitnih posledic za okolje, na podlagi evidentiranja porabljene energije in surovin ter z njimi povezanimi odpadki in v okolje sproščenimi emisijami. Ocena posledic za okolje naj bi praviloma vključevala vse vplive na okolje skozi celotno življenjsko dobo izdelka, tj. „od zibelke do groba“ (*angl. Cradle to Grave*). V vrednotenje vplivov na okolje skozi celoten življenjski cikel izdelka je pravilom treba zajeti vse faze, od izkopavanja surovin, načrtovanja in proizvodnje materialov ter delov polizdelka ali izdelka, transporta med posameznimi proizvodnimi fazami, distribucije končnih izdelkov, pakiranja, uporabe, vzdrževanja, recikliranja, končnega odlaganja izrabljenih izdelkov na odpad, vse do *used during this laundering procedure. Its main components are an external supply and storage CO_2 tank, cooling unit, high-pressure pump, heat exchangers, two cleaning vessels (500 ml, 5,000 ml) and a separator. The UHDE high-pressure device uses the so-called closed system, where after each laundering treatment, contaminated CO_2 is recycled and the impurities and CO_2 are separated. The purified CO_2 is led into a storage tank and prepared for re-usage.*

A one-bath LCO_2 laundering disinfection procedure was performed in a laboratory at conditions which were identical to the disinfection conditions of a Gamma S35 Electrolux (Sweden) commercial prototype laundering machine installed at our research partner at WFK Krefeld (Germany).

After loading the cleaning vessel with the volume of 500 ml, containing bioindicators and a laundering agent, the vessel was loaded with CO_2, having the purity > 99.7% [40]. After the LCO_2 treatment of bioindicators for 25 min at pressure of 50 bar and temperature 50 °C, a decompression phase followed, i.e. slowly lowering from the working to atmospheric pressure within 15 min.

The sequence of phases and conditions for the performed LCO_2 laundering procedure is shown in Table 3. The scheme for the used LCO_2 equipment is shown in Figure 2.

2.4 Laundering agents

An industrial laundering detergent was used during the investigated chemo-thermal laundering procedure. This was liquid, highly concentrated and strongly alkaline, consisting of sodium hydroxide, potassium hydroxide, glycolic acid, non-ionic surfactants, phosphonates and optical bleaching agents, plus a disinfection agent (a solution of hydrogen peroxide, peracetic acid, acetic acid) and a neutralising agent (solution of acetic acid).

A commercial dry-cleaning detergent (2-(2-butoxyethoxy) ethanol, alcohols, non-ionic-surfactant), soluble in LCO_2 up to 12 ml/l LCO_2 were added to LCO_2 during the LCO_2 laundering procedure [41].

pridobivanja, proizvodnje in distribucije energije ter sproščenih emisij v okolje [50]. Pri tem je treba poudariti, da je lahko v središču raziskave z metodologijo LCA tako izdelek kot tudi storitev.

Načela in cilji metodologije LCA, meje sistema ocenjevanja, viri zbiranja podatkov o snovnih in energetskih tokovih ter njihovih analiz, kot tudi postopki vrednotenja vplivov na okolje so navedeni v standardih skupine SIST EN ISO 14000. Standardi varovanja okolja so relativno novi v primerjavi z drugimi standardi za vzorčenje, preskušanje in analitske metode za spremljanje in nadzor posebnih okoljskih vidikov. Organizacijam naj bi ponujali orodje za učinkovito ukrepanje pri določitvi odgovornosti in stalnem ocenjevanju ravnanj, postopkov in procesov [51]. Metodologija LCA je po standardu SIST 2011 [51] opredeljena s štirimi standardi SIST EN ISO 14040, 14041, 14042, 14042, ki se nanašajo na naslednje faze ocenjevanja: definiranje načel in okvirjev, popis vseh vhodno/izhodnih snovnih in energijskih tokov (LCI), ovrednotenje vplivov na okolje (LCIA), predstavitev in razlaga analize LCA. Medtem ko so prva, druga in četrta faza vrednotenja LCA podrobno opredeljene v standardih, je sistem vrednotenja, ki je predmet tretje faze, tj. povezave zbranih podatkov s škodljivimi učinki na okolje še vedno v fazi razvoja in dopolnjevanja. Običajno ugotovljeni parametri, kot npr. trdni odpadki, emisije odpadnih vod, energetske emisije, emisije plinov v zrak, različno vplivajo na obremenjevanje okolja, s čimer se povečuje zapletenost ocenjevanja in medsebojnega vpliva veličin sistema. Za oceno vplivov LCIA so bili razviti različni modeli ocenjevanja, kot metoda mejnih koncentracij, metoda odstopanj od ciljne vrednosti, ocena tveganja na podlagi tipa okolja, v katero so emisije izpuščene, koncept korelacije med emisijami znane in neznane kemične substance t. i. *angl. benchmarking* [50]. Pomanjkljivost vrednotenja vplivov na okolje se odraža v različnih pristopih ocenjevanja (vpliv na lokalno ali globalno onesnaževanje) ter v uporabi različnih dejavnikov škodljivosti in indeksov obremenjevanja okolja (globalno segrevanje ozračja, zakisanje ozračja, krčenje ozonske plasti, rakotvornost, tvorba fotokemičnega smoga, evtrofikacija, toksičnost, vplivi na počutje itd.). Najpogosteje uporabljane ocene vplivov na okolje se podajajo na podlagi naslednjih metod, med katerimi ni korelacij: *CML2001, CERA-Cumulative Energy Requirements Analysis, Eco-indicator 99, Ecological footpint, EDP-Ecosystem Damage Potential, EDIP2003-Environmental Design of Industrial Products, IMPACT 2002+, IPCC 2001, TRACI, SLCI-Selected Life Cycle Inventory Indicators* [50, 52–57].

Znano je, da emisije toplogrednih plinov (TGP) ogljikovega dioksida (CO_2), metana (CH_4), dušikovega oksida (N_2O), ozona (O_3), hidrofluoroogljikov (HFC-ji), perfluoroogljikov (PFC-ji) in žveplovega heksafluorida (SF_6), ki so posledica človekove dejavnosti, odločilno prispevajo k učinku tople grede ter s tem na podnebne spremembe. Antropogene emisije teh plinov so povezane predvsem s proizvodnjo in porabo fosilnih goriv, z nekaterimi industrijskimi procesi, s kmetijstvom in ravnanjem z odpadki. Potencial

2.5 Evaluation of laundry wastewater parameters

After sampling the wastewaters from different chemo-thermal laundering phases, the samples were evaluated according to regulations [42, 43, 44]. The standards and evaluation methods for washing wastewater are noted in Table 4.

2.6 Evaluation of disinfection effects

The disinfection laundering procedure must achieve according to the SIST14065 and NFXP07172 standards [45, 46] the reduction of bacteria by 5 log and fungi by 4 log. Microorganism colonies on textile bioindicators (CFU, Colony Forming Units) were counted before and after the disinfection laundering procedure, and the calculation of reduction efficiency (RED) was performed as determined by the SIST20734, SIST20645, SIST6222 standards [47–49] and [7, 39].

2.7 LCA, LCI analyses

The LCA methodology proved to be the most appropriate method to objectively evaluate environmental impacts. The LCA methodology evaluates the environmental impacts associated with a particular product or service, in order to assess any potential consequences for the environment. This evaluation is based on the recording of raw materials and energy consumption, and the waste and emissions released into the environment. This evaluation should include all environmental impacts throughout the whole lifecycle of a product or process, i.e. "from cradle to grave". The environmental risk evaluation must cover all the product phases from the mining of raw materials, designing and manufacturing materials, semi-finished and finished products, transportation among production phases, distribution of finished products, packaging, use/reuse, sustenance, recycling, waste management, all the way to the acquisition, production and distribution of energy, and emissions released into the environment [50]. It should be pointed out that the centre of the LCA research can be represented by a product and not only a process or service.

The principles and objectives of the LCA methodology, the boundaries of evaluation, sources for collecting data on raw materials and ener-

globalnega segrevanja, ki se podaja z indeksom GWP_{TGP} *(angl. Global Warming Potential)*, je definiran kot „potencial segrevanja podnebja zaradi toplogrednega plina v primerjavi s potencialom segrevanja podnebja zaradi CO_2" [58–60]. Za vsak TGP je izračunan specifični indeks GWP_i na podlagi enačbe [61],

$$GWP_i(t) = \frac{\int_0^t a_g x_g(t)dt}{\int_0^t a_{CO_2} x_{CO_2}(t)dt} \qquad (1)$$

kjer je

a – koeficient zadrževanja dolgovalovnega sevanja (W/m^2 *kg*)

x – razgradnja plina v ozračju (kg/s)

g – TGP (CH_4), N_2O, *HFC, PFC,* SF_6)

t – časovno razdobje (20, 100, 500 let)

$GWP_i\,(t)$ *– potencial globalnega segrevanja za posamičen TPG v časovnem obdobju (kg* CO_2 *eq)*

Lastnosti in specifični indeksi GWP_i nekaterih TGP so navedeni v preglednici 5.

Table 5: Characteristics and characterisation factors GWP_i *for GHG [61]*

Substance		Atmospheric lifetime (years)	$GWP_i(100)$ (kg CO_2 eq)
Carbon dioxide	CO_2	–	1
Methane	CH_4	12	25
Nitrous oxide	N_2O	114	298
Sulphur hexafluoride	SF_6	3,.200	22,800
Hydrofluorocarbons	HFC	4.9–270	124–14,800
Perfluorocarbons	PFC	740–50,000	7,390–22,800

Za izračun GWP_{TGP} se upošteva enačba [62, 63],

$$GWP_{TGP}\,(t) = \Sigma\,(m_i\,(t) \times GWP_i(t)) + (m_{i+1}\,(t) \times GWP_{i+1}(t)) + \ldots + (m_{i+n}\,(t) \times GWP_{i+n}(t)), \qquad (2)$$

kjer je

$m_{i,\,i+1,\ldots,i+n}$ *(t) masa TGP – za časovno obdobje t (kg)*

$GWP_{i,\,i+1,\ldots,i+n}$ *(t) – specifični indeks globalnega segrevanja TGP za časovno obdobje t (kg* CO_2 *eq)*

t – časovno obdobje (20, 100, 500 let)

GWP_{TGP} *(t) – potencial globalnega segrevanja za časovno obdobje t (kg* CO_2 *eq)*

Sežig fosilnih goriv in intenzivno kmetijstvo sta poglavitna vira človekovega zakisljevanja okolja. Najpomembnejši povzročitelji so emisije plinov, žveplovega dioksida (SO_2), dušikovih oksidov (NO_x), amonijaka (NH_3) ter hlapnih organskih snovi (VOC), ki ob *gy flows, as well as the mode of environmental impact proceedings are listed in the ISO 14000 family standards. The environmental management standards are relatively new compared to other standards, e.g. the standards for sampling, testing and analytical methods for monitoring and inspecting special environmental aspects. The standards should provide companies with a tool for an efficient determination of responsibility and permanent evaluation of practices, procedures and processes [51]. As stated in the SIST2011 standard [51], the LCA methodology is defined within four SIST EN ISO standards 14040, 14041, 14042, 14042, which relate to the following evaluation phases: goal and scope definition, inventory analysis of all input/output raw material and energy flows (LCI), environmental impact assessment (LCIA), and the presentation and interpretation of LCA analyses. The first, second and fourth phase of the LCA assessment are specified in standards in detail, while the third phase about the linking of collected data with harmful influences on the environment is still under development, being updated. Generally specified parameters, e.g. solid waste, wastewater emissions, energy emissions, gas emissions have different impacts on the environment, thus increasing the complexities of interaction between the evaluations and quantities of system parameters. Various evaluation methods have been developed for the LCIA impact assessment, i.e. critical volumes method, deviation from target values, risk assessment based on the kind of environment where emissions are released, the concept of correlation between emissions for known and unknown chemical substances, the so-called benchmarking [50]. The disadvantage of environmental impact assessments is reflected in various evaluation approaches (impact on local or global pollution) and the uses of different environmental impact factors (global warming potential, acidification, shrinking ozone layer,* cancerogenity, *photochemical ozone creation, eutrophication, toxicity, effect on human health etc). The bases for evaluating impact assessment are the following methods with no correlation among them: CML2001, CERA-Cumulative Energy Requirements Analysis, Eco-indicator 99, Ecological*

reagiranju z dušikovimi oksidi in ob prisotnosti sončne svetlobe lahko proizvedejo fotokemične oksidante [64]. Škodljivi učinki zakisljevanja se kažejo z vplivi na zdravje ljudi, gozdne ekosisteme in zgradbe. Emisije NO_X in NH_3 lahko povzročijo tudi nasičenost tal ali vode z dušikom, kar povzroči evtrofikacijo, tj. čezmerno kopičenje hranilnih snovi [60, 65, 66].

Potencial zakisljevanja AP *(angl. Acidification Potential),* ki se izraža kot indeks zakisljevanja okolja, se izračuna po enačbi,

$$AP = \Sigma (m_i \times AP_i) + (m_{i+1} \times AP_{i+1}) + \ldots + (m_{i+n} \times AP_{i+n}), \qquad (3)$$

kjer je

$m_{i,\, i+1, \ldots, i+n}$ – *masa posameznega TGP (kg)*
$AP_{i,\, i+1, \ldots, i+n}$ – *utežni faktor TGP (kg SO_2 eq/kg)*
AP – potencial zakisljevanja (kg SO_2 eq)

Utežni faktorji AP_i najpogostejših povzročiteljev zakisljevanja, ki se upoštevajo pri izračunu indeksa zakisljevanja *AP,* so prikazani v preglednici 6 [67].

Table 6: Characterisation factors AP_i for some causers of acidification [67]

Substance		AP_i (kg SO_2 eq)
Sulphur dioxide	SO_2	1.00
Nitrogen oxides	NO_x	0.70
Ammonia	NH_3	1.88
Hydrochloric acid	HCl	0.88

Cilj analize LCA je bil zbrati, ovrednotiti ter podati oceno vplivov na okolje dveh razkuževalnih postopkov nege tekstilij. Analizirani so bili vhodno/izhodni parametri kemijsko-termičnega in enokopelnega postopka nege LCO_2, medtem ko preostali elementi sistema, kot so proizvodnja uporabljenih strojev, pralnih in razkuževalnih sredstev, vseh vrst transporta, pakiranja, skladiščenja ter postopki obdelave odpadnih vod ter recikliranja odpadkov, niso bili predmet tokratnega proučevanja z metodologijo LCA.

Za vsak razkuževalni postopek nege tekstilij so bili v prvem koraku evidentirani vsi parametri procesa nege tekstilij. Na podlagi posnetka stanja in zajetih podatkov so bile izdelane blokovne tehnološke sheme, ki so vsebovale vhodne (bioindikatorji, pralna/razkuževalna/nevtralizirna sredstva, voda, CO_2, energija, čas trajanja) in izhodne (izpusti vod, izpusti CO_2 v okolje) parametre, na podlagi katerih so bile postavljene bilančne sheme procesa (LCI). Sledile so ocene vplivov razkuževalnih postopkov nege na okolje (LCIA), ki so bile izvedene na podlagi podatkovnih baz korelacijskih in emisijskih faktorjev vpliva na okolje Medvladnega foruma za podnebne spremembe IPCC [68], Skupnega raziskovalnega centra EU JRC ELCD Database [66], računalniških orodij *footpint, EDP-Ecosystem Damage Potential, EDIP2003-Environmental Design of Industrial Products, IMPACT 2002+, IPCC 2001, TRACI, SLCI-Selected Life Cycle Inventory Indicators [50, 52–57].*

It is well-known that the emissions of greenhouse gases (GHG), emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), all caused by human activities, contribute to the greenhouse effect and consequently, to climate changes. The anthropogenic emissions of these gases are mainly associated with the production and usage of fossil fuels, with some industrial production processes, agriculture and waste management. The global warming potential indicator, which gives the GWP_{GHG} index, is defined as "the global warming potential of a greenhouse gas compared to the potential global warming due to carbon dioxide" [58–60]. The characterisation factor GWP_i for each GHG was calculated based on equation (1) [61], where:

a – radiative forcing coefficient for long wavelength radiation (W/m^2kg),

x – concentration of GHG g at time t after release,

g – GHG (CH_4, N_2O, HFC, PFC, SF_6),

t – time-intervals over which the integrations are made (20, 100, 500 years), and

$GWP_i(t)$ – characterisation factor for GHG g at time t.

The characteristics and characterisation factors GWP_i for GHG are shown in Table 5. The GWP_{GHG} indicator is calculated based on equation (2) [62, 63], where:

$m_{i,\, i+1,\ldots,i+n}$ – mass of GHG (kg),

$GWP_{i,\, i+1,\ldots,i+n}(t)$ – characterisation factor for GHG i (kg CO_2 eq) at time t,

t – time-intervals over which the integrations are made (20, 100, 500 years), and

$GWP_{TGP}(t)$ – global warming potential indicator (kg CO_2 eq).

Fossil-fuel combustion and intensive agriculture are the predominant man-made sources of environmental acidification. The main causes are the released emissions of acid gases, e.g. sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and volatile organic compounds

GEMIS-Global Emission Model for Integrated Systems [69]. Ocena obremenitve okolja za kemijsko-termični in LCO_2 razkuževalni postopek nege je bila narejena po metodi CML2001 [56, 67]. Na podlagi porabljene električne energije v razkuževalnih postopkih so bile izračunane emisije plinov pri proizvodnji električne energije v sedemindvajsetih državah članicah Evropske unije (EU27) in za države podjetij projekta ACCEPT (Nemčija, Nizozemska, Velika Britanija, Švedska, Slovenija), pri čemer je bila upoštevana struktura virov za proizvodnjo električne energije (*angl. electricity mix*) v podatkovni bazi JRC ELCD Database II za leto 2002 [66]. V nadaljevanju so bili ovrednoteni vplivi na okolje na podlagi izračunov potenciala globalnega segrevanja GWP_{100} in potenciala zakisljevanja okolja *AP ob* upoštevanju specifičnih indeksov GWP_i in utežnih faktorjev povzročiteljev zakisljevanja okolja AP_i.

3 Rezultati z razpravo

Za dva razkuževalna postopka nege tekstilij, kemijsko termični in v okviru evropskega raziskovalnega projekta „ACCEPT" razvit enokopelni LCO_2, ki sta zagotavljala enako stopnjo razkuževanja, so bile izvedene raziskave vrednotenja vplivov na okolje. Uporabljena je bila metodologija vrednotenja odpadnih pralnih vod, kot jo predpisuje slovenska okoljevarstvena zakonodaja, ter metodologije LCA za popis snovnih in energetskih tokov LCIA in oceno vplivov na okolje LCIA.

Rezultati meritev ekoloških parametrov odpadnih pralnih vod kemijsko-termičnega razkuževalnega procesa so podani v preglednici 7. Rezultati analiz LCA in LCI in ocena obremenitev vplivov na okolje za kemijsko-termični in enokopelni postopek nege LCO_2 so prikazani v preglednicah od 8 do 12.

Posebej skrb zbujajoč vpliv na okolje kažejo odpadne pralne vode uporabljenega kemijsko-termičnega razkuževalnega postopka nege tekstilij (preglednica 7). Izstopajo pralne odpadne vode predpranja z znatnimi prekoračitvami mejnih vrednosti izpustov v vode: amonijevega dušika za 6,62 mg N/l, celotnega fosforja za 0,5 mg P/l, KPK za 200 mg O_2/l, BPK_5 za 239 mg O_2/l. Tudi odpadne pralne vode glavnega pranja dokaj prekoračijo mejne vrednosti pri temperaturi za 33,7 oz. 23,7 °C, amonijevega dušika za 1,12 mg N/l, KPK za 65 mg O_2/l. Vrednosti parametrov odpadnih vod izpiranja so pod mejnimi vrednostmi, medtem ko nevtralizacijske odpadne pralne vode znova prekoračijo dovoljeno vsebnost celotnega fosforja za 0,1 mg P/l in BPK_5 za 26 mg O_2/l. Iz rezultatov v preglednici 7 je razvidno, da vrednost amonijevega dušika doseže najvišjo vrednost v vodah predpranja (11,62 mg/l) ter nato upada v vodi glavnega pranja za 47,33 %, izpiralni vodi za 62,82 % in nevtralizacijski za 73,15 %. Pri zasledovanju vrednosti KPK in BPK_5 lahko opazimo podoben trend padanja, saj v vodi glavnega pranja upadeta KPK za 42,19 % in BPK_5 za 51,52 %, v izpiralni vodi upade KPK za 82,81 % in BPK_5 za 90,53 %, medtem ko

(VOC), which can produce photochemical oxidants with reactions with nitrogen oxides in the presence of sunlight [64]. The damaging effects of acidification are manifested in humans' health, forest ecosystems and buildings. The emissions of NO_X and NH_3 have negative impacts on the soil or water satiation with nitrogen, causing eutrophication, i.e. excessive accumulation of nutrients [60, 65, 66].

The acidification potential indicator AP is calculated with equation (3), where,

$m_{i,\ i+1,\dots,i+n}$ – mass of GHG (kg),
$AP_{i,\ i+1,\dots,i+n}$ – characterisation factor of GHG (kg SO_2 eq/kg), and
AP – acidification potential indicator (kg SO_2 eq).

je upad v nevtralizacijski vodi nekoliko manjši (KPK za 70,31 %, BPK_5 za 80,68 %) nasproti vrednostim v pralnih vodah predpranja. Vzroke enormnih prekoračitev lahko iščemo v vrsti in količini uporabljenih pralnih, razkuževalnih in nevtralizacijskih sredstev. Rezultati raziskave vodijo k sklepu, da odpadne vode kemijsko-termičnega razkuževalnega postopka niso primerne za izpust v vode, kot tudi ne za ponovno uporabo brez predhodnega čiščenja.

Table 7: Values of investigated chemo-thermal laundering wastewater parameters (average of three laundering procedures)

Parameter	Unit	Laundering phase			
		Pre-washing	Main washing	Rinsing	Neutralisation
Temperature	°C	34	63.7	30.4	22.3
pH		9.1	8.1	7.8	7.3
Suspended substances	(mg/l)	0.0004	0.0072	0.0009	0.0003
Sedimented substances	(ml/l)	0.50	< 0.5	4.00	3.50
Chlorine-free	(mg/l)	0.40	0.20	0.10	0.10
Nitrogen ammonia	(mg/l)	11.62	6.12	4.32	3.12
Total phosphorus	(mg/l)	2.50	1.51	1.95	2.10
COD	(mg O_2/l)	320.00	185.00	55.00	95.00
BOD_5	(mg O_2/l)	264.00	128.00	25.00	51.00
AOX	(mg/l)	0.136	0.057	0.049	0.043
An. and non-ionic tens.	(mg/l)	2.96	2.94	0.54	0.00

Posnetek snovnih in energetskih tokov kaže, da znaša poraba električne energije (preglednica 8) za kilogram opranih tekstilij pri kemijsko-termičnem razkuževalnem postopku 3700 kJ, medtem ko je pri enokopelnem razkuževalnem postopku LCO_2 manjša za 75,68 % (900 kJ). Pretežni del energije se pri kemijsko-termičnem postopku porabi za segrevanje pralnih kopeli v fazi predpranja (46,5 %) in pranja (49,45 %), medtem ko na fazi izpiranja in nevtralizacije odpade 3,30 % in 1,10 % porabljene električne energije. Velik porabnik električne energije so električni grelci, medtem

Table 8: Results of LCA and LCI analyses and environmental impact assessments for chemo-thermal and one-bath LCO_2 procedure (for 1 kg of laundered textile)

Parameter	Unit	Disinfection laundering procedure	
		Chemo-thermal	One-bath LCO_2
Energy	kJ	3,700	900
Duration	min	36.23	44.00
Water	l	9.23	–
Laundering agent	ml	15.30	4.00

The characterisation factors for some of the main GHG causers of acidification, which are considered during the calculation of the acidification indicator AP, are shown in Table 6 [67].

The goal of the LCA analysis was to collect, evaluate and compare the environmental impacts of two laundering procedures. The input/output parameters of both, the chemo-thermal and one-bath LCO_2 laundering procedures were analysed during the research. Other system elements, e.g. the washing machine, laundry detergent and disinfection agent production, all types of transport, packaging and storage, and wastewater treatment and recycling of waste, were excluded from this study.

All parameters for each disinfection laundering procedure were recorded during the first steep. The recorded and collected data presented the basis for preparing a technological block-diagram with inlets (bioindicators, laundering/disinfection/neutralizing agents, water, CO_2, energy, laundering time) and outlets (discharge of water and CO_2 emissions into the environment) parameters. The LCI schemes of laundering processes were prepared based on these data. The following environmental impact assessments of disinfection laundering procedures (LCIA) were performed by considering the databases of the characterisation and emission factors obtained from the Intergovernmental Panel on Climate Change (IPCC) [68], ELCD database of EC Join Research Centre, Institute for Environment and Sustainability (EU JRC) [66] and Global Emission Model software package for Integrated Systems (GEMIS) [69]. The environmental impact assessments of chemo-thermal and LCO_2 disinfection laundering procedures were performed according to the CML2001 method [56, 67]. The measured energy consumptions for disinfection laundering procedures were the basis for calculating the GHG gas emissions of the 27 member states of the European Union (EU27) and of the member states of the ACCEPT research project (Germany, Netherland, UK, Sweden, Slovenia). These calculations took into consideration the structures of the sources for electricity production (electricity-mix) for the year 2002, as available in the JRC ELCD Database II [66]. Later, the global warming potential indicator

ko so električni motor za vrtenje bobna, črpalke za črpanje sveže vode, pralnih sredstev, pralnih ter nevtralizacijske kopeli, mikroprocesorska enota in električni ventili zanemarljivi porabniki. Pri enokopelnem razkuževalnem postopku LCO_2 se 92,36 % električne energije porabi za hlajenje CO_2 z električnimi črpalkami in ventilatorji v fazi dekompresije (61,57 %) in recikliranja (30,79 %) CO_2, ki sledita koncu faze nege. Relativno veliko porabo električne energije za hitro hlajenje CO_2 bi bilo smiselno nadomestiti z vodnim sistemom hlajenja.

Razkuževalni postopek nege LCO_2 traja dlje za nekaj manj kot 8 minut v primerjavi s kemijsko-termičnim (preglednici 2 in 3), kar je posledica počasnega izpusta in hlajenja CO_2 (17 min), s čimer se prepreči nastanek „suhega ledu“. V nasprotju s kemijsko-termičnim postopkom, pri katerem trajajo faze predpranja, pranja in izpiranja enako dolgo (11,06 min), medtem ko je faza nevtralizacije dvakrat krajša, je postopek nege LCO_2 bolj razgiban. Dvema kratkima fazama (2 min) črpanja zraka iz negovalne komore in komprimiranja ter segrevanja CO_2 sledi faza nege, ki je relativno dolga (25 min) ter zagotavlja pričakovano stopnjo razkužitve negovanih tekstilij. Prav tako je treba poudariti, da je bilo treba pri obdelavi z LCO_2 samo eno pralno sredstvo (4 ml/l CO_2), medtem ko je kemijsko-termični postopek zahteval pralno sredstvo, ojačevalec, tenzid, razkuževalno in nevtralizacijsko sredstvo (15,30 ml/kg tekstilij). Eden pomembnih kriterijev, ki daje bistveno prednost enokopelnemu postopku $LCO_{2,}$ je nedvomno dejstvo, da pri obdelavah ni bilo treba uporabiti vode, na čemer temeljijo klasični razkuževalni postopki nege tekstilij. Čeprav smo raziskali tudi učinke vode in LCO_2 na razkuževanje tekstilnih bioindikatorjev [70], v nasprotju s Cinquenamijem [31] nismo ugotovili bistvenih zvišanj stopenj redukcije mikroorganizmov, zato smo izločili vodo iz postopka nege z LCO_2. Z vodo je povezano tudi dejstvo, da je bilo treba po kemijsko-termičnem postopku tekstilije še sušiti (OE 35 %), kar je zahtevalo podaljšanje časa obdelave in dodatno energijo za odparevanje preostanka vode. In nasprotno, po končanem postopku nege z LCO_2 so bili preizkušani tekstilni bioindikatorji suhi na dotik, zato sušenje ni bilo potrebno.

Predhodni zaključki, povezani z vodo, potrebno energijo in časom nege, kažejo enak trend tudi pri analizah emisij plinov, ki jih povzročata raziskovana razkuževalna postopka nege. Pri primerjavi rezultatov emisij TGP in plinov, ki povzročajo zakisljevanje (preglednici 9 in 10), lahko kaj hitro opazimo njihovo pestrost ter znatna nihanja med državami partnericami raziskovalnega projekta. Tako je opazna velika razlika pri emisijah CO_2, ki jih povzroča kemijsko-termični postopek nege (preglednica 9) na Švedskem (37,56 g CO_2/kg tekstilij) in Nizozemskem (253,41 g CO_2/kg tekstilij) ter v evropskem povprečju EU-27 (195,39 g CO_2/kg tekstilij). Slovenija je z emisijami 202,80 g CO_2/kg tekstilij pri dnu razpredelnice, kar ne velja za emisije NO_2 (140,28 g NO_2/kg tekstilij) in CH_4 (13,41 g CH_4/kg tekstilij), kjer je krepko nad preostalimi državami in povprečjem Evropske unije (109,10 g NO_2/kg tekstilij, 9,47 g

GWP$_{GHG}$ *(100 years) and potential acidification indicator AP, regarding the GWP*$_i$ *and AP*$_i$ *factors were calculated.*

3 Results and discussion

Two disinfection laundering procedures, the chemo-thermal and, within the European research "ACCEPT" project, the developed one-bath LCO$_2$ *procedure were conducted with regard to environmental impact assessments. Both procedures ensured the same disinfection efficiency. Wastewater methodology was used in the research as defined by the Slovenian environmental legislation and the LCA methodology for raw-material and energy inventories (LCI), and the environmental impact assessments (LCIA).*

CH_4/kg tekstilij). Opisano dejstvo velja tudi za emisije TGP in plinov zakisljevanja okolja za enokopelni razkuževalni postopek LCO_2 (preglednica 10). Pri tem je treba opozoriti, da so emisije TGP pri postopku LCO_2 za 75,26 % manjše kot emisije pri kemijsko-termičnem razkuževalnem postopku. Odstopanja med emisijami enakih plinov v različnih državah so posledica zastopanosti primarnih virov za proizvodnjo električne energije, ki se spreminja od države do države ter od enega do drugega ocenjevalnega obdobja. Struktura primarnih virov za proizvodnjo električne energije in z njimi povezane vrednosti emisij plinov za široko paleto držav so sestavni del podatkovne baze metodologije LCA JRC ELCD Database II [66]. Na podlagi podatkov, prikazanih v preglednici 11, je razvidno, da je struktura konvencionalnih in obnovljivih virov za proizvodnjo električne energije med državami sila raznolika. Po podatkih iz leta 2002 je delež premoga pri proizvodnji električne energije najmanjši na Švedskem (1,60 %) in največji v Nemčiji (49,80 %), kateri sledi Slovenija s 36,08 %. Deležem uporabljenega fosilnega goriva so primerne tudi emisije NO_X, ki pomembno vplivajo na podneb-

Table 9: Emissions of GHG and acidification substances among member states for the country of project partner and EU27 average (for 1 kg of laundered textile)

Parameter	Unit	Country					
		Germany	UK	Netherlands	Sweden	Slovenia	EU27
CO_2	g	240.52	217.03	253.41	37.56	202.80	195.39
NO_2	g	67.68	137.15	78.22	14.29	140.28	109.10
CH_4	g	10.28	12.16	7.76	0.73	13.41	9.47
SO_2	g	0.26	0.95	0.15	0.04	4.38	1.12
NO_x	g	8.56E-10	4.71E-10	5.54E-10	4.67E-09	2.67E-09	1.54E-09
NH_3	g	3.10E-03	1.21E-03	3.16E-03	4.18E-04	5.08E-04	1.51E-03
HCl	g	6.02E-09	2.83E-09	4.87E-09	1.13E-08	7.20E-09	6.18E-09

Table 10: Emissions of GHG and acidification substances for one-bath LCO$_2$ *laundering procedure for the country of project partner and EU27 average (for 1 kg of laundered textile)*

Parameter	Unit	Country					
		Germany	UK	Netherlands	Sweden	Slovenia	EU27
CO_2	g	58.51	52.79	61.64	9.14	49.33	47.53
NO_2	g	16.46	33.36	19.03	3.48	34.12	26.54
CH_4	g	2.50	2.96	1.89	0.18	3.26	2.30
SO_2	g	0.06	0.23	0.04	0.01	1.06	0.27
NO_x	g	2.08E-10	1.15E-10	1.35E-10	1.13E-09	6.49E-10	3.74E-10
NH_3	g	7.55E-04	2.95E-04	7.69E-04	1.02E-04	1.23E-04	3.67E-04
HCl	g	1.46E-09	6.89E-10	1.19E-09	2.75E-09	1.75E-09	1.50E-09

Table 11: Structure of prime energy sources for electricity production for the country of project partner and EU27 average (for the year 2002) (JRC ELCD Database II [66])

Energy source	Country/Share (%)					
	Germany	UK	Netherlands	Sweden	Slovenia	EU27
Coal	49.80	32.10	24.95	1.60	36.08	29.60
Natural gas	10.70	39.71	62.70	1.30	2.00	18.00
Heavy fuel oil	0.80	1.80	2.90	2.00	0.50	6.00
Nuclear	28.80	22.70	4.14	46.30	37.64	31.70
Waste	1.50	0.44	2.60	0.00	0.00	0.70
Hydro	4.90	1.90	0.17	45.60	23.18	11.10
Wind	2.80	0.32	0.94	0.40	0.00	1.10
Solid biomass	0.10	0.21	1.30	2.50	0.50	0.80
Gaseous biomass	0.60	0.82	0.30	0.20	0.10	0.30
Others	0.00	0.00	0.00	0.10	0.00	0.70
Total (%)	100.00	100.00	100.00	100.00	100.00	100.00

Table 12: GWP and AP indicators for chemo-thermal and one-bath LCO$_2$ disinfection laundering procedures (for 1 kg of laundered textile)

Country	Disinfection laundering procedure			
	Chemo-thermal		One-bath LCO$_2$	
	GWP$_{TGP}$ (g CO$_2$ eq)	AP (g SO$_2$ eq)	GWP$_{TGP}$ (g CO$_2$ eq)	AP (g SO$_2$ eq)
Germany	318.48	0.27	77.47	0.07
UK	366.35	0.95	89.11	0.23
Netherlands	339.39	0.16	82.55	0.04
Sweden	52.58	0.04	12.79	0.01
Slovenia	356.49	4.38	86.71	1.06
EU27	313.95	1.12	76.37	0.27

The results of the chemo-thermal laundering wastewater parameters are shown in Table 7, whereas the results of the LCA and LCI analyses, and the environmental impact assessments for both, the chemo-thermal and one-bath LCO$_2$ procedures, are in Tables 8–12.

The chemo-thermal laundering wastewaters showed a particularly distressing impact on the environment (cf. Table 7). The pre-washing wastewaters were all at the forefront, where the parameters exceeded the limit values for the emissions into water: nitrogen ammonia

ne spremembe. Po prikazanih podatkih je Slovenija pri proizvodnji električne energije nad povprečjem EU27 pri izkoriščanju jedrskega goriva (37,64 %) in vodne energije (23,18 %) ter pod povprečjem pri obnovljivih virih energije z izkoriščanjem vetrne in sončne energije, biomase in bioplina. Prav tako je treba poudariti, da se v objavljenih letnih poročilih [65, 71] že kaže zmanjšanje emisij TGP. Lastnosti struktur konvencionalnih in obnovljivih virov za proizvodnjo električne energije se ustrezno odražajo tudi v potencialih globalnega segrevanja in zakisljevanja, ki ju povzročata primerjana razkuževalna postopka nege tekstilij. Iz preglednice 12 je razvidno, da izvedba kemijsko-termičnega razkuževalnega postopka daje najnižja indeksa GWP_{100} in AP na Švedskem (52,58 g CO$_2$ eq/kg *by 6.62 mg N/l, total phosphorus by 0.5 mg P/l, COD by 200 mg O_2/l, and BOD5 by 239 mg O_2/l. Even the wastewaters of the main washing exceeded the limit values in the cases of temperature by 33.7 and 23.7 °C, respectively, nitrogen ammonia by 1.12 mg N/l and COD by 65 mg O_2/l. The values for the rinsing wastewaters were below the set thresholds, while the neutralisation wastewaters again exceeded the limit concentrations for total phosphorus by 0.1 mg P/l and BOD_5 by 26 mg O_2/l. It can be seen from the results in Table 7 that the values for nitrogen ammonia achieved the highest values for pre-washing wastewaters (11.62 mg/l) and then declined in the main washing by 47.33%, when rinsing by 62.82%, and with neutralisation wastewaters by 73.15%. The same declining trend could be observed in the cases of COD and BOD_5 values in wastewaters: in the main washing waters, the COD values declined by 42.19% and BOD_5 by 51.52%, in the spinning-waters, the COD declined by 82.81% and BOD_5 by 90.53%, while in the neutralisation waters, the reduction was lower (COD by 70.31%, BOD_5 by 80.68%) versus the values of pre-washing wastewaters. The reasons for the enormous excess could be the types and amounts of the used detergents, and the disinfection and neutralisation agents. Based on the results of this study, it can be concluded that the chemo-thermal wastewaters are unsuitable for a direct discharge into rivers or lakes, as well as for a re-use within the laundering procedures without any form of a wastewater treatment.*

The analyses of raw-material and energy flows (cf. Table 8) showed that the chemo-thermal laundering procedure consumed 3,700 kJ of energy, while the one-bath LCO_2 disinfection procedure consumed 75.68% less energy (900 kJ). The chemo-thermal laundering procedure consumed the most energy for heating the laundering bath during the pre-washing (46.5%) and main washing (49.45%) phases, whereas during the rinsing and neutralisation phases, it consumed 3.30% and 1.10% of electrical energy. The major energy consumers were the electrical heaters, while for the electrical motor which rotates the washing drum the pumps for pumping fresh water, the laundering agents, the laundering and neutralisation baths, the microproces-

tekstilij, 0,04 g SO_2 eq/kg tekstilij) ter najvišjega v Sloveniji (356,49 CO_2 eq/kg tekstilij, 4,38 SO_2 eq/kg tekstilij), medtem ko znaša za povprečje EU27 GWP_{100} 313,95 CO_2 eq/kg tekstilij in *AP* 1,12 SO_2 eq/kg tekstilij. Vrednotenje ocen vplivov na okolje kaže, da sta indeksa globalnega segrevanja GWP_{100} in *AP* pri enokopelnem razkuževalnem postopku LCO_2 nege tekstilij štirikrat nižja kot pri klasičnem kemijsko-termičnem.

4 Sklepi

Skorajda ni človekove dejavnosti, pri kateri ne bi nastajale emisije TGP, katerih posledica so podnebne spremembe, ki se odražajo v globalnem dvigu povprečne letne temperature, povečanju povprečne količine padavin, dvigu gladine morja, krčenju ledenikov in rasti števila ekstremnih vremenskih dogodkov. Skrb zbuja dejstvo, da zaradi človekovih dejavnosti naraščajo koncentracije toplogrednih plinov v ozračju veliko hitreje kot po naravni poti [52]. Strategije gospodarskega razvoja in varovanja okolja temeljijo na zamenjavi obstoječih in razvoju novih proizvodnih tehnologij, zamenjavi goriv in surovin ter na trajnostno naravnani proizvodnji in porabi energije [72].

Rezultati opravljene raziskave kemijsko-termičnega postopka nege kažejo, da neprimerna kakovost odpadnih pralnih vod močno obremenjuje okolje. Enak učinek na okolje povzročajo tudi energetske zahteve, saj je potreben dokaj velik vložek električne energije za dosego pralnih in razkuževalnih učinkov, kar se negativno odraža na visokem potencialu globalnega segrevanja in zakisljevanja. Ob bok klasičnemu postopku je postavljen na novo razvit razkuževalni postopek nege bolnišničnih tekstilij, tj. enokopelni postopek LCO_2. S pomočjo metodologije LCA je bilo ugotovljeno, da enokopelni razkuževalni postopek nege tekstilij LCO_2 izpolnjuje okoljska pričakovanja. Doseženi so bili zahtevana redukcija mikroorganizmov, nega brez prisotnosti vode ter bistveno manjša poraba električne energije in pralnega sredstva, kar vse skupaj pripomore k redukciji energije in majhnim okoljskim obremenitvam z emisijami TGP in plinov zakisljevanja.

Kljub doseženemu napredku lahko tehnologijo LCO_2 na področju razkuževanja še vedno razvrstimo med nove tehnologije nege tekstilij. Izboljšanje učinkov odstranjevanja nečistoč [73], razvoj novih pralnih in pomožnih sredstev, robustna strojna oprema, visoki investicijski stroški so samo nekatere izmed pomanjkljivosti, ki zahtevajo nadaljnje raziskave in razvoj ter zavirajo nadomestitev klasičnih mokrih in suhih postopkov z LCO_2 postopki čiščenja in razkuževanja tekstilij.

5 Zahvala

Zahvaljujemo se Evropski uniji za finančno podporo pri izvedbi projekta FP7-SME-2007 222051 „ACCEPT – Advanced CO_2 Cle-

sor unit and the electro valves the consumption was negligible. During the one-bath LCO2 disinfection procedure, 92.36% of electrical energy was consumed for the cooling of CO2 with electrical pumps and ventilators during the decompression phase (61.57%) and during the CO2 recycling phase (30.79%), both following at the end of the cleansing phase. An important contribution to reducing high electricity consumption would undoubtedly be a substitution of the existing cooling system with a water cool-device.

The LCO$_2$ disinfection procedure lasted for about 8 min longer when compared to the chemo-thermal procedure (cf. Tables 2 and 3), which was due to the slow decompression and the CO$_2$ cooling (17 min) to prevent "dry ice". In contrast to the chemo-thermal procedure, where the pre-washing, main washing and spinning phases were equally long (i.e. 11.06 min), the neutralisation phase took half the time and the LCO$_2$ procedure was more dynamic. After the two short phases (2 min), the air-evacuation, compression and heating of CO$_2$ followed a relatively long-lasting laundering phase (25 min), which assured the expected disinfection levels of textiles.

It is also important to emphasise that the LCO$_2$ procedure demanded the usage of only one laundering agent (4 ml/l CO$_2$), while the chemo-thermal procedure required a detergent, builder, tenside, and disinfection and neutralising agents (15.30 ml/kg of textiles).

One important advantage of the one-bath LCO2 procedure is the fact that the treatment was performed without the presence of water, unlike the chemical-thermal disinfection laundry process, which is based on a water bath. Although the study researched the disinfection effect of the water and LCO2 disinfections of textile bioindicators [70], unlike Cinquenami [31], no significant increases were found in the levels of microorganisms; therefore, water was excluded from the LCO$_2$ laundering procedure. The water was also connected to the fact that after the chemo-thermal procedure, the laundered textiles needed to be dried (35% pick-up), which prolonged the treatment time and used up extra energy for the residue water evaporation. In contrast, after the finished LCO$_2$ laun-

aning as an Ecological Process Technology", kakor tudi podjetjem *Chemische Fabrik Kreussler & Co. GmbH* Wiesbaden (Nemčija), *Fred Butler Sweden AB* Lidingö (Švedska) ter *WFK Forschungsinstitut für Reinigungstechnologie* Krefeld (Nemčija).

6 Literatura

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dering procedure, the textile bioindicators were dry to the touch; thus, additional drying was unnecessary.

Previous conclusions relating to water, energy demand and treatment time pointed out the same trend during the analysis of gas emissions caused by investigated disinfection laundering procedures. When comparing the results for GHG emissions with those emissions, causing global warming and acidification (cf. Tables 9 and 10), their diversity and significance could easily be seen among the member states of the ACCEPT research project. The great difference in CO_2 emissions (cf. Table 9) was noticeable as caused by the performance of the chemo-thermal laundering procedure in Sweden (37.56 g CO_2/kg of textiles) and the Netherlands (253.41 g CO_2/kg of textiles), while in the EU27, the average is 195.39 g CO_2/kg of textiles. Slovenia is with 202.80 g CO_2/kg of textiles among the states with the lowest CO_2 emissions, which does not apply to the emissions of NO_2 (140.28 g NO_2/kg of textiles) and CH_4 (13.41 g CH_4/kg of textiles), which are higher than in other states and than the EU27 average (109.10 g NO_2/kg of textiles, 9.47 g CH_4/kg of textiles). This fact also applies to GHG and the emissions of acidification into the environment for the one-bath LCO_2 disinfection laundering procedure (cf. Table 10). Thus, it is important to draw attention to the fact that the GHG emissions are by 75.26% lower for the LCO_2 procedure than the emissions from the chemo-thermal disinfection laundering procedure. These deviations between the same gas emissions in different countries are caused by the quantity of primary sources present for electricity production, which vary from country to country. The structures of primary sources for electricity generation and with them the related gas emissions for a wide-range of countries are integral parts of the LCA JRC ELCD Database II methodology [66]. The data in Table 11 show the evident diversity among the countries regarding their structures of conventional and renewable sources for electricity production. According to the data from the year 2002, the usage of coal during the electricity generation is the lowest in Sweden (1.60%) and the highest in Germany (49.80%), followed by Slovenia with 36.08%.

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The displayed data show that the production of electricity in Slovenia is above the EU27 average when exploiting nuclear fuel and hydropower, and below the EU27 average regarding the renewable energy through wind and solar energy, biomass and biogas. It should also be noted that in the published annual reports [65, 71], the reductions in GHG emissions are shown.

The structures of conventional and renewable sources for electricity production are reflected in the GWP and AP indicators caused by comparing the disinfection laundering procedures of textiles. Table 12 shows that the chemo-thermal disinfection procedures performed in different countries give the lowest GWP_{100} and AP indicators in Sweden (52.58 g CO_2 eq/kg of textiles, 0.04 g SO_2 eq/kg of textiles) and the highest in Slovenia (356.49 CO_2 eq/kg of textiles, 4.38 SO_2 eq/kg of textiles), while the EU27 average for GWP_{100} is 313.95 CO_2 eq/kg of textiles and for AP 1.12 SO_2 eq/kg of textiles. The environmental impact assessment reflects the fact that the GWP_{100} and AP indicators for the one-bath LCO_2 disinfection laundering procedure are four times lower compared to the classical chemo-thermal procedure.

4 Conclusions

There is almost no human activity which does not create emissions of GHG, which result in the climate changes, reflecting in the rise of average global temperatures, increase in the average amount of precipitation, sea level rises, shrinking glaciers and occurrences of extreme weather events. The fact causing the most concern is that the concentrations of GHG in the air, caused by human activities, are increasing much faster than in a natural way [52]. The development of economic and environmental protection is based on the replacement of existing products and by developing new technologies on the exchange of fuels and raw materials, regarding a sustainable production and energy consumption [72].

The results from this study show that inadequate qualities of laundering wastewaters greatly burden the environment. The same effects on the environment are caused by their en-

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ergy requirements. The required cleaning and disinfection effects need a high input of electrical energy, which is negatively reflected in high global warming and acidification potential factors. Alongside the classical procedure, there is a newly developed one-bath LCO$_2$ disinfection laundering procedure for hospital textiles. In this paper, with the help of LCA, it was established that the one-bath LCO$_2$ procedure meets the environmental expectations. The required reductions in microorganisms, treatment without the presence of water, and important lower amounts of consumed electricity and the laundering agent were achieved, all of which contribute to a reduction in energy and low environmental impacts, with low emissions of GHG and acidification gases.

Despite the achieved progress, the LCO$_2$ technology could in the field of disinfection be classified among new textile care technologies. However, the cleansing efficiency improvement [73], the development of new detergents and additives, robust equipment and high investment costs are just some of the faults that require further research and development and obstruct the substitution of classical dry and wet procedures with the LCO$_2$ cleansing and disinfection procedures for textiles.

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