Life cycle assessment of simultaneous pyrethroid extraction in soil matrices: A comparative study with QuEChERS method

Miranti Ariyani1*, Mariska Margaret Pitoi1, Ajeng Arum Sari1, Retno Yusiasih1, Tiny Agustini Koesmawati1 and Sunardi2,3

1 Research Unit for Clean Technology, National Research and Innovation Agency, Jl. Cisitu, Sangkuriang, Bandung, West Java 40135 Indonesia
2 Department of Biology, Faculty of Mathematic and Natural Sciences, Universitas Padjadjaran, Jl. Raya Bandung-Sumedang Km. 21, Jatinangor, Sumedang 45363, Indonesia
3 Graduate Programme on Environmental Studies, Postgraduate School, Universitas Padjadjaran, Jl. Dipati Ukur No. 35, Bandung 40132, Indonesia

*E-mail: miranti.ariyani@gmail.com

Abstract. The gate-to-gate system boundary was employed to determine the greenness of sample preparation methods for simultaneous pyrethroids analysis using life cycle assessment (LCA). The LCA of an established QuEChERS method was assessed and compared to the proposed modified QuEChERS method. A comparative LCA was carried out with a functional unit defined as the amount of pyrethroid recovered (80-110%) from a 5 g soil. The life cycle inventory and life cycle impact assessment (LCIA) were performed on Open LCA 1.10.3 software. The inventory analysis shows that the amount of equipment, material, and energy input were greater in the proposed modified QuEChERS method than the established QuEChERS method, except for chemicals used. The life cycle assessment impact shows that among the nine impact parameters generated, the established QuEChERS method was more environmentally benign than the proposed modified QuEChERS method. However, in term of carcinogenic toxicity impact on humans, the proposed modified QuEChERS method outperformed the established QuEChERS method. This study confirmed the contribution of life cycle assessment to assess the environmental impact for the analytical procedure.

Keywords: Life cycle assessment; pyrethroid; soil; ultrasound-assisted extraction

1. Introduction
The green extraction for contaminant isolation, particularly for emerging contaminants, from environmental matrices has been widely applied since the sample treatment and extraction process was the most pollution source in analytical procedures. The high amount used of organic solvent and energy required during the extraction process, along with the high-risk consequences to both humans and the environment, are the basic idea how green extraction process was emerge [1].

Several extraction processes based on green analytical chemistry for pyrethroids analysis in soil matrix have been proposed [2–4]. The application of ultrasonic-assisted extraction for pyrethroids extraction from soil has been successfully applied either in conventional methods [5,6] or newly developed method based on green analytical chemistry through miniaturization and QuEChERS
methods [3,7,8]. Compared to the Soxhlet application, the introduced green extraction methods, ultrasonic-assisted extraction has reduced the environmental impact through sample miniaturization and less solvent used [2], [9], [10], [11].

Pyrethroids are well recognized as a substitute pest control agent in agriculture for organophosphate pesticides due to their higher effectiveness and shorter half-life than other classes of pesticides [12,13]. Furthermore, due to their higher affinity for organic carbon and clay in the soil, pyrethroids persist longer [2,12]. However, nowadays, pyrethroids has been proven was found in the surface water and bioaccumulated in the aquatic organism and humans [8,13].

However, the evaluation of the application of green analytical method impact to the environment is limited. The evaluation of how more environmentally benign the analytical method has been performed using NEMI (national environmental methods index) which evaluated four key terms including nature of reagents, hazardous nature of processes and product, corrosiveness, and waste generated [1]. Another instrument was penalty point and eco-scale concept [14], and the most recent one is GAPI (green analytical procedure index) which developed based on NEMI and analytical eco-scale [15]. However, these tools are primarily qualitative and semi-quantitative. Therefore, the utilization of life cycle assessment as a holistic tool to assessed environmental changes and impact during all stages of a defined analytical method is required.

Life cycle assessment has been widely used for assessed the sustainability used of product, material, and technologies [16] which consist of goal and scope, inventory analysis, impact assessment, and interpretation [17]. The LCA has largely been applied for evaluating bio-based materials as well as the process such as bioplastics [18], biofuels [19], hybrid glass fibre composite [20], nanomaterials [21], and sustainable processes such as green extraction of bio-active compounds [22], green dyeing process [23], and wastewater treatment [24,25]. However, the application of LCA in terms of process, particularly in the green analytical chemistry process, is limited. Most of it was partial since it was considered time-consuming and complicated [26]. The application of LCA in analytical chemistry has been performed for green solvent selection during the process design [27–29] and more comprehensive for evaluating the environmental impacts of the ultrasound-assisted extraction application in the valorisation of industrial food by-products [30].

However, to the best of our knowledge the application of life cycle assessment in green extraction process is limited [30], moreover the application of life cycle assessment in pesticide extraction process based on the green analytical chemistry principle compared to the established QuEChERS method is not available. QuEChERS or the quick, easy, cheap, effective, rugged and safe is one of the extraction processes claimed as the greenest methodology as an alternative to the traditional extraction method [31]. In the present study, the life cycle assessment of a developed extraction method or modified QuEChERS [8] was assessed and compared to the European standard extraction method [7]. In this study, the modified QuEChERS from previous research [8] was validated and has been proven suitable for pyrethroid analysis in soil matrix. Similarly, the QuEChERS extraction procedure established from the European method EN15662 2008 [7] was claimed as a suitable method for pyrethroid extraction in the soil.

This study aimed to evaluate the life cycle of the proposed modified QuEChERS method and established QuEChERS methods. In this study, (i) the inventory analysis of input and output for each method was performed, (ii) the environmental impact for each method was assessed, and (iii) the environmental impact of each method generated was compared and interpreted. This study confirmed the contribution of life cycle assessment to assess how green the extraction process as it claimed on green analytical chemistry principle.

2. Material and Methods

2.1. Pyrethroid extraction

The proposed method for pyrethroid extraction in this study was previously explained in detail [8]. Briefly, five pyrethroids were extracted from the soil using the ultrasonic-assisted extraction method. A
0.1 µg.g⁻¹ mixed standard solution consists of lambda-cyhalothrin, permethrin, cypermethrin, fenvalerate, and deltamethrin in n-hexane, was added into the centrifuge tube (50 mL) contained 5 g soil (wet weight). The sample was vortexed for 1 minute, and 20 mL n-hexane was added into the soil sample. Extraction was performed for 30 minutes in an ultrasonic bath (Branson 3510) and centrifuged at 4000 rpm for 5 minutes. Extraction was performed twice, therefore total duration time for ultrasonic was 60 minutes. After the supernatant was separated, a 1-mL aliquot was subjected to clean up using a small piece of glass wool and anhydrous sodium sulfate to remove the water before injecting it into the GC-ECD column.

Globally, the conventional extraction process for pyrethroid was referred to QuEChERS method from the European (EN15662 2008) [7]. The soil (5 g) consists of 0.2 µg.g⁻¹ mixed pyrethroids standard in acetonitrile was weighed into a Teflon tube (50 mL), and 10 mL of acetonitrile was added. The sample was vortexed for 1 minute and sonicated for 10 minutes in a 195-W ultrasonic bath (J.P. Selecta). The QuEChERS buffer-salt mixture was added, then shake vigorously using vortex for 1 minute, following by sonicated at 10 minutes for separation. The sample was then centrifuged at 4000 rpm for 10 minutes. 1.5 mL aliquot was sampled, vortexed, and centrifuged at 4000 rpm for 1 minute and 10 minutes, respectively. A 0.7-mL aliquot was then drying and resuspended using 0.7 mL of n-hexane before analyzed using GC-ECD.

2.2. Life cycle assessment
2.2.1. Goal and scope definition
The gate-to-gate LCA system boundary focused on the extraction step was performed in this study (see Figure 1). In this study, only the extraction and clean-up method related to the recovery pyrethroid was involved in the analysis. The rest step, such as evaporation of the solvents, was excluded from the assessment due to the information limitation.

The functional unit (FU) was defined as the amount of pyrethroid recovered (80-110%) from the 5 g soil. The recovery of 0.1 µg.g⁻¹ and 0.2 µg.g⁻¹ of pyrethroids from the soil were chosen for modified QuEChERS and established QuEChERS method, respectively. This value was chosen based on recoveries value obtained for five pyrethroids extracted which was in the range 80-100% based on AOAC (Association of Official Analytical Chemists International) [32]. The estimation of recovery for each method was previously explained in detail [7,8].

2.2.2. Life cycle inventory analysis
The inventory data analysis was performed using data obtained from experimental data and databases. Generic data from Ecoinvent 7.3, ELCD 3.2, NEEDS, and EXIOBASE, embodied in Open LCA 1.10.3 software, were used in this study [33]. The input for LCI in this study was extraction equipment, material, and energy consumption during extraction. The description of LCI for each item is given below.

2.2.2.1. Extraction equipment
As an input, the mass and type of each piece of equipment was weighed using the data from the supplier. In the case of ultrasonic bath, each type of materials used in the equipment, such as stainless steel, polypropylene, and electric cables, was included and assessed their wastes. However, due to the data limitation, only the mass of ultrasonic bath body and its accessories (cover, tray, baskets, and electric cables) which were written on the manual book assessed in this study.

Furthermore, the specification of the other equipment used in both extraction processes, such as centrifuge and vortex, were assuming similar thus excluded from this assessment. The estimation of mass for each piece of equipment was quantified using allocated mass equipment considering the total mass equipment, extraction duration, equipment lifetime, and mean daily usage duration of each equipment [30].
2.2.2.2. Materials
In this stage, the material used for the extraction, including chemicals and consumables, was used as an input for the assessment. The amount and volume of chemicals (standard, solvent, etc) were quantified, meanwhile before weighed; each consumable was characterized based on their material. All materials included as an input for modified QuEChERS and established QuEChERS method are listed in Table 1. The soil matrices were excluded from the assessment since only a tiny amount of sample was used.

Table 1. Life cycle inventory for pyrethroid extraction input.

| Input               | Modified QuEChERS | Standard QuEChERS |
|---------------------|-------------------|-------------------|
| **Equipment (kg)**  |                   |                   |
| Allocated mass for ultrasonic bath (Branson 3510) | 1.3E-04 | |
| Allocated mass for ultrasonic bath (195-W) | 6.8E-05 | |
| **Chemicals Materials (kg)** |                   |                   |
| n hexane            | 0.026             | 0.005             |
| Fenvalerate         | 1E-04             | 1E-04             |
| Deltamethrin        | 1E-04             | 1E-04             |
| Lambda cyhalothrin  | 1E-04             | 1E-04             |
| Cypermethrin        | 1E-04             | 1E-04             |
| Permethrin          | 1E-04             | 1E-04             |
| Anhydrous sodium sulphate (Na2SO4) | 5E-04 | |
| Glass wool          | 5E-05             |                   |
| Magnesium sulphate (MgSO4) | 0.004 | |
| Acetonitrile        | 0.008             |                   |
| Natrium chloride (NaCl) | 0.001 | |
| Sodium hydrogenocitrate sesquihdrate (C6H8Na2O8) | 5E-04 | |
| Sodium citrate (Na3C6H5O7) | 0.001 | |
| Primary Secondary Amine (PSA) | 1.5E-04 | |
| Magnesium sulphate (MgSO4) | 1.5E-04 | |
| Bonded Silica C18   |                   | 0.018             |
| **Consumable Materials (kg)** |                   |                   |
| Centrifuge tube 50 mL | 0.013             | 0.018             |
| Glass vial 2 mL     | 0.003             | 0.002             |
| Syringe filter      | 8.9E-04           |                   |
| Syringe             | 0.005             |                   |
| Glass pippete       | 0.003             |                   |
| **Energy consumption** |                 |                   |
| Electricity consumption (kWh) | 0.414             | 0.186             |
2.2.2.3. Energy consumption during extraction process
In this study the energy used for transporting the material from the supplier to the laboratory where the extraction was performed, was excluded. Although the supplier for each chemical and material was written, the limited information regarding the exact location of the supplier (local or overseas) will bias the result.

The electricity consumption for each equipment was quantified using electricity specification written on manual book for each equipment and calculated based on the duration used for each equipment. The duration for each piece of equipment used in the extraction process was previously explained on the pyrethroid extraction section above. The ratio of electricity source was adjusted for each country. In this study, the mix electricity data generated from Ministry of Energy and Mineral Resources was used for Indonesia (coal 56%, natural gas 22%, oil 9%, hydropower 8%, thermal 5%, and insignificant amount of other renewable energies) meanwhile the Portugal electricity (hydropower 13%, windpower 20%, thermal power 65%, and other 2%) was used for established QuEChERS method. The ratio amount of electricity used then converted to CO2 emission for an output.

2.2.3. Life cycle impact assessment
Life cycle impact assessment was performed using Recipe (Midpoint and Endpoint) and ILCD 2011 embedded in Open LCA software. The eighteen environmental impacts which were covers by Recipe was assessed including fine particulate matter formation, fossil resource scarcity, freshwater ecotoxicity, freshwater eutrophication, global warming, human carcinogenic toxicity, human non carcinogenic toxicity, ionizing radiation, land use, marine ecotoxicity, marine eutrophication, mineral resource scarcity, ozone formation (human health and terrestrial ecosystem), stratospheric ozone depletion, terrestrial acidification, terrestrial ecotoxicity, and water consumption. The ILCD 2011 was employed to determine the impact of each method employed on mineral fossil and renewable resources depletion, which does not cover in Recipe.

3. Results and Discussion
In this study, the life cycle assessment was performed using gate-to-gate system boundary, where the assessment was focussing on the extraction process in the laboratory (see Figure 1). Based on the previous study using the standard QuEChERS method [7], the pyrethroid was extracted as much as 80-100% from the soil matrices as well as in our modified QuEChERS method. However, the number of equipment, materials, and energy consumption used by each method during the extraction process was different, thus generated different impacts on the environment.

The extraction process is known as the laborious step since it involves large amount of energy besides organic solvents, and consumables. Energy is the main aspect of the green extraction process particularly in using the ultrasounds since the main concern of this process is reducing the extraction time by providing an efficient extraction process using ultrasonic energy [1,31]. In this study, the impact of energy consumption to the environment was assessed from the number of kg CO2 generated. The number of kg CO2 emission due to electricity used generated from our modified method was higher three order magnitude than that used by the established QuEChERS method (see Table 3). The differences of CO2 emission generated from both methods depends on the type of energy used for electricity. The dominant energy source for electricity used was green energy in Portugal, contributing to the lower amount of kg CO2 emission due to the extraction process. Almost all the energy sources for electricity used in Portugal came from renewable resources; meanwhile, nearly 87% of the energy source in Indonesia was classified as fossil fuel and dominated by coal (56%).

From the material perspective, the analysis shows that polypropylene, steel, wire coating, glass, polyethylene, tetrafluoroethylene, and rubber were the potential waste generated from the equipment and consumables used in the extraction process (see Table 2). Based on the mass generated, the wire coating was the output that has the most significant mass, followed by plastic (polypropylene, polyethylene), glass, tetrafluoroethylene, steel, and rubber. These wastes have various impacts to the environment according to their end-of-life.
Wire coating is classified as waste electrical and electronic equipment (WEEE). Most of the end-of-life treatment of this e-waste is incineration and landfilling, associated with the various potential risks [34]. Inadequate disposal of this waste will contribute to the harmful impacts on the environment and pose a risk to human and other organisms due to the presence of various substances such as heavy metals and halogenated compounds, and other potentially harmful substances as constituents of this electrical equipment [34,35].

In addition to the electrical and electronic equipment waste, the utilization of disposable consumables such as the single-use plastic is the main concern in evaluating the sustainability of the analytical methodologies proposed from the environmental perspective. The reduction of the disposable material is one of the main concerns which has been proposed to drastically reduce the laboratory waste as well as an environmental risk during the extraction process. Polypropylene and polyethylene are classified into single-use plastics [36]. Plastic disposal through landfilling will generate various environmental impacts particularly long-term impact since plastic has been proven to degrade slowly and potential to be fragmented into small pieces called microplastic [37,38]. Several studies show that microplastics have caused negative impacts on the ecological system and human health through the ingestion of contaminated food [39,40]. Moreover, the chemicals embedded in microplastics such as additives and chemicals absorbed from the surrounding ambience will raise the hazard potential risk. Like the electronic and plastic waste, the inadequate end-of-life of other wastes generated from the extraction process such as rubber, steel, and glass will also cause adverse effect to the environment [41,42].

Besides single-use consumables, solvent is the main concern in developing the green extraction process [1]. The utilization of chemicals in the extraction process will generate the amount of waste to the environment and might be dangerous to human, aquatic, and terrestrial organisms. Compared to the established QuEChERS method, the modified QuEChERS method used less amount and type of chemicals, all classified as Group 3, not classifiable as to carcinogenicity to human [43]. The established QuEChERS method uses various types of chemicals that are mostly classified as irritant and non-carcinogenic chemicals. In addition to that point, permethrin is the one and only chemical used in both studies which known carcinogenic to human even though the study result is still inconsistent [44].
Table 2. Life cycle inventory for pyrethroid extraction output (in kilogram).

| Input                      | Modified QuEChERS | Standard QuEChERS |
|----------------------------|-------------------|-------------------|
| **Equipment**              |                   |                   |
| Polypropylene waste        | 0.003             |                   |
| Steel waste                | 3.2E-04           | 6.78E-5           |
| Wire coating waste         | 0.1873            |                   |
| **Chemicals**              |                   |                   |
| n hexane                   | 0.026             | 0.005             |
| Fenvalerate                | 1E-04             | 1E-04             |
| Deltamethrin               | 1E-04             | 1E-04             |
| Lambda cyhalothrin         | 1E-04             | 1E-04             |
| Cypermethrin               | 1E-04             | 1E-04             |
| Permethrin                 | 1E-04             | 1E-04             |
| Anhydrous sodium sulphate (Na2SO4) | 5E-04       |                   |
| Glass waste                | 5E-05             |                   |
| Acetonitrile               |                   | 0.008             |
| Magnesium sulphate (MgSO4) |                   | 0.004             |
| Sodium chloride (NaCl)     |                   | 0.001             |
| Sodium hydrogenocitrate sesquihdrate (C6H8Na2O8) | 5E-04       |                   |
| Sodium citrate (Na3C6H5O7) |                   | 0.001             |
| Primary Secondary Amine (PSA) | 1.5E-04       |                   |
| Silicon dioxide            |                   | 5E-05             |
| **Consumable materials**   |                   |                   |
| Polyethylene waste         | 0.003             |                   |
| Tetrafluoroethylene waste  | 0.001             |                   |
| Rubber waste               | 6E-04             |                   |
| Glass waste                | 0.005             |                   |
| Glass                      | 0.002             |                   |
| Tetrafluoroethylene        | 0.018             |                   |
| **Energy consumption**     |                   |                   |
| CO₂ from electricity       | 0.1087            | 0.0067            |

The combination impact of the improper handle of solid waste and chemicals generated along with the generous amount of energy consumption from both extraction processes will give an impact to the environment in a different way. In this study, the environmental impact was assessed using Recipe employed in life cycle assessment [45]. Among the eighteen environmental impacts covered by Recipe, only 10 types of impact were generated from equipment, materials, and energy consumption used consist of seven types for midpoint impact and three types of endpoint impact (see table 3).
Table 3. Comparison of LCIA for each pyrethroid extraction method.

| Type of Impact                              | Unit             | Modified QuEChERS | Standard QuEChERS | Method     |
|---------------------------------------------|------------------|-------------------|-------------------|------------|
| Global warming                              | kg CO₂ eq        | 1.09E-01          | 6.66E-03          | Recipe     |
| Global warming – freshwater ecosystem       | Species.yr       | 8.32E-15          | 5.09E-16          | Recipe     |
| Global warming – human health               | Species.yr       | 1.01E-07          | 6.18E-09          | Recipe     |
| Global warming – terrestrial ecosystem      | Species.yr       | 3.04E-10          | 1.86E-11          | Recipe     |
| Freshwater ecotoxicity                      | kg 1.4-DCB       | 1.73E+01          | 1.73E+01          | Recipe     |
| Human toxicity (carcinogenic)               | kg 1.4-DCB       | 2.65E-03          | 4.02E-02          | Recipe     |
| Human toxicity (non-carcinogenic)           | kg 1.4-DCB       | 6.72E-02          | 4.17E-02          | Recipe     |
| Terrestrial ecotoxicity                     | kg 1.4-DCB       | 3.03201           | 3.03441           | Recipe     |
| Marine toxicity                             | kg 1.4-DCB       | 2.83884           | 2.3883            | Recipe     |
| Mineral, fossil & renewable resource depletion | kg Sb eq       | 4.96E-09          | -                 | ILCD 2011  |

Using the Recipe endpoint method, each impact of global warming to human health, freshwater ecosystem, and terrestrial ecosystem was interpreted. The effect of global warming from both methods' extraction process was highest on human health, followed by impact on terrestrial and freshwater ecosystems. The impact of global warming due to the emission of CO₂, especially to human health, is various. Loss of the species due to the temperature increase was one of the causes that linked global warming and the freshwater and terrestrial ecosystem disruption. In this study, due to the higher electricity consumption during the extraction process, our modified QuEChERS method was contributed higher to global warming than the former method.

Meanwhile from material and chemicals used perspective, the number of raw materials from equipment used in our modified QuEChERS method was more various than the former method consists of polypropylene, steel, and wire coating, glass, polyethylene, tetrafluoroethylene, and rubber. Otherwise, the number of chemicals used was less. The types and amount of equipment such as ultrasonic baths and consumables used for each method will generate the different types of waste according to the various type of raw materials used to build the equipment. Our life cycle impact assessment shows that from human toxicity perspective, the potential carcinogenic impact due to the chemicals used in the established QuEChERS method was higher but lower for non-carcinogenic impact compared to our modified QuEChERS method. Finally, this work demonstrated how the life cycle assessment was applicable to use as an instrument to define which one was the greenest methods among two or more analytical methods.
4. Conclusion
This study contributes to an investigation on the life cycle assessment applications to determine the greenness of green analytical extraction proposed. A comparative LCA between a different green extraction process shows that the utilization of equipment, materials, and energy by former method was more environmentally friendly than our modified QuEChERS method based on global warming, toxicity, and a resource depletion impact parameter. However, based on carcinogenic toxicity impact on humans, the latter method was safer than the former.

Acknowledgment
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors wish to thank E-Layanan Sains, The National Research and Innovation Agency for their technical support.

References
[1] Armenta S, Garrigues S, Esteve-Turrillas F A and de la Guardia M 2019 Green extraction techniques in green analytical chemistry TrAC Trends Anal. Chem. 116 248–53
[2] Albaseer S S, Rao R N, Swamy Y V and Mukkanti K 2010 An overview of sample preparation and extraction of synthetic pyrethroids from water, sediment and soil J. Chromatogr. A 1217 5537–54
[3] Rafique N, Tariq S R and Ahmed D 2016 Monitoring and distribution patterns of pesticide residues in soil from cotton/wheat fields of Pakistan Environ. Monit. Assess. 188 1–12
[4] Aznar R, Moreno-Ramón H, Albero B, Sánchez-Brunete C and Tadeo J L 2017 Spatio-temporal distribution of pyrethroids in soil in Mediterranean paddy fields J. Soils Sediments 17 1503–13
[5] Lyytikäinen M, Kukkonen J V K and Lydy M J 2003 Analysis of pesticides in water and sediment under different storage conditions using gas chromatography Arch. Environ. Contam. Toxicol. 44 437–44
[6] Ali M A and Baugh P J 2003 Pyrethroid soil extraction, properties of mixed solvents and time profiles using GC/MS-NICI analysis Intern. J. Environ. Anal. Chem. 83 909–22
[7] Bragança I, Lemos P C, Delerue-Matos C and Domingues V F 2019 Assessment of pyrethroid pesticides in topsoils in northern Portugal Water, Air, Soil Pollut. 230 1–10
[8] Ariyani M, Pitoi M M, Koesmawati T A, Maulana H, Endah E S and Yusiasih R 2020 Pyrethroid residues on tropical soil of an Indonesian tea plantation: analytical method development, monitoring, and risk assessment Sustain. Environ. Res.
[9] Pico Y 2013 Ultrasound-assisted extraction for food and environmental samples TrAC Trends Anal. Chem. 43 84–99
[10] Tobiszewski M and Namieśnik J 2017 Greener organic solvents in analytical chemistry Curr. Opin. Green Sustain. Chem. 5 1–4
[11] Bishnu A, Chakrabarti K, Chakraborty A and Saha T 2009 Pesticide residue level in tea ecosystems of Hill and Dooars regions of West Bengal, India Environ. Monit. Assess. 149 457–64
[12] Oros D R and Werner I 2005 Pyrethroid insecticides: an analysis of use patterns, distributions, potential toxicity and fate in the Sacramento-San Joaquin Delta and Central Valley (Citeseer)
[13] Aznar-Alemany Ò and Eljarrat E 2020 Introduction to pyrethroid insecticides: chemical structures, properties, mode of action and use Pyrethroid Insectic. 1–16
[14] Galusza A, Migaszewski Z M, Koniczka P and Namieśnik J 2012 Analytical Eco-Scale for assessing the greenness of analytical procedures TrAC Trends Anal. Chem. 37 61–72
[15] Płotka-Wasylka J 2018 A new tool for the evaluation of the analytical procedure: Green Analytical Procedure Index Talanta 181 204–9
[16] Heijungs R, Huppes G and Guinée J B 2010 Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life
cycle analysis *Polym. Degrad. Stab.* **95** 422–8

[17] Hauschild M Z 2018 Introduction to LCA methodology *Life Cycle Assessment* (Springer) pp 59–66

[18] Pawelzik P, Carus M, Hotchkiss J, Narayan R, Selke S, Wellisch M, Weiss M, Wicke B and Patel M K 2013 Critical aspects in the life cycle assessment (LCA) of bio-based materials—Reviewing methodologies and deriving recommendations *Resour. Conserv. Recycl.* **73** 211–28

[19] Hjuler S V and Hansen S B 2018 LCA of biofuels and biomaterials *Life cycle assessment* (Springer) pp 755–82

[20] La Rosa A D, Cozzo G, Latteri A, Recca A, Björklund A, PARRINELLO E and Cicala G 2013 Life cycle assessment of a novel hybrid glass-hemp/thermoset composite *J. Clean. Prod.* **44** 69–76

[21] Miseljic M and Olsen S I 2018 LCA of Nanomaterials *Life Cycle Assessment* (Springer) pp 817–33

[22] Kyriakopoulou K, Papadaki S and Krokitas M 2015 Life cycle analysis of β-carotene extraction techniques *J. Food Eng.* **167** 51–8

[23] Agnhage T, Peruwelz A and Behary N 2017 Towards sustainable Rubia tinctorum L. dyeing of woven fabric: how life cycle assessment can contribute *J. Clean. Prod.* **141** 1221–30

[24] Corominas L, Byrne D, Guest J S, Hospido A, Roux P, Shaw A and Short M D 2020 The application of life cycle assessment (LCA) to wastewater treatment: A best practice guide and critical review *Water Res.* **116058**

[25] Larsen H F 2018 LCA of wastewater treatment *Life Cycle Assessment* (Springer) pp 861–86

[26] Tufvesson L M, Tufvesson P, Woodley J M and Börjesson P 2013 Life cycle assessment in green chemistry: overview of key parameters and methodological concerns *Int. J. Life Cycle Assess.* **18** 431–44

[27] Capello C, Fischer U and Hungerbühler K 2007 What is a green solvent? A comprehensive framework for the environmental assessment of solvents *Green Chem.* **9** 927–34

[28] Capello C, Wernet G, Sutter J, Hellweg S and Hungerbühler K 2009 A comprehensive environmental assessment of petrochemical solvent production *Int. J. Life Cycle Assess.* **14** 467–79

[29] Amelio A, Genduso G, Vreysen S, Luis P and Van der Bruggen B 2014 Guidelines based on life cycle assessment for solvent selection during the process design and evaluation of treatment alternatives *Green Chem.* **16** 3045–63

[30] Vauchel P, Colli C, Pradal D, Philippot M, Decossier S, Dhubester P and Dimitrov K 2018 Comparative LCA of ultrasound-assisted extraction of polyphenols from chicory grounds under different operational conditions *J. Clean. Prod.* **196** 1116–23

[31] Armenta S, Garrigues S and de la Guardia M 2015 The role of green extraction techniques in Green Analytical Chemistry *TrAC Trends Anal. Chem.* **71** 2–8

[32] Van Der Grift B, Broers H P, Berendrecht W L, Rozemeijer J C, Osté L A and Griffioen J 2015 High-frequency monitoring reveals nutrient sources and transport processes in an agriculturedominated lowland water system *Hydrol. Earth Syst. Sci. Discuss.* **12** 8337–80

[33] Delta G 2020 OpenLCA

[34] Sepúlveda A, Schluep M, Renaud F G, Streicher M, Kuehr R, Hagelüken C and Gerecke A C 2010 A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: Examples from China and India *Environ. Impact Assess. Rev.* **30** 28–41

[35] Tsydenova O and Bengtsson M 2011 Chemical hazards associated with treatment of waste electrical and electronic equipment *Waste Manag.* **31** 45–58

[36] Chen Y, Awasthi A K, Wei F, Tan Q and Li J 2020 Single-use plastics: Production, usage, disposal, and adverse impacts *Sci. Total Environ.* **141772**

[37] Rillig M C 2012 Microplastic in terrestrial ecosystems and the soil?

[38] Schöpel B and Stamminger R 2019 A comprehensive literature study on microfibres from
washing machines *Tenside Surfactants Deterg.* **56** 94–104

[39] Markic A, Niemand C, Bridson J H, Mazouni-Gaertner N, Gaertner J-C, Eriksen M and Bowen M 2018 Double trouble in the South Pacific subtropical gyre: Increased plastic ingestion by fish in the oceanic accumulation zone *Mar. Pollut. Bull.* **136** 547–64

[40] Campanale C, Massarelli C, Savino I, Locaputo V and Uricchio V F 2020 A detailed review study on potential effects of microplastics and additives of concern on human health *Int. J. Environ. Res. Public Health* **17** 1212

[41] Sagar M, Nibedita K, Manohar N, Kumar K R, Suchismita S, Pradnyesh A, Reddy A B, Sadiku E R, Gupta U N and Lachit P 2018 A potential utilization of end-of-life tyres as recycled carbon black in EPDM rubber *Waste Manag.* **74** 110–22

[42] Butler J H and Hooper P D 2019 Glass waste *Waste* (Elsevier) pp 307–22

[43] Organization W H 2010 *WHO Recommended Classification of Pesticides by Hazard and Guidelines to Classification 2009* (World Health Organization)

[44] Boffetta P and Desai V 2018 Exposure to permethrin and cancer risk: a systematic review *Crit. Rev. Toxicol.* **48** 433–42

[45] Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J and Van Zelm R 2009 ReCiPe 2008 *A life cycle impact Assess. method which comprises Harmon. Categ. Indic. midpoint endpoint Lev.* **1** 1–126