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Diagnosing the environmental impacts of typical fatliquors in leather manufacture from life cycle assessment perspective

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Abstract

The environmental impacts of typical fatliquors were diagnosed by the life cycle assessment of industrial production and use (post-tanning) processes. Life cycle impact assessment and sensitivity analysis showed that fatliquor and fatliquoring operation were the major contributors to the environmental impacts of post-tanning because a large amount of fatliquors was consumed during fatliquoring operation. The environmental impacts of fatliquors decreased in the following order: chlorinated paraffin (CP) > sulfonated rape oil (SNR) > sulfated rape oil (SR) > phosphated rape oil (PR) > oxidized–sulfited rape oil (OSR). Sulfuric acid, fuming sulfuric acid, and chlorine used for fatliquor modification gave the main contribution to most impact categories for SR, SNR, and CP production, whereas rape oil contributed the most for PR and OSR production. OSR use process reduced the primary energy demand, abiotic depletion potential, and global warming potential by 38.5%, 56.0%, and 48.5%, respectively, compared with CP use process. These results suggested that biomass-derived fatliquors, especially oxidized–sulfited and phosphate modified fatiliquors, helped reduce the environmental burdens in leather manufacturing.

Keywords: Fatliquor, Life cycle assessment, Natural fatliquor, Synthetic fatliquor, Modification, Environmental impact

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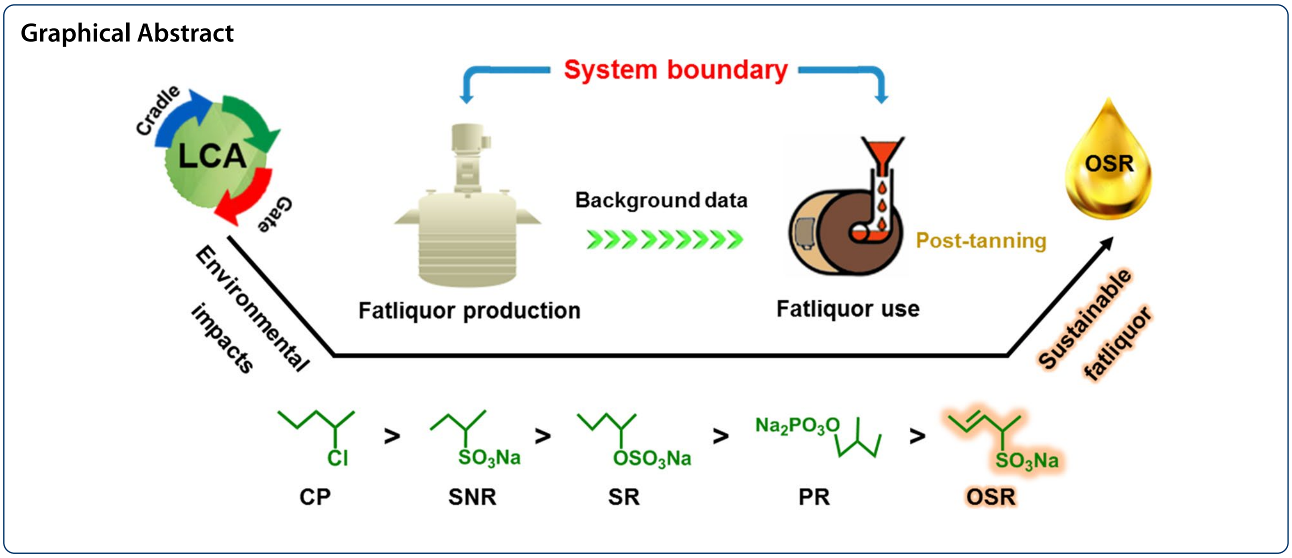

1 Introduction

Fatliquors are essential chemicals for leather processing because they can act as a lubricant to prevent collagen fibers from bonding, and they impart leather with softness, fullness, and extensibility [1, 2]. The commonly used fatliquors primarily include natural fatliquors derived from vegetable oils and animal fats and synthetic fatliquors derived from petrochemicals [3, 4]. Among them, chemically modified natural oils and fats are the most popular ones due to their good hydrophilicity. Mainstream modification methods for fatliquors include sulfation, sulfonation, oxidation–sulfitation, and phosphorylation [5]. Modified natural fatliquors were regarded as more environment friendly than synthetic fatliquors because of the former's renewable and abundant sources [6]. Fatliquors with high biodegradability were also considered to have low environmental impact [7, 8]. However, environmental impact assessment involves the effects of chemicals, energy input, and waste output on resource consumption, climate change, ecosystem quality, and human health [9]. Obviously, existing evaluation methods focusing on the biodegradability of fatliquors would result in one-sided conclusions. A comprehensive environmental impact assessment for fatliquors is needed to provide guidance for their product and process design for future leather manufacture.

Life cycle assessment (LCA) is a decision-making tool for evaluating and quantifying the environmental impact of targeted products, activities, or processing during its life cycle stage [10, 11]. This methodology is extensively used to compare the total environmental performance and diagnose the environmental hotspots (i.e., the main contributor to environmental burdens) in energy [11], building [10], food [12], packing [13], and chemical industry [14] fields. In the leather industry, LCA is increasingly being applied to evaluate the environmental impacts for the entire leather processing (adopt a "cradle to grave" approach) [15], a certain stage (beamhouse, tanning, and post-tanning) [16–18], a single operation (e.g., unhairing and deliming) [19, 20], and even leather chemicals (e.g. detergents and nano-hydroxyapatite; adopt a "cradle to gate" approach) [21, 22]. Tasca and Puccini [18] applied LCA to evaluate the environmental impacts of leather fatliquors, such as epoxidized vegetable oil and sulpho chloro paraffin. The production parameters of the two fatliquors were obtained from literatures and a production plant located in India, and the environmental impacts of fatliquors' production on climate change, freshwater eutrophication, and human toxicity were evaluated. Then, these LCIA results were used as the background data for the LCA of fatliquors' use processes. Nevertheless, to the authors' knowledge, no other studies have applied LCA to diagnose the environmental impact of various fatliquors except for the work of Tasca and Puccini [18] because background data on fatliquors cannot be obtained from literature or databases. Undoubtedly, this fact hinders further understanding of the environmental impacts of fatliquor sources and modification methods and undermines efforts to develop sustainable fatliquors.

The present work established for the first time the background databases of five typical fatliquors, including sulfated rape oil (SR), sulfonated rape oil (SNR), oxidized–sulfited rape oil (OSR), phosphated rape oil (PR), and chlorinated paraffin (CP) by using LCA. Then, LCA was applied to assess the environmental impacts of the use process (post-tanning) of these fatliquors

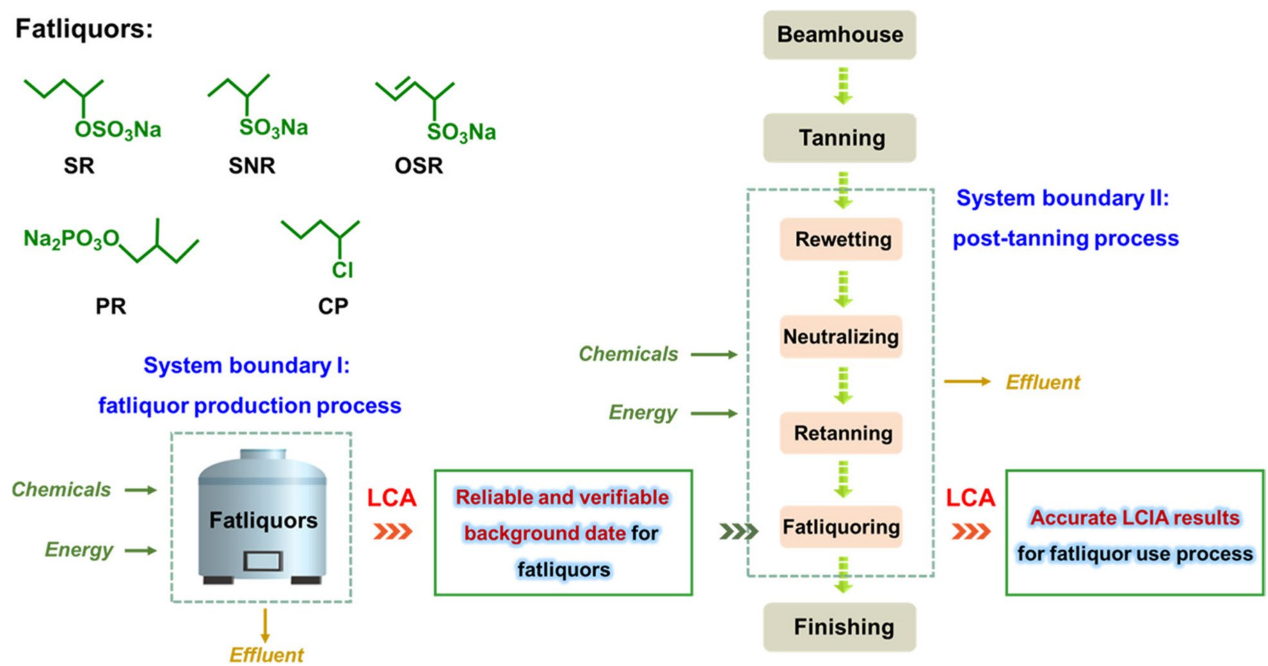

Fig. 1 System boundaries of fatliquor production and use processes

based on the established background data. Sensitivity analyses were then performed to identify the impacts of chemicals, energy, and effluents during post-tanning on the life cycle impact assessment (LCIA) results. Uncertainty analysis was also performed to evaluate the data quality of LCIA results. The results can diagnose the environmental impacts of the production and use processes of typical fatliquors and provide data support for decision making on ecological fatliquor design.

2 Materials and methods

2.1 Materials

The materials used for the production and use processes of SR, SNR, OSR, PR, and CP were industrial grade.

2.2 Goal and scope definition

The goal of this study was the environmental impact assessment for the production and use of fatliquor. The assessment followed a cradle-to-gate approach that considered the product life cycle from resource extraction to the factory gate, including raw materials mining, fatliquor manufacturing, and use processes. The disposal of fatliquored leather was not considered.

2.3 Functional unit and system boundary

The LCA of fatliquor production and use processes was performed. For fatliquor production, we selected SR, SNR, OSR, PR, and CP as the product models (Fig. 1), and the functional unit was defined as producing 1000 kg of fatliquor. The system boundary I for fatliquor production (Fig. 1) involved raw materials extraction, electrical and thermal energy supply, effluent discharge, and all production activities within the boundary. As for the fatliquor use process, the functional unit was defined as processing 1000 kg of shaved wet blue because wet blue was a raw material for post-tanning. Leather processing included beamhouse, tanning, post-tanning, and finishing [23]. However, the main difference in the use process of fatliquors was from post-tanning rather than the other stages. Thus, the system boundary II for fatliquor use process (post-tanning; Fig. 1) involved the chemicals and energy input and effluent output in the operations of rewetting, neutralizing, retaning, and fatliquoring.

2.4 Life cycle inventory analysis

The life cycle inventories (LCIs) in this study were divided into two parts: LCIs for fatliquor production process (Fig. 2) and LCIs for fatliquor use process (Fig. 3). Explanations of the LCIs are summarized as follows.

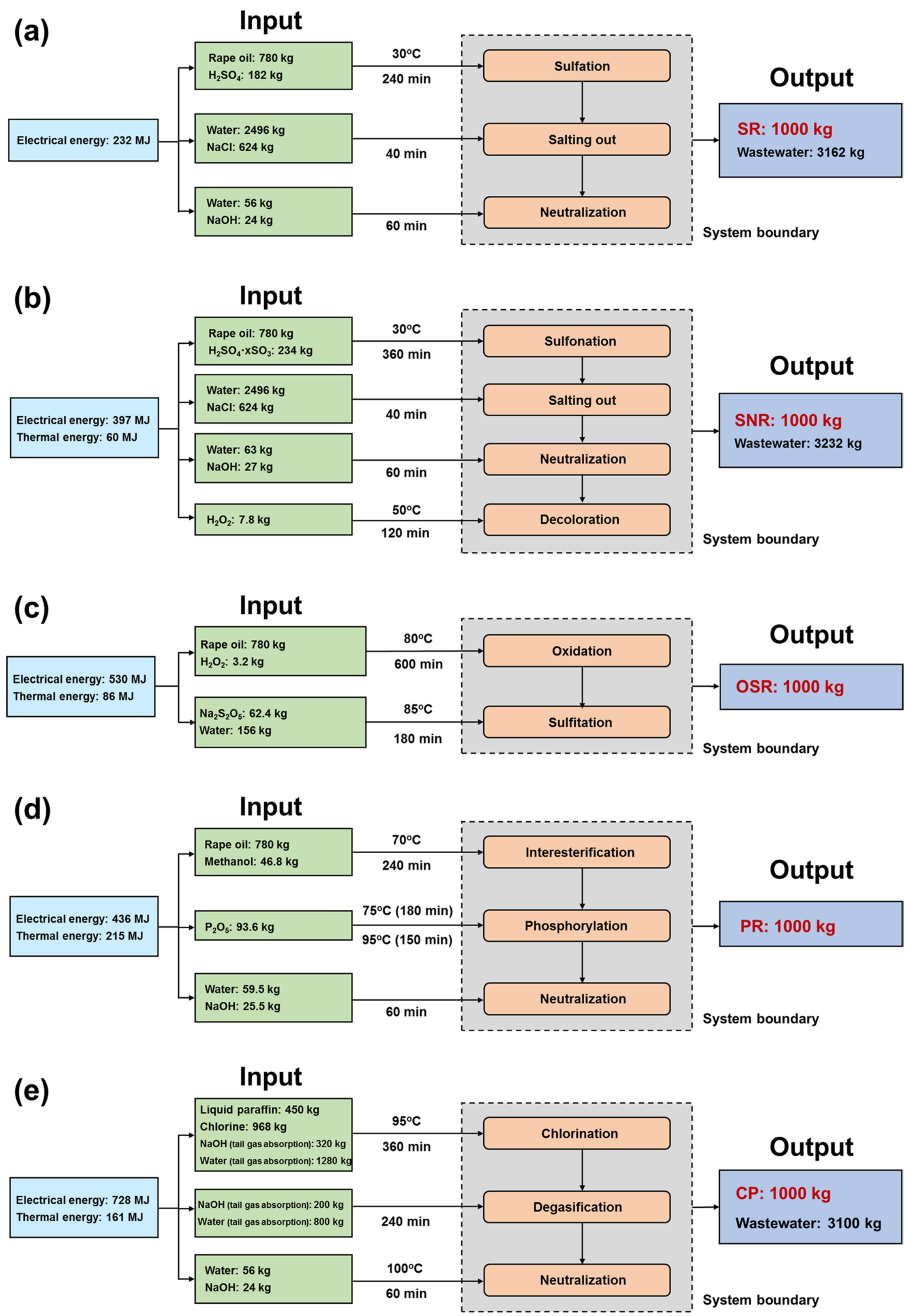

Fig. 2 Energy, chemical, and effluent inventories for SR (**a**), SNR (**b**), OSR (**c**), PR (**d**), and CP (**e**) production

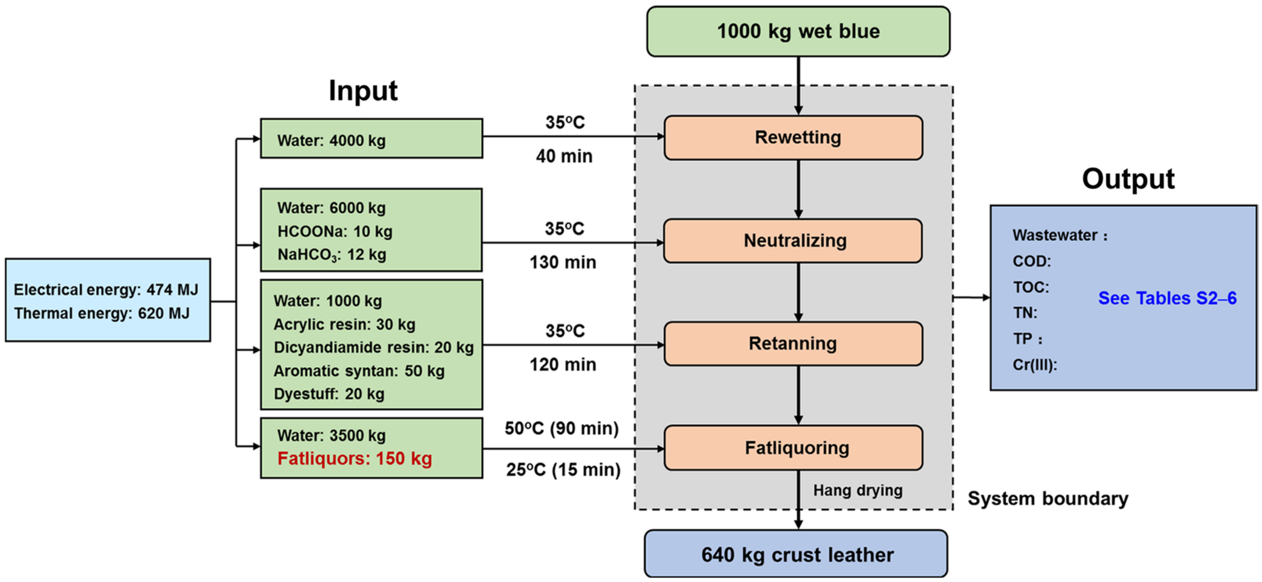

Fig. 3 Energy, chemical, and effluent inventories for fatliquor use process

2.4.1 Fatliquor production

LCIs were comprised of the industrial-scale production data, including input (chemicals and energy) and output (product and effluent) during the fatliquor production process, collected from a typical leather chemical company located in Deyang, China (Fig. 2). SR was prepared by sulfating rape oil with H_2SO_4 to introduce sulfate ester bonds through an addition reaction, salting out with brine to remove excess H_2SO_4, and neutralizing with liquid caustic soda (modification mechanism, flow sheet, and production equipment; Additional file 1: Fig. S1). SNR was prepared by sulfonating rape oil with fuming H_2SO_4 to introduce sulfonic acid groups through nucleophilic substitution, salting out with brine, neutralizing with liquid caustic soda, and decoloring with H_2O_2 (Additional file 1: Fig. S2). OSR was prepared by oxidizing rape oil with air to form the peroxide intermediate and then sulfitating with $Na_2S_2O_3$ to introduce sulfonic acid groups (Additional file 1: Fig. S3). PR was prepared by hydroxylating rape oil with methanol through interesterification, phosphorylating rape oil with P_2O_5 to introduce phosphate ester bonds, and neutralizing with liquid caustic soda (Additional file 1: Fig. S4). CP was prepared by chlorinating rape oil with Cl_2 through electrophilic substitution under light condition to introduce chlorine groups, removing and absorbing excess Cl_2 and part of the HCl by degassing tower and tail gas absorption tower, respectively, and ultimately neutralizing with liquid caustic soda (Additional file 1: Fig. S5). All fatliquor production processes were performed in a 3-ton reactor equipped with a stirring motor (a stirring power of 11 kW) and a stirring paddle, and the reactor was heated with 0.7 MPa and 170 °C steam. Moreover, the reactor used for CP production was equipped with a lamp (power = 4 kW) for exciting Cl_2 to produce Cl· that needed to react with liquid paraffin. The liquid raw materials were fed into the reactor or elevated tank through a feed pump with a power of 2.5 kW and an efficiency of 6 ton/h. The electricity and steam consumed for various operations of fatliquor production processes originated from long-term calculations and statistics of the factory (details see Additional file 1: Tables S1–S5), and the total energy consumption decreased in the following order: CP (889 MJ) > PR (651 MJ) > OSR (616 MJ) > SNR (457 MJ) > SR (232 MJ) (Fig. 2). A small amount of SO_3 released during SPF production was negligible, and the exhaust gas (Cl_2 and HCl) generated in CP production was assumed to be completely absorbed by the tail gas absorption tower. SR and SNR production processes generated about 3 tons of wastewater because of salting-out operation, and CP production process generated 3 tons of wastewater because of tail gas absorption.

2.4.2 Fatliquor use process

The LCIs of the SR, SNR, OSR, PR, and CP use processes were collected from a typical tannery located in a famous tannery district in Xinji, China, and the input and output data are shown in Fig. 2. The post-tanning process is shown in Additional file 1: Table S6. In a typical procedure, 1000 kg of wet blue was loaded in a 20 kW wooden drum, and rewetted with water, degreasing agent, and formic acid. Then, sodium formate and

Table 1 Description of impact categories [9]

Impact category	Main list substances and characterization factor	Unit	Characterization model
PED	Natural gas (1)[a], coal (1)…	MJ	CML2002
ADP	Fe (1.66e−6), Mn (2.35e−5)…	kg Sb eq	CML2002
WU	H_2O (1)	kg	Swiss Ecoscarcity
GWP	CO_2 (1), CH_4 (25), N_2O (310)…	kg CO_2 eq	IPCC2013
AP	SO_2 (1), NOx…	kg SO_2 eq	Accumulated exceedance
EP	NH_3-N (0.33), P (3.06), N (0.42)…	kg PO_4^{3-} eq	EUTREND
ET	CH_3Cl (11.66), Hg (12066)…	CTUe[b]	USEtox
HTC	As (3.92e−4), Cr(VI) (5.34e−3)…	CTUh[c]	USEtox
HTNC	Hg (0.85), Cr (1.59e−9)…	CTUh	USEtox

[a] Natural gas (1) represents that the characterization factor of natural gas in PED is 1; [b]CTUe represents Comparative Toxic Unit for ecosystems; [c]CTUh represents Comparative Toxic Unit for humans

sodium bicarbonate were added into the drum to adjust the float pH from 4.0 to 5.5 for the deep penetration of retanning agents and fatliquor into leather. The neutralized wet blue was retanned with acrylic resin, dicyandiamide resin, aromatic syntan, and dyestuff. Hot water and fatliquor were subsequently added into the drum for fatliquoring. The above post-tanning chemicals were fixed in leather with formic acid. Finally, 640 kg of crust leather was obtained after hang drying. Considering that the wooden drum had a good thermal insulation effect, the bath temperature was controlled by adding hot water heated with 0.7 MPa and 170 °C steam. The energy consumption of forklift transportation and hang dry was not accounted. The waste output parameters including chemical oxygen demand (COD), total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), and Cr(III) loads in effluent caused by leather processing are shown in Additional file 1: Tables S7–S11. The COD load of CP use process (170.4 kg per ton of wet blue) was evidently higher than that of SR, SNR, OSR, and PR use processes (136.4–145.7 kg per ton of wet blue), whereas the Cr(III) load of CP use process (0.4 kg per ton of wet blue) was lower than that of the other four processes (0.6–1.1 kg per ton of wet blue). The reason was that compared with SR, SNR, OSR, and PR, the chlorine groups in CP had the weakest interaction with Cr(III), resulting in the lowest uptake of CP by leather and the least release of Cr(III) from leather. TP was detected only in PR fatliquoring wastewater because PR contains phosphate ester bonds. Cr(VI) was undetected in all wastewaters of various fatliquor use processes.

2.5 LCIA

The LCA of fatliquor production and use processes was performed using eFootprint (website: https://www.efootprint.net/login) according to the procedures proposed by the ISO standards [24, 25]. eFootprint is an online LCA evaluation and management platform developed by IKE Environmental Technology Co. Ltd. Chengdu, China and is extensively used to evaluate the environmental impacts of chemical products [26–28]. The selected impact categories in the present study were primary energy demand (PED), abiotic depletion potential (ADP), water use (WU), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), freshwater ecotoxicity (ET), human toxicity cancer effects (HTC), and human toxicity no cancer effects (HTNC). The description of these impact categories is presented in Table 1. The calculation principle of the characteristic value of impact categories was as follows. The input and output variables of the list substances in each life cycle stage were multiplied by the corresponding coefficients, and then the products were added. For instance, the GWP of a certain life cycle stage was calculated according to Formula (1) [9, 28].

$$GWP_i = \sum_i \sum_j E_{ij} \times CF_j \tag{1}$$

where GWP_i is the GWP in the ith life cycle stage, E_{ij} is the input and output variables of the jth list substance (i.e., CO_2, CH_4, and N_2O; see Table 1) in the ith life cycle stage, and CF_j is the coefficient (i.e., 1, 25, and 310; Table 1) of the jth list substance.

The input and output variables were from the industrial-scale production data (Figs. 2, 3), and the coefficients were derived from the characterization model (Table 1). The background data are described in Additional file 1: Table S12. The background data of energy consumption (including electricity, water, and steam) and most of the chemical materials (such as sulfuric acid, fuming sulfuric acid, and hydrogen peroxide) originated from the local CLCD-China-ECER 0.8 database, which

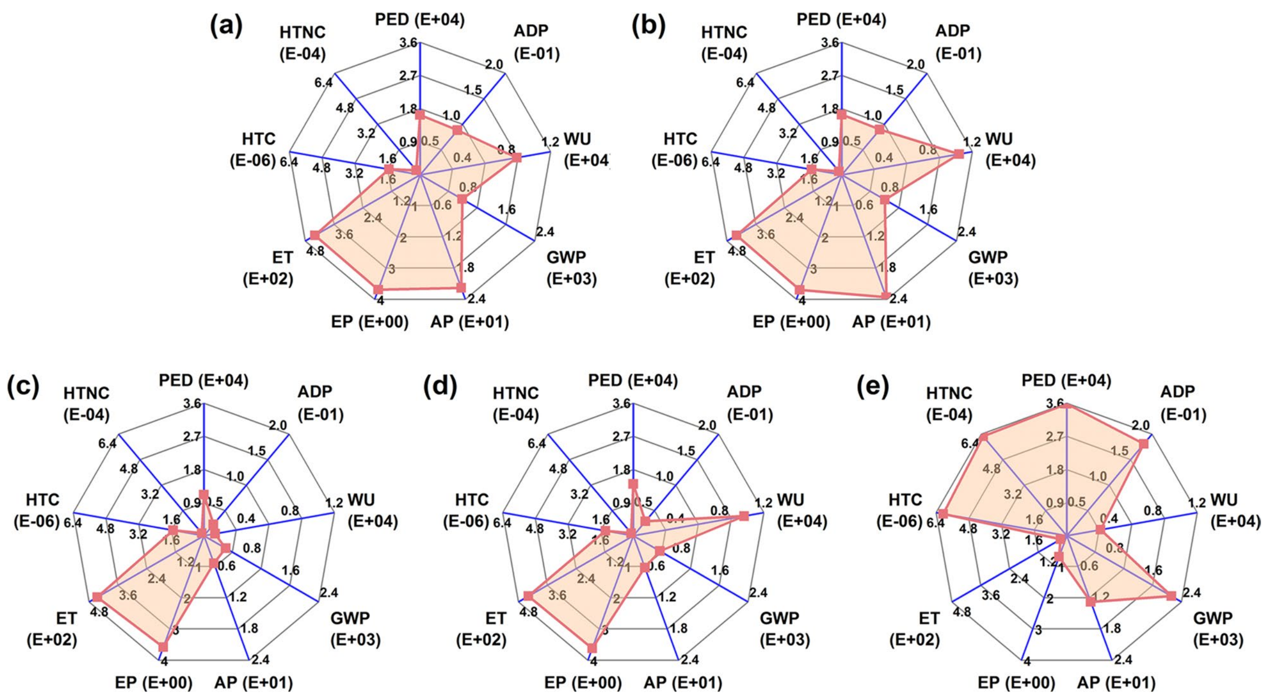

Fig. 4 LCIA results of SR (**a**), SNR (**b**), OSR (**c**), PR (**d**), and CP (**e**) production processes (obtained from the characteristic values shown in Additional file 1: Tables S13–S17)

represents the average level of industrial production in China. The background data of rape oil, sodium pyrosulfite, sodium formate, and dicyandiamide resin were from the Ecoinvent 3.1 database. The background data of sodium chloride, sodium hydroxide, and chlorine were from ELCD 3.0 database. The total neglected input flows should not exceed 5% according to the cut-off rule [29, 30], so the upstream production data of degreasing agent and formic acid could be overlooked because their weight was less than 1% of the final product weight.

2.6 Sensitivity and uncertainty analyses

Sensitivity analysis was performed to reveal the impacts of key chemicals, energy, and effluents during post-tanning on the LCIA results [31]. Sensitivity was defined as the ratio of the percentage change of the dependent variable to the percentage change of the independent variable [32]. A higher sensitivity of a certain variable indicated that the variable had a greater impact on the environment and was the key to reducing the environmental loads [33]. A variation of ± 10% was considered, and the sensitivity was calculated using Formula (2) [34, 35].

$$\mathrm{Sen}sitivity_{ij} = \frac{\Delta Index_i / Index_i}{\Delta Inventory_j / Inventory_j} \tag{2}$$

where $Sensitivity_{ij}$ is the sensitivity of the jth substance to the ith impact category, $\Delta Inventory_j/Inventory_j$ is the percentage change of the jth substance (i.e. rape oil, sulfuric acid, electricity, etc.), and $\Delta Index_i/Index_j$ is the percentage change of the ith impact category (i.e. PED, GWP, EP, etc.). All sensitivities higher than 0.1 were assumed to be sensitive.

Uncertainty analysis was performed to evaluate the data quality of LCIA results [36] because varying technology levels in different countries and regions at different time led to various calculation results [28]. Lower uncertainty reflected better data quality for LCIA results. The uncertainty of the LCIA results was calculated by two Monte Carlo simulations with 95% confidence interval according the built-in algorithm in eFootprint [37].

3 Results and discussion

3.1 Environmental impacts of fatliquor production process

The environmental impacts of fatliquor production were assessed by LCA in this section. The LCIA results of the five typical fatliquor production processes are detailed in Additional file 1: Tables S13−S17 and further summarized in Fig. 4. The radar graphs show the characteristic values of nine environmental impact categories for fatliquor production. PED, ADP, and WU reflect the resource consumption; GWP reflect climate change;

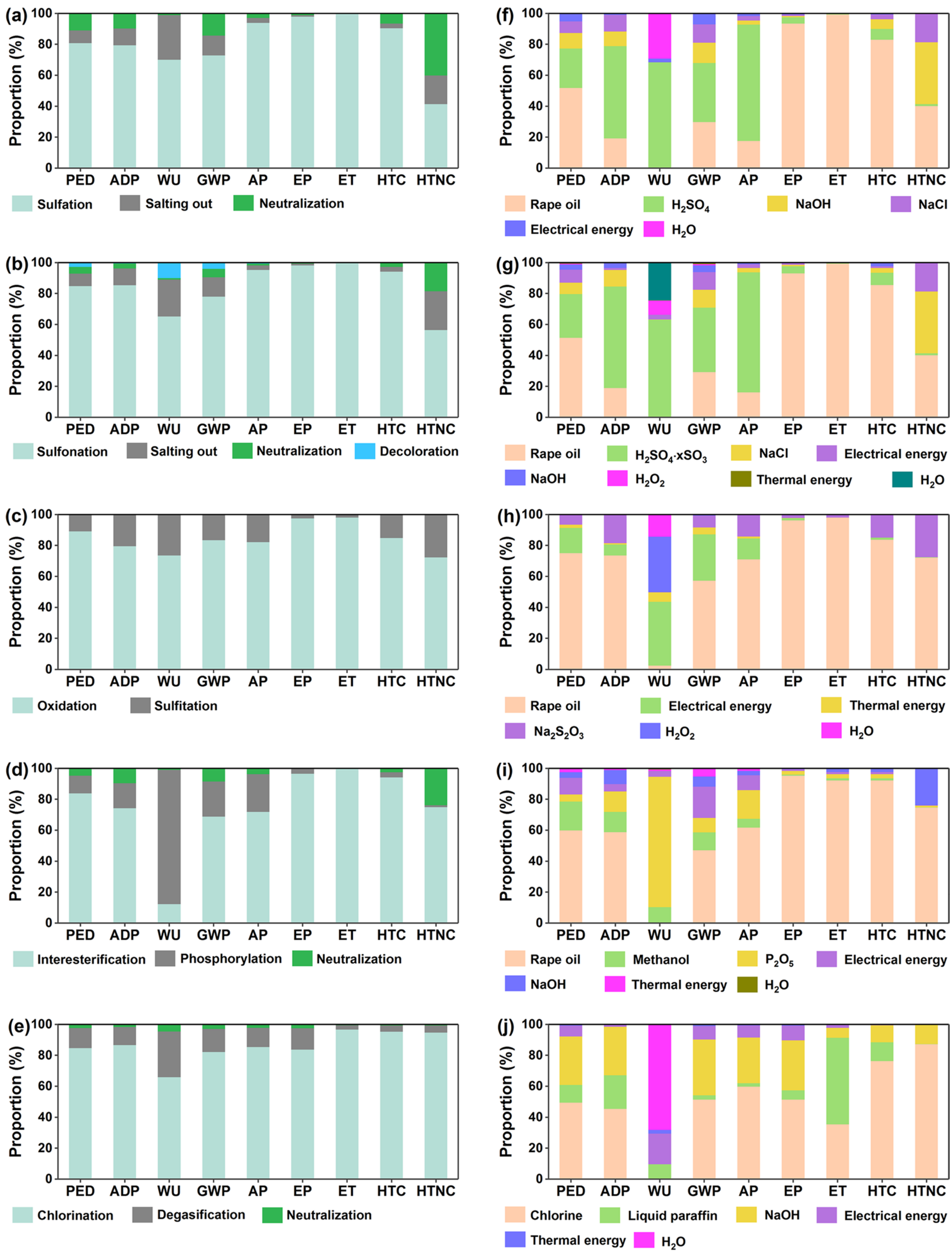

Fig. 5 Contribution of operations for SR (**a**), SNR (**b**), OSR (**c**), PR (**d**), and CP (**e**) preparation processes. Contribution of chemicals and energy for SR (**f**), SNR (**g**), OSR (**h**), PR (**i**), and CP (**j**) preparation processes (obtained from the characteristic values shown in Additional file 1: Tables S13–S17)

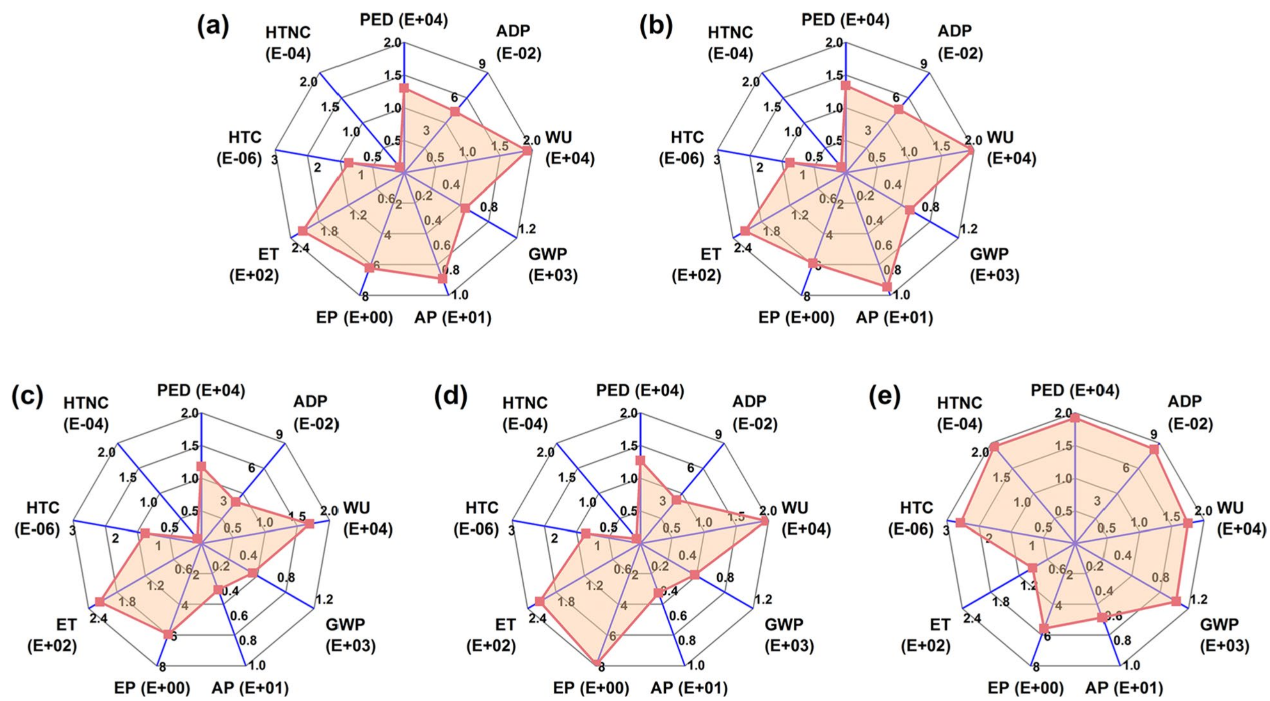

Fig. 6 LCIA results of SR (**a**), SNR (**b**), OSR (**c**), PR (**d**), and CP (**e**) use processes (obtained from the characteristic values shown in Additional file 1: Tables S18–S22)

AP, EP, and ET reflect ecosystem quality; and HTC and HTNC reflect human health [21, 38]. A large colored area in the radar graph represents a high overall environmental burden for fatliquor production [39]. Obviously, the pink areas of the five fatliquor production processes in Fig. 4 indicated that the overall environmental loads followed the order CP > SNR > SR > PR > OSR. The CP production process exhibited much high environmental impacts on PED, ADP, GWP, HTC, and HTNC (Fig. 4e) owing to the consumption of non-renewable liquid paraffin and toxic chlorine (Fig. 5j). The SR, SNR, OSR, and PR prodution processes showed high impacts on ET and EP (Fig. 4a–d) because of the consumption of massive rape oil (Fig. 5f–i) that likely caused water eutrophication and affect ecological quality [7]. These findings suggested that compared with petrochemical-derived fatliquors, biomass-derived fatliquors, especially oxidized–sulfited and phosphate modified fatiliquors, exerted low environmental impacts on resource consumption, climate change, and human health but high impacts on ecological quality.

The detailed LCIA results in Additional file 1: Tables S13−S17 were normalized (the characteristic value of a certain object divided by the sum of the characteristic values of all objects), and the contribution (values from 0 to 100% visualized with the colored columns) of different operations, chemicals, and energy to the environmental impacts are illustrated in Fig. 5. Results showed that the sulfation (Fig. 5a), sulfonation (Fig. 5b), oxidation (Fig. 5c), interesterification (Fig. 5d), and chlorination (Fig. 5e) operations for fatliquor production highly contributed to most impact categories. These phenomena were due to the fact that the operations mentioned above consumed an enormous amount of chemicals and energy (Fig. 2). Rape oil, a renewable biomass resource [40], was the main contributor to all impact categories, except for WU, for OSR and PR production (Fig. 5h, i). This result meant that OSR and PR production had a relatively low environmental impact [9], consistent with the LCIA results in Fig. 4. Sulfuric acid and fuming sulfuric acid were the major contributors to ADP, WU, GWP, and AP for SR and SNR production (Fig. 5f, g). This finding was due to the fact that sulfuric acid production consumed non-renewable sulfur/pyrite [41] and generated greenhouse gases (e.g., N_2O and NO) [42] and acid gases and acid gases (e.g., SO_2 and SO_3) [43]. Chlorine had evidently higher negative influences on the environment than liquid paraffin for CP production (Fig. 5j) because chlorine production through the electrolysis method consumed substantial energy [44]. Direct electrical and thermal energy supplies only weakly contributed to various environmental categories for the five fatliquor production (Fig. 5f–j). Comparison of Figs. 4 and 5 shows that reducing or avoiding the use of sulfuric acid, fuming sulfuric acid, and chlorine for fatliquor modification

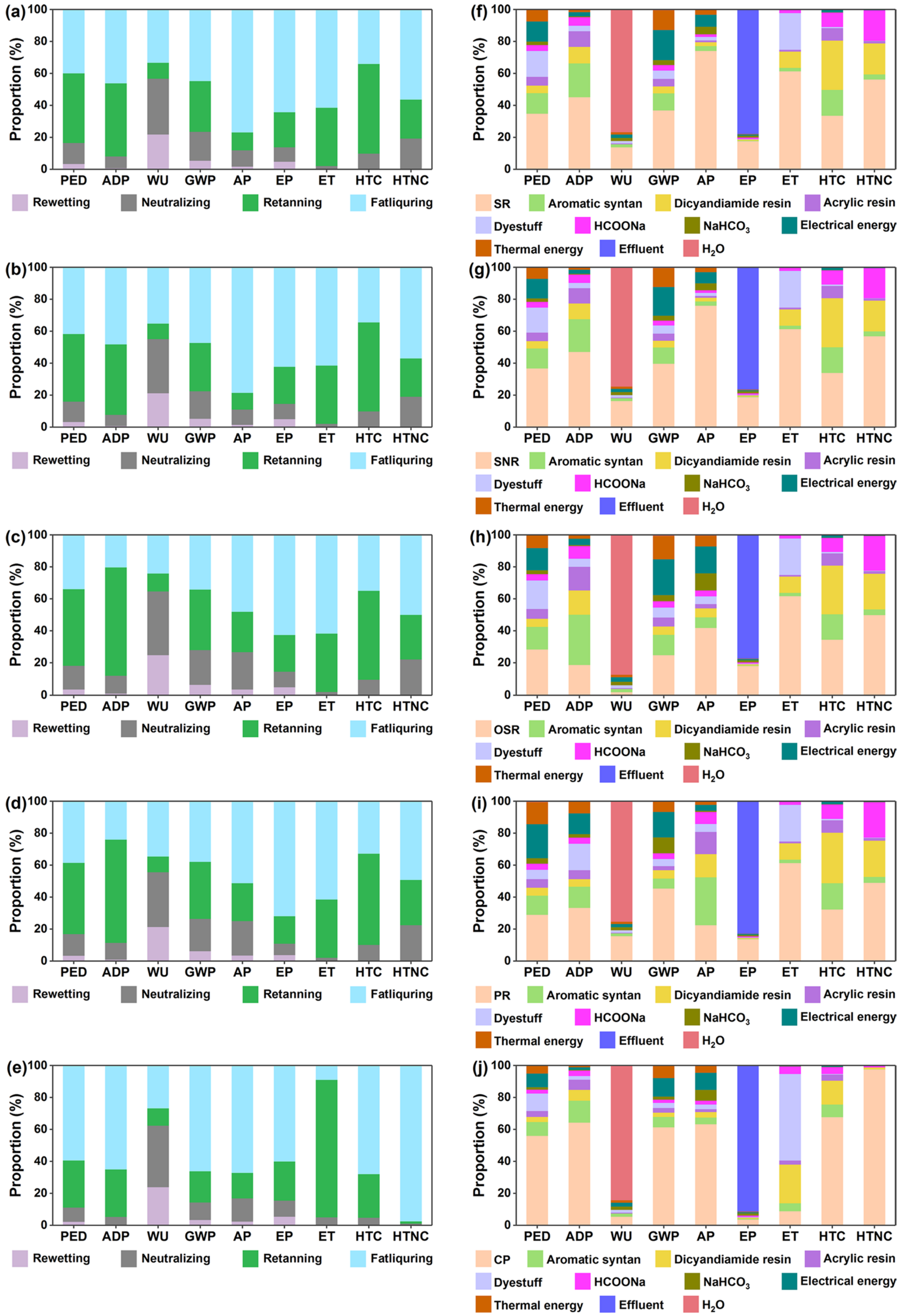

Fig. 7 Contribution of operations for SR (**a**), SNR (**b**), OSR (**c**), PR (**d**), and CP (**e**) use processes. Contribution of chemicals and energy for SR (**f**), SNR (**g**), OSR (**h**), PR (**i**), and CP (**j**) use processes (obtained from the characteristic values shown in Additional file 1: Tables S18–S22)

Table 2 Sensitivities of chemicals, energy, and effluents to impact categories for various fatliquor use processes

Use process	Variation	PED	ADP	WU	GWP	AP	EP	ET	HTC	HTNC
SR	Chemicals	0.802	0.959	0.964	0.688	0.895	0.211	0.998	0.984	0.996
	Energy	0.198	0.041	0.036	0.312	0.105	0.010	0.002	0.016	0.004
	Effluents	0.000	0.000	0.000	0.000	0.000	0.779	0.000	0.000	0.000
SNR	Chemicals	0.807	0.960	0.760	0.701	0.902	0.274	0.998	0.984	0.996
	Energy	0.192	0.040	0.035	0.298	0.098	0.010	0.002	0.016	0.004
	Effluents	0.001	0.000	0.206	0.001	0.000	0.716	0.000	0.000	0.000
OSR	Chemicals	0.782	0.939	0.718	0.627	0.762	0.265	0.998	0.984	0.996
	Energy	0.218	0.061	0.041	0.372	0.237	0.010	0.002	0.016	0.004
	Effluents	0.001	0.000	0.241	0.001	0.001	0.725	0.000	0.000	0.000
PR	Chemicals	0.797	0.941	0.757	0.648	0.777	0.201	0.998	0.983	0.996
	Energy	0.202	0.058	0.035	0.351	0.222	0.008	0.002	0.017	0.004
	Effluents	0.001	0.000	0.208	0.001	0.001	0.791	0.000	0.000	0.000
CP	Chemicals	0.866	0.973	0.728	0.808	0.850	0.127	0.996	0.992	1.000
	Energy	0.134	0.027	0.039	0.191	0.150	0.011	0.004	0.008	0.000
	Effluents	0.001	0.000	0.232	0.001	0.001	0.862	0.000	0.000	0.000

benefited the reduction in environmental burdens of fatliquors.

3.2 Environmental impacts of fatliquor use process

The environmental impacts of the five fatliquor use processes were compared based on the background data established by LCA of fatliquor production in Sect. 3.1. The LCIA results of the fatliquor use processes are detailed in Additional file 1: Tables S18−S22 and further summarized in Fig. 6. The overall environmental impacts of fatliquor use processes followed the order CP > SNR > SR > PR > OSR. This tendency was consistent with that of fatliquor production processes (Fig. 4) because fatliquoring operation and its primarily used material, i.e. fatliquor, were the main contributor to most of the impact categories for the fatliquor use processes, followed by retanning operation and retanning agents (aromatic syntan, dicyandiamide resin, acrylic resin, and dyestuff) (Fig. 7).

The CP use process (Fig. 6e) presented a greater impact on PED, ADP, GWP, HTC, and HTNC than the other fatliquor use processes (Fig. 6a–d). Compared with the CP use process, the OSR use process reduced PED, ADP, GWP, HTC, and HTNC by 38.5%, 56.0%, 48.5%, 50.7%, and 95.0%, respectively. These results indicated that biomass-based fatliquors helped improve the sustainability of leather processing and reducing greenhouse gas emissions [45, 46].

The five fatliquor use processes had similar characteristic values (around 1.8E + 04 kg) on WU (Fig. 6) because they all consumed 14.5 tons of industrial tap water (Additional file 1: Table S6) and produced 14.2 tons of wastewater (Additional file 1: Tables S7–S11) for processing 1 ton of wet blue. The SR and SNR use processes showed high environmental impact on AP (Fig. 6a, b) because SR and SNR had high contributions to AP (Fig. 7f, g). The SR, SNR, OSR, and PR use processes presented high environmental impact on EP and ET (Fig. 6a–d) because of the discharge of effluents with high organic content and the use of biomass-derived fatliquors (Fig. 7f–i).

In summary, the large amount of fatliquors used in fatliquoring operation and the high environmental impacts for fatliquor production processes were the main factors affecting the environmental burdens of post-tanning. The use of biomass-derived fatliquors improved the long-term prospects of leather manufacture in terms of resource consumption, climate change, and human health, but it lowered the ecological quality.

3.3 Sensitivity and uncertainty analyses

The sensitivities of chemicals, energy, and effluents for the five fatliquor use processes are shown in Table 2. The sensitivities of chemicals to most impact categories were much higher than those of energy and effluents (Table 2), indicating that the chemicals had the greatest impact on the environment. Thus, environment friendly leather manufacture should focus on the development and application of sustainable leather chemicals. Among the chemicals used in post-tanning, all five fatliquors showed high sensitivities in PED, ADP, GWP, AP, ET, HTC, and HTNC (Additional file 1: Tables S23–S27). These results demonstrated that fatliquor was a key substance in post-tanning chemicals for reducing environmental loads, consistent with the LCIA results in Fig. 7. The sensitivities of retanning agents such as aromatic syntan, dicyandiamide resin, and acrylic resin ranked second to fatliquors in terms of PED, ADP, and GWP. This finding was due to the fact that the existing retanning agents were primarily derived from petrochemicals [47, 48], and their production processes inevitably caused high energy and abiotic consumption, as well as greenhouse gas emissions. Moreover, aromatic syntan and dicyandiamide resin showed high sensitivities in ET, HTC, and HTNC because the toxic and carcinogenic formaldehyde is an important monomer for their synthesis reaction [48–50]. Therefore, the utilization of biomass-based substitutes for fatliquor and retanning agent production and use requires consideration in future leather manufacture.

Energy supply, especially electrical energy, was found to be another important factor influencing PED, GWP, and AP (Tables 2 and Additional file 1: Tables S23–S27). This phenomenon was due to the reliance on coal combustion of hybrid electricity of China (i.e., 68.5% coal power, 17.4% hydropower, 4.7% nuclear power, 6.0% wind power, and 3.4% solar power) [51], causing resource consumption and greenhouse and acid gas emissions. As China's energy supply shifts from fossil energy to renewable energy, the environmental impact of energy supply is expected to be reduced [52]. The effluents discharged during post-tanning, especially retanning and fatliquoring effluents, were recognized to be the main sources of EP (Tables 2 and Additional file 1: Tables S23–S27) because of the incomplete uptake of retanning agents and fatliquors [53]. Thus, high exhaustion retanning and fatliquoring operations are also recommended.

The uncertainties of various impact categories for the five fatliquor use processes are shown in Additional file 1: Tables S28–S32. All uncertainties were less than 10%, indicating a high data quality of our LCIA results [9]. This phenomenon was primarily due to the collection of our inventory data (Fig. 3) from the industrial-scale production data of a typical tannery in China, and most background data originated from the local CLCD database. To further reduce the uncertainties of LCIA results, a possible approach was to obtain inventory data of fatliquor use process from more tanneries, which represented the average production level of the entire leather industry.

4 Conclusions

The environmental impacts of typical fatliquors for leather manufacturing were comprehensively assessed and quantified using LCA. Uncertainty analysis demonstrated that LCA of fatliquor production processes enabled the background data to be available for accurately evaluating the environmental impacts of fatliquor use processes. Fatliquor and corresponding fatliquoring operation were the main contributors to most impact categories in post-tanning. Natural fatliquor use processes, especially OSR and PR use processes, showed remarkably lower environmental burdens on resource consumption, climate change, and human health than petrochemical-derived synthetic fatliquor use process. Sulfuric acid, fuming sulfuric acid, and chlorine used for fatliquor production played important roles in the environmental impacts of SR, SNR, and CP. The large amount of fatliquors used in fatliquoring operation was the main factor affecting the environmental burdens of post-tanning. Thus, the sustainability of fatliquors should be highly valued, and biomass-based fatliquor modified by oxidation–sulfitation or phosphorylation was strongly recommended to reduce the environmental impact on leather processing. This work can provide data support for the ecological design of leather fatliquors.

Abbreviations

ADP: Abiotic depletion potential; AP: Acidification potential; COD: Chemical oxygen demand; CP: Chlorinated paraffin; EP: Eutrophication potential; ET: Freshwater ecotoxicity; GWP: Global warming potential; HTC: Human toxicity cancer effects; HTNC: Human toxicity no cancer effects; LCA: Life cycle assessment; LCI: Life cycle inventory; LCIA: Life cycle impact assessment; OSR: Oxidized–sulfited rape oil; PED: Primary energy demand; PR: Phosphated rape oil; SR: Sulfated rape oil; SNR: Sulfonated rape oil; TN: Total nitrogen; TOC: Total organic carbon; TP: Total phosphorus; WU: Water use.

Supplementary Information

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Additional file 1: SR (**Fig. S1**), SNR (**Fig. S2**), OSR (**Fig. S3**), PR (**Fig. S4**), and CP (**Fig. S5**) modification mechanisms (a), flow sheets (b), and production equipment (c). Detailed electrical and thermal energies consumed in each operation for SR (**Table S1)**, SNR (**Table S2**), OSR (**Table S3**), PR (**Table S4**), and CP (**Table S5**) production (unit: MJ per ton of SR). Fatliquor use process (post-tanning process) (**Table S6**). Detailed output parameters of each operation in SR (**Table S7**), SNR (**Table S8**), OSR (**Table S9**), PR (**Table S10**), and CP (**Table S11**) use processes (unit: kg per ton of wet blue). Description of background data (**Table S12**). Characteristic values of various impact categories for SR (**Table S13**), SNR (**Table S14**), OSR (**Table S15**), PR (**Table S16**), and CP (**Table S17**) production processes. Characteristic values of various impact categories for SR (**Table S18**), SNR (**Table S19**), OSR (**Table S20**), PR (**Table S21**), and CP (**Table S22**) use processes. Sensitivities of chemicals, energy, and effluent to impact categories for SR (**Table S23**), SNR (**Table S24**), OSR (**Table S25**), PR (**Table S26**), and CP (**Table S27**) use processes. Uncertainty analysis of various impact categories for SR (**Table S28**), SNR (**Table S29**), OSR (**Table S30**), PR (**Table S31**), and CP (**Table S32**) use processes.

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Authors' contributions

YY developed the methodological framework, performed the calculations, analyzed the data, and wrote the initial draft. QS collected the life cycle inventory and analyzed the data. YZ formulated the research goals and aims, supervised the project, and revised the manuscript. YL performed the calculations.

YW supervised the project. BS revised the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this manuscript and the additional file. The authors declare that the data in this article are reliable.

Declarations

Competing interests
The authors declare that they have no competing interests.

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