Article

Environmental Analysis of Sustainable and Traditional Cooling and Lubrication Strategies during Machining Processes

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Abstract: Due to rising demands of replacing traditional cooling strategies with sustainable cooling strategies, the development of sustainable strategies such as minimum quantity lubrication (MQL) of nano-cutting fluids (NCFs) is on the rise. MQL of NCFs has received a lot of attention due to its positive impact on machining process efficiency. However, environmental and human health impacts of this strategy have not been fully investigated yet. This work aims to investigate the impacts of MQL of molybdenum disulfide (MoS_2), multi-walled carbon nanotubes (MWCNTs), titanium dioxide (TiO_2), and aluminum oxide (Al_2O_3) NCFs by employing a cradle-to-gate type of life cycle assessment (LCA). Besides, this paper provides a comparison of the impacts and machining performance when utilizing MQL of NCFs with other cooling strategies such as traditional flood cooling (TFC) of conventional cutting fluids and MQL of vegetable oils. It was found that NCFs have higher impacts than conventional cutting fluids and vegetable oils. The impacts of TiO_2-NCF and MoS_2-NCF were lower than the impacts of MWCNTs-NCF and Al_2O_3-NCF. MQL of NCFs presented higher impacts by 3.7% to 35.4% in comparison with the MQL of vegetable oils. TFC of conventional CFs displayed the lowest impact. However, TFC of conventional cutting fluids is contributing to severe health problems for operators. MQL of vegetable oils displayed higher impacts than TCFs of conventional cutting fluids. However, vegetable oils are considered to be environmentally friendly. According to the findings, the MQL of vegetable oils is the most sustainable strategy for machining processes with associated low/medium cutting temperatures. While MQL of TiO_2 and MoS_2 NCFs are the sustainable strategy for machining processes associated with high cutting temperatures.

Keywords: life cycle assessment; nano-cutting fluids; cooling strategies; environmental impact; human health

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1. Introduction

Usage of cutting fluids (CFs) results in increasing the machining process efficiency in terms of power reduction, rust control, and tool life improvement. CFs improve tool life and workpiece surface quality, during any metal cutting operation by decreasing the cutting temperatures [1]. A certain CF's lubrication property is significant, due to its influence on the friction between the cutting tool-workpiece interface. Appropriate lubrication decreases the friction and prompts smooth chip flow from the workpiece over the cutting tool [1]. Besides, proper lubrication decreases the effects of built-up-edge, which results in surface finish improvement [1]. In addition, CFs can remove formed chips from the

cutting zone and accordingly prevent any potential surface damage on the machined workpiece due to the flying chips [1]. Besides, one of the most significant CFs' parameters is the cooling effect which directly influences the generated high heat during cutting processes [1].

CF developments have advanced and their chemical compositions have become more complex to cover large numbers of machining combinations [2]. CFs can be categorized into three main categories: oil-based, gas-based, and aqueous-based. Oil-based CFs are sorted into the subcategories: mineral oils, animal oils, and vegetable oils [2,3]. Oil-based CFs tend to contain chemical additives to enhance their properties [2]. Gas-based CFs are fluids in gaseous form. Aqueous-based cutting fluids are categorized into solution-based and emulsion-based, which are synthetic and semi-synthetic, respectively. Aqueous-based CFs are presented in a concentrated form. This concentrated form is mixed with water to achieve a specific concentration. Besides, they tend to be transparent and watery due to the water content. Oil particles are presented within semi-synthetic CFs and, usually, additives are utilized to decrease oil particle sizes [2]. Semi-synthetic oils produce better cooling properties in comparison to synthetic oils, however, they can easily be contaminated when they are in contact with other machine fluids [4].

From an environmental and personal health impact perspective, CFs can be hazardous due to the toxicity of some of their components, especially CFs that are mineral-based [2]. The need for removal of toxic materials within CFs forces entities like the Environmental Protection Agency (EPA) to follow specialized chemical or physical treatment procedures [2]. According to a previous study conducted in the early 1970s by the National Institute for Occupational Safety and Health (NIOSH), the exposure to CFs increases the risk of carcinoma (a type of cancer) in various organs within the human body [5]. NIOSH reported that around 1.2 million workers are exposed to CFs [5]. In addition, CFs can evaporate during use, due to the high temperatures generated during machining operations. The vaporization of CFs expands exposure possibilities of its toxins in the forms of fluidic mist, smoke, odors, and fumes [2]. Exposure to these toxic chemicals can contribute to other serious health problems for operators. Health problems include dermatological diseases, genetic diseases, respiratory diseases, and lung cancer [2].

According to the increasing demand for achieving the requirements of sustainable and smart manufacturing [6,7], growing public awareness of CFs' environmental impacts, demands for environmentally and economically reliable CFs have grown. Since the 1990s, researchers have started looking at candidates that suit these demands [2,8]. Demands for bio-based lubricants have increased between 2011 to 2018 by around 58% [2]. One of the suitable candidates is vegetable oils, which are biodegradable, present acceptable machining performances, and their usages are economically justifiable when compared to more costly lubricants like synthetic CFs. In comparison to mineral (petroleum) oils, vegetable oils have less toxicity within their compositions and are renewable which makes them environmentally friendly [8]. Vegetable oils' desirable lubrication property is derived from its triglyceride structure [8]. Their ability to decrease friction between the tool-workpiece interface and reduce tool wear comes from their long and polar fatty acid chains. Besides, their ability to provide a reliable viscosity is from their strong intermolecular interactions [8]. In terms of process performance, vegetable oils can provide a lower coefficient of friction for machining processes in comparison to mineral-based oils. Furthermore, vegetable oils have a higher flash point than mineral-based oils, which makes vegetable oils less flammable [2,4]. Nonetheless, vegetable oils have their drawbacks, which are low reliability under high loads, poor rust control, and low thermal stability [8].

Adding solid particles in the scales of millimeters, micrometers, and nanometers enhances the thermal conductivity of conventional and biodegradable cutting fluids. However, solid particles in the scales of millimeters and micrometers tend to have poor stability when mixed with base fluids. This prompts the usage of nano-sized solid particles [9]. CFs with nano-sized solid particles are referred to as nano-cutting fluids (NCFs). Usage of NCFs offers many advantages including significant friction reduction, bearing effect, mending effect, protective film effect, and polishing effect [10]. In machining,

nanoparticles are added to improve the heat transfer capabilities. It has been found that even a small amount of appropriate nanoparticles can result in substantial improvements in the fluid's ability to remove heat from the tool-workpiece interface [11]. The production of these fluids can be divided into three distinct parts: production of the base fluid, production of nanoparticles, and dispersion. Depending on the type of particles that are needed, a series of chemical and mechanical processes are required to produce usable nanoparticles. Common nanoparticles that have been explored for use in machining fluids include TiO_2, Al_2O_3, MoS_2, single-walled carbon nanotubes, and multi-walled carbon nanotubes [12]. Vegetable oils are shown to have very good tribological properties due to the structure of their molecules. The triglyceride structures allow strong lubricant films to be formed at the tool-workpiece interface during machining, significantly reducing the friction and cutting forces [8]. However, these same structures feature strong intermolecular interactions, causing a lower heat transfer ability than what is desired. Therefore, vegetable oils are excellent base fluids, since the introduction of nanoparticles can improve the thermal conductivity of the fluid. Previous work showed the effectiveness of adding 1 wt.% of MoS_2 nanoparticles to existing vegetable oils. Where heat transfer that resulted in tool wear and surface roughness improved by 15.5% and 22.5% for the same process [13]. Graphite is a well-known lubricant additive, as the structure of graphite allows planes of carbon atoms to slide over each other with ease. It was shown that this behavior remains intact when graphite nanoparticles are introduced to a cutting fluid [14].

Machining processes can be conducted under different types of environments, which can be categorized into commonly used traditional flood cooling (TFC), minimum quantity lubrication (MQL), cryogenic cooling, and dry machining. Minimum quantity lubrication (MQL) technique is also known as near dry lubrication [2,15], micro lubrication, and near-dry machining [15]. MQL is viewed as an environmentally friendly cooling technique and it is economically justifiable to use [5,16]. MQL techniques apply a fine mist of air-CF mixture into the cutting zone. The mixture contains minimal amounts of CFs, and it is applied through a nozzle that is around 1 mm in diameter. The mixture is applied at an approximate pressure of 600 kPa and flow rates between 50 mL/h to 2 L/h [2], unlike TFC that uses flow rates in the range of 50 L/h to 1000 L/h [16]. Advantages of MQL include its elimination of disposal and recycling problems associated with CFs, because of the tiny amounts of CFs used/consumed in cutting processes.

During the last decade, nano-cutting fluids with MQL (MQL-NCFs) have received increasing attention. This strategy has the potential to enhance heat transfer and tribological properties by using nano-cutting fluids using a small quantity of CF. Wusiman et al. [17] studied heat transfer properties of dispersed multi-walled carbon nanotubes (MWCNTs) with two types of surfactants in distilled water. NCF of 0.5 wt.% CNT with 0.25 wt.% of sodium dodecylbenzene sulfonate showed enhanced thermal performance of 2.8% in comparison to the base fluid of distilled water. Hegab [18] discussed NCFs' potentials to enhance process performance while machining Inconel 718 when employing the MQL technique. MWCNTs and Al_2O_3 nano-additives were utilized with a base fluid of rapeseed oil. MWCNTs nano-additives displayed smaller tool wear than Al_2O_3 nano-additives. Das et al. [19] investigated mixing aluminum oxide nanoparticles with radiator coolant, then applying the MQL cooling technique during machining 4340 AISI alloy steel. The used NCF displayed better machining performance in terms of flank tool wear, in comparison to soluble water and compressed air coolants. Rapeti et al. [20] analyzed mixing molybdenum disulfide (MoS_2) particles with three types of vegetable oils: coconut oil, sesame oil, and canola oil. These NCFs were utilized when turning AISI 1040 steel. Coconut oil with 0.5% MoS_2 nanoparticle inclusion presented the highest performance, which reduced cutting forces, tool wear, surface roughness, and cutting temperature by 37%, 44%, 39%, and 21%, respectively. Gupta et al. [21] discussed machining performances of Inconel 800 alloy when applying sunflower oil with three types of nano-additives: Al_2O_3, MoS_2, and graphite. Results indicated that graphite had the highest machining performance in comparison to the other nano-additives. Sen et al. [22] studied the machining performance when using MQL during milling of Inconel 690. Different concentrations of Al_2O_3 nanoparticles were investigated, which ranged between

0.5% to 5%. Palm oil was the base fluid for the nanoparticles. In conclusion, Al_2O_3 nanoparticles with a concentration of 2.5% displayed the best performance, in comparison to other concentrations, dry machining, and flood cooling of pure palm oil.

Researchers have claimed that the usage of the hybrid strategy of MQL-nano-vegetable base fluids is one of the most sustainable machining techniques [17–23]. Previous works have focused only on machining performance enhancement when using this strategy without studying the environmental and human health impacts. However, it is commonly known that the manufacturing processes of nanoparticles are energy-intensive processes [24]. Few studies have been conducted to evaluate the environmental and human health impacts of the nanoparticles, but environmental inventory data about the life cycle stages of nanoparticles is not available, especially the use and end-of-life stages [24]. Furthermore, information about exposure routes, exposure potentials, and the level of toxicity of the nanoparticles is limited [25]. Besides, there is a need to compare the impacts MQL of NCFs with other cooling strategies such as traditional flood cooling (TFC) of conventional CFs and MQL of vegetable oils. Due to the mentioned gaps and potentials of using nano-vegetable base fluids, there is a need to investigate the environmental and human impacts of this process thoroughly.

The goal of this paper is to investigate the environmental and human health impacts associated with NCFs. Multiple like cycle assessments (LCAs) were conducted for various types of NCFs including nanoparticles of molybdenum disulfide (MoS_2), multi-walled carbon nanotubes (MWCNTs), titanium dioxide (TiO_2), and aluminum oxide (Al_2O_3). Two vegetable oils (soybean and rapeseed oils) were utilized as a base fluid for each type of NCF. LCAs covered material extraction and manufacturing stages of the base fluids. Besides, the conducted LCAs included synthesis processes of the nanoparticles and the preparation process (dispersion process) of the NCFs. Additionally, LCA comparisons between two conventional CFs, two vegetable oils, and eight NCFs are conducted and presented. The functional unit in this work is based on CFs in a volumetric content of 150 mL including 1 wt.% of the nano-additives. Besides, LCA comparisons between the three cooling strategies were conducted and presented. The compared cooling strategies are flood cooling of conventional cutting fluids, MQL of vegetable oils, and MQL of NCFs. The conducted LCAs of the different cooling strategies covered the required quantities of the CFs and the related power consumption for machining (turning process) an industrial application of a single AISI 4043 bolt. Besides, this paper offers an overall evaluation of the considered cooling strategies through human health impacts at machining process, environmental and human health impacts at end-of-life stage, and machining performance. The layout of this paper is broken down into the following. Section 2 presents the methodology used in this work. Section 3 presents the results and discussion of the conducted LCAs. Section 4 presents an overall evaluation of the considered cooling strategies. Finally, the conclusion section provides a summary of the findings and possible points for future work.

2. Materials and Methods

This study aims to investigate the environmental and human health impacts of three cooling strategies. These cooling strategies are flood cooling using conventional CFs, MQL using vegetable oils, and MQL using nano-cutting fluids. Figure 1 displays three cooling strategies. Life cycle assessment (LCA) is the tool that is used to assess the environmental and human health impacts of each cooling strategy. LCA covers all stages of any product which are: material extraction stage, manufacturing stage, usage stage, and end-of-life stage. This tool is commonly used to analyze the environmental impacts [26–28]. Proper usage of this tool provides users with the knowledge to select the most desirable sustainable machining process for their specific jobs. LCAs analyze a product's impacts on three areas: natural environment (ecosystem), human health, and natural resources. The guidance standard and principles of LCA are explained in ISO 14040 [29]. The execution of LCA includes four main steps:

(a) The first step includes the goal and scope definition of the assessment, as interpreted in ISO 14041 [30]. It includes the purpose of the LCA, the definition of the considered product, and the needed resources to conduct the LCA.

(b) The second step represents the inventory analysis according to ISO 14041. It shows the product's material flow. It also provides information during all four stages of the product's life in regard to input quantities, consumed amounts of different types of energy and water, and consumed resources during transportation during each of the product's four life stages.

(c) The third step is the impact assessment according to ISO 14042 [31]. During this step, the environmental and health impacts of products are calculated. This step is considered to be the most important one, due to its crucial impact on the conducted LCA's results.

(d) The fourth and final step is used to represent the results interpolation according to ISO 14043 [32]. Results of conducted LCA are analyzed and conclusions are provided to the end-user.
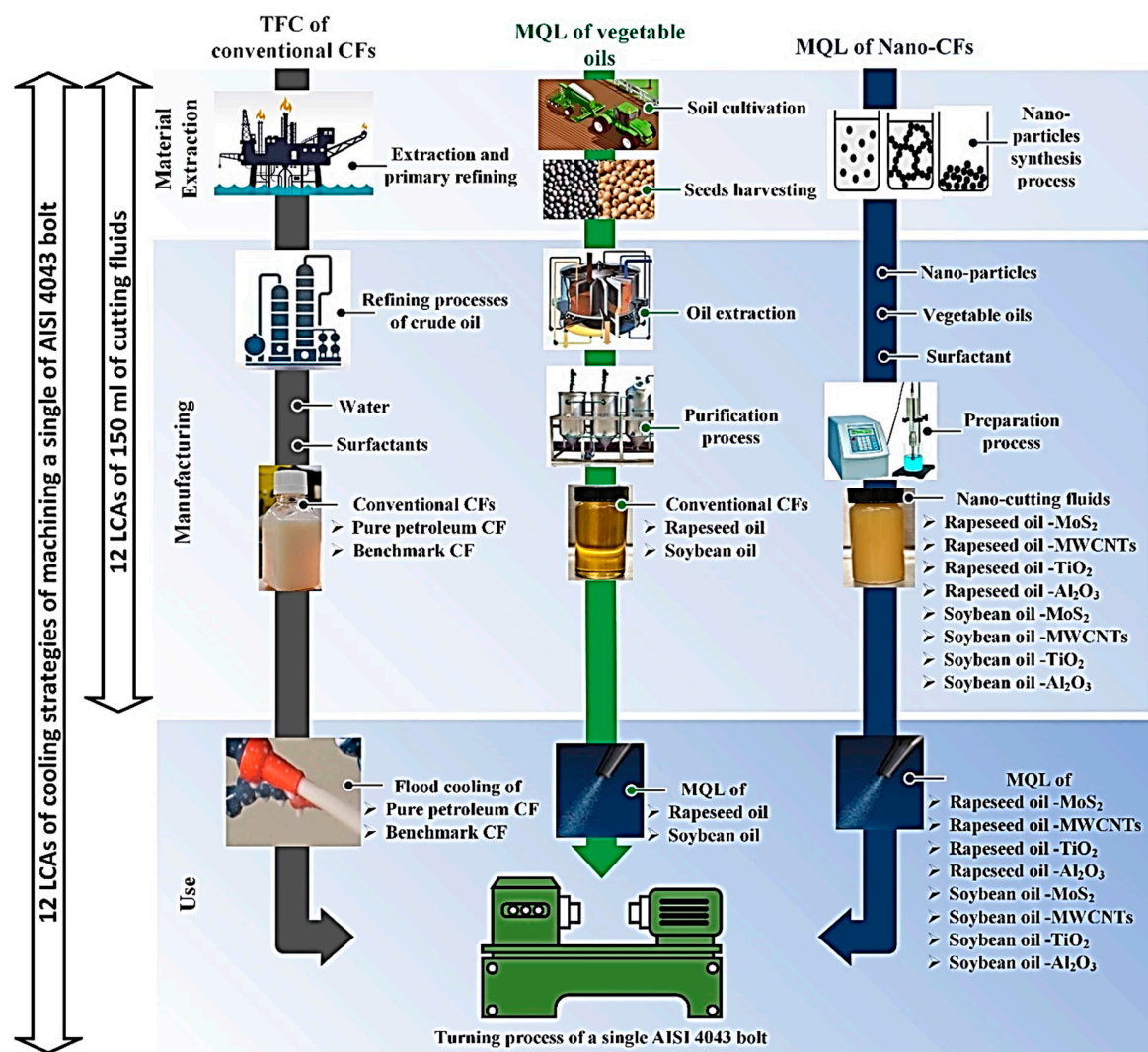

Figure 1. Life cycle assessment (LCA) system boundary of the three considered cooling strategies.

2.1. The System Boundary of the Cooling Strategies

There are various systematic approaches to conduct LCAs, and these approaches are referred to as system boundaries. System boundaries are also categorized as follows: Cradle-to-grave, cradle-to-gate, gate-to-gate, and gate-to-grave. The cradle-to-grave approach includes all four life cycle stages. The cradle-to-gate approach includes the first two stages of the four life cycle stages, which are the

material extraction and manufacturing stages. The gate-to-gate approach covers only the manufacturing stage, while gate-to-grave covers all stages to expect the material extraction stage.

In this study, the cradle-to-gate system boundary is considered within the conducted LCAs for 12 CFs. The material extraction and manufacturing stages for the CFs were considered, as shown in Figure 1. Besides, the other conducted LCAs for 12 cooling strategies covered the use stage (machining process). Regarding traditional flood cooling (TFC) of conventional CFs, the material extraction stage includes crude oil extraction, and the manufacturing stage covers oil desalting, distillation, and purification processes. Considering MQL of vegetable oils, the material extraction stage includes oilseeds harvesting and cleaning processes, while the manufacturing stage includes pre-treatment processes of the oilseeds, extraction, and the refining processes. For MQL of NCFs, the material extraction stage and the manufacturing stage of vegetable oils are considered. Besides, the material extraction stage also includes extraction inputs of various nano-additives. Included nano-additives are molybdenum disulfide (MoS_2), aluminum oxide (Al_2O_3), multi-walled carbon nanotubes (MWCNTs), and titanium dioxide (TiO_2). The manufacturing stage of MQL of NCF also covers nano-additive fabrication techniques and the two-step approach used in preparing the nano-fluids. Furthermore, executed LCAs includes the usage stage of the three cooling techniques during machining processes. The use stage includes the related cutting energy, pumping energy, compressor energy, and the quantity of coolant for turning a single AISI 4043 bolt.

2.2. IMPACT 2002+

Outputs and emissions of life cycle stages contribute to negative impacts in three areas: (a) The ecosystem, (b) resources, and (c) human health [33]. For modeling life cycle impacts, there are different approaches such as the midpoint assessment model, endpoint assessment model, and a hybrid assessment model. The midpoint model depends on determining the number of impacts for each area. The endpoint model (damage approach) concludes with an impact for each impacted area. The hybrid model combines midpoint and endpoint models. These models are used to convert LCA inventory analyses into LCA impact indicators during the third step of conducting LCA. These impact indicators are calculated by considering the characterization factor for each emission. Menoufi [34] discussed the differences between these modeling methods for life cycle impact assessment (LCIA). The midpoint model is adopted in CML, TRACI, and EDIP 2003. The endpoint model is considered in EPS 2000, EI99, Eco Scarcity, and JEPIX. The hybrid model is employed in IMPACT 2002+, RECIPE, LIME, and LUCAS. Various available software packages include LCA inventory database and LCIA methods such as SimaPro, OpenLCA, and GaBi LCA software where the databases describe the production of several materials, chemicals, and energies. Besides, they contain databases for describing the post-use stage of materials.

In this paper, IMPACT 2002+ is employed to calculate the LCA impacts of the cooling strategies. This life cycle impact assessment methodology is a hybrid model, which combines both the midpoint model and the endpoint model [35]. Besides, it covers a wide range of the impact categories (midpoints and endpoints), and a large number of substances. Four damage categories and 14 midpoint impact categories are included in this model, as listed in Table 1. Each damage category contains several midpoint impact categories. The midpoint impact categories are utilized in LCAs of the primary components of the CFs. While damage impact categories are used in LCAs of the considered CFs and cooling strategies. The damage categories are human health, ecosystem quality, climate change, and resources. The human health damage category includes the human toxicity (carcinogens and non-carcinogens), respiratory, ozone layer depletion, and ionizing radiation categories. The ecosystem quality damage category includes aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial nitrification, aquatic acidification, aquatic eutrophication, and land occupation. Both human health and ecosystem quality damage categories cover the photochemical oxidation midpoint category. Climate change damage only includes a global warming category. Resources damage considers non-renewable energy and mineral extraction midpoint categories. Table 1 displays the unit for each midpoint and damage

category. To calculate the impact of any category, a characterization factor of each chemical's emission for each specific impact category must be considered. Damage characterization factors of the midpoint characterization potential have been mentioned in [35], where authors considered emissions per person per year for western Europe as normalization factors for damage categories. SimaPro 7 software package has been utilized in this study to conduct IMPACT 2002+ methodology for three cooling strategies. Besides, Table 1 presents normalization factors for the damage categories used in SimaPro 7.

Table 1. Units of the midpoint impact categories and normalization factors of damage categories.

Midpoint Impact Category	Unit	Damage Category	Unit	Normalization Factor
Carcinogens	kg C_2H_3Cl eq			
Non-carcinogens	kg C_2H_3Cl eq			
Respiratory inorganics	kg PM2.5 eq	Human health	DALY	141
Ionizing radiation	Bq C-14 eq			
Ozone layer depletion	kg CFC-11 eq			
Photochemical oxidation	kg C_2H_4 eq			
Aquatic ecotoxicity	kg TEG water			
Terrestrial ecotoxicity	kg TEG soil			
Terrestrial nutrification	kg SO_2 eq	Ecosystem	PDF * m^2 * yr	0.000073
Land occupation	m^2 org.arable			
Aquatic acidification	kg SO_2 eq			
Aquatic eutrophication	kg PO_4 eq			
Global warming	kg CO_2 eq	Climate change	kg CO_2 eq	0.000101
Non-renewable energy	MJ primary	Resources	MJ primary	0.00000658
Mineral extraction	MJ surplus			

2.3. Functional Unit

A functional unit acts as a reference that is used to relate the system's inputs and outputs. This enables comparisons between different systems. The functional unit must be clearly defined, and it is considered to be a key element for conducting LCAs. Two functional units are presented in this paper. The first functional unit is used when conducting LCAs for CFs, while the second one is used when conducting LCAs for cooling strategies.

The first functional unit was selected based on the available information in literature considering quantities of preparing nano-cutting fluid. Padmini et al. [36] considered using 100 mL to prepare different types of nanofluid. Different vegetable oils and MoS_2 nanoparticles were included during the preparation process. Produced fluids were presented with different contents of nano-additives, ranging between 0 vol% to 1 vol%, with increments of 0.25%. Machining performances of each nano-additive fluid were examined. Wusiman et al. [17] employed 50 mL of distilled water with 0.5 wt.% of CNT. Hegab [37] investigated the usage of Al_2O_3 and MWCNTs when machining difficult-to-cut materials. Two percent and 4% of nano-additives were added with rapeseed oil during the preparation of 100 mL of nanofluids. Zhu el al. [38] investigated and discussed the thermal conductivity characteristics of water with 0.1% Al_2O_3 of nano-additives in 150 mL volumetric content. Das et al. [19] utilized 2.5 g of Al_2O_3 with 500 mL of base fluid of radiator coolant and distilled water with a ratio of 1:4. Based on the reviewed literature, the functional unit in this work is based on CFs in a volumetric content of 150 mL. For the NCFs, 1 wt.% of the nano-additives is considered as the functional unit. The second functional unit used in this work is an AISI 4043 industrial machined bolt. The bolt has a length of 200 mm and a diameter of 42 mm. Besides, the used bolt is manufactured by

local small to medium-sized enterprises (SME) in Western Australia [39]. The conducted LCAs in this paper cover the machining a single AISI 4043 bolt.

3. Results and Discussion

Results of LCAs for 12 CFs and 12 LCAs cooling techniques are presented, compared, and discussed in this section. Executed LCAs can be categorized into two parts. The first part covers the LCAs of the considered CFs, while the second part covers the whole LCAs of the considered cooling strategies. The first part included LCAs for two conventional CFs, two vegetable oils, and eight NCFs. The NCFs used were combinations of four nano-additives and the used vegetable oils. Each vegetable oil was used as the base fluid for each nano-additive. In addition, LCAs of CFs were based on a volumetric amount of 150 mL. The second part was an expansion of the first category, which included CFs' cooling techniques. Cooling techniques included in the second category were: flood cooling for two conventional CFs, MQL cooling technique for two vegetable oils, and MQL cooling technique for eight NCFs. Finally, CFs cooling strategies' LCAs were based on machining a single AISI 4043 bolt.

### 3.1. Life Cycle Assessment (LCA) of Conventional Cutting Fluids

LCAs were conducted for two types of conventional CFs: pure mineral oil and a benchmark CF that consists of mineral oils and petroleum feedstock surfactants [40]. The LCA of the pure mineral oil includes offshore extraction processes of crude oil, primary refining processes, transportation of the extracted oil to the coast via pipelines, transportation of the crude oil to the refinery, and the refining processes of the oil. Benchmark CF consists of 0.75 wt.% of petroleum oil, 0.3 wt.% anionic surfactant of sodium petroleum sulfonate, 0.4% of nonionic surfactant of diisoproponalamine, and 98.55 wt.% water. The benchmark CF is considered as a microemulsion of petroleum oil in water. The sodium petroleum sulfonate is obtained from the reaction of sulfur with linear alkyl, and diisoproponalamine is obtained from ammonia and propylene oxide. Figure 2a displays conducted LCAs' midpoint impacts of 150 mL of pure petroleum oil and benchmark CF, respectively. Petroleum oil presents a high impact on non-renewable energy (i.e., resources damage category) and lower impacts for the other midpoints. Results for benchmark cutting fluid displays high impacts for ionizing radiation, aquatic ecotoxicity, and non-renewable energy and lower impacts for the other midpoints. Non-renewable energy has the highest midpoint impact at 13 MJ primary in petroleum oil's LCA, the same midpoint impact in benchmark CF is lower at 0.19 MJ primary. Aquatic ecotoxicity has the highest midpoint impact at 0.191 kg TEG water in benchmark CF's LCA, the same midpoint impact in petroleum oil's LCA is higher at 0.490 kg TEG water.

3.2. LCA of Vegetable Oils

LCAs were conducted for two types of vegetable oils: rapeseed oil and soybean oil. LCAs for both vegetable oils include material extraction and manufacturing stages. The material extraction stage includes the following processes: Soil cultivation, sowing, weed control, fertilization, harvesting, and grain drying. In this study, the allocation factor for 1 kg of rapeseed oil is 74.3% of oil and 25.7% of the meal, while the allocation factor for 1 kg of soybean oil is 34.5% of oil and 65.5% of the meal. Both vegetable oils have different densities at 22 °C where the rapeseed oil has a density of 913.3 kg/m^3, and soybean oil has a density of 915.7 kg/m^3 [41]. The 150 mL of each oil-weighted differently due to their different densities. Rapeseed seeds weighed 0.2211 kg and soybean seeds weighed 0.4725 kg. The manufacturing stage includes seeds (i.e., oil mill) processing and purification processes of the extracted oil. Figure 2b displays conducted LCAs midpoint impacts of 150 mL of rapeseed oil and soybean oil, respectively. Rapeseed oil presents high impacts for aquatic ecotoxicity and terrestrial ecotoxicity and lower impacts for the other midpoints. Soybean oil displays higher impacts on non-renewable energy, land occupation, and ionizing radiation. Lower impacts are displayed for the other midpoints. Terrestrial ecotoxicity has the highest midpoint impact at 741 kg TEG soil in rapeseed oil's LCA, the same midpoint impact in soybean oil is lower at −87.1 kg TEG soil. Ionizing radiation

has the highest midpoint impact at 4.25 Bq C-14 eq in soybean oil's LCA, the same midpoint impact in rapeseed oil's LCA is higher at 6.81 Bq C-14 eq.

(**a**)

(**b**)
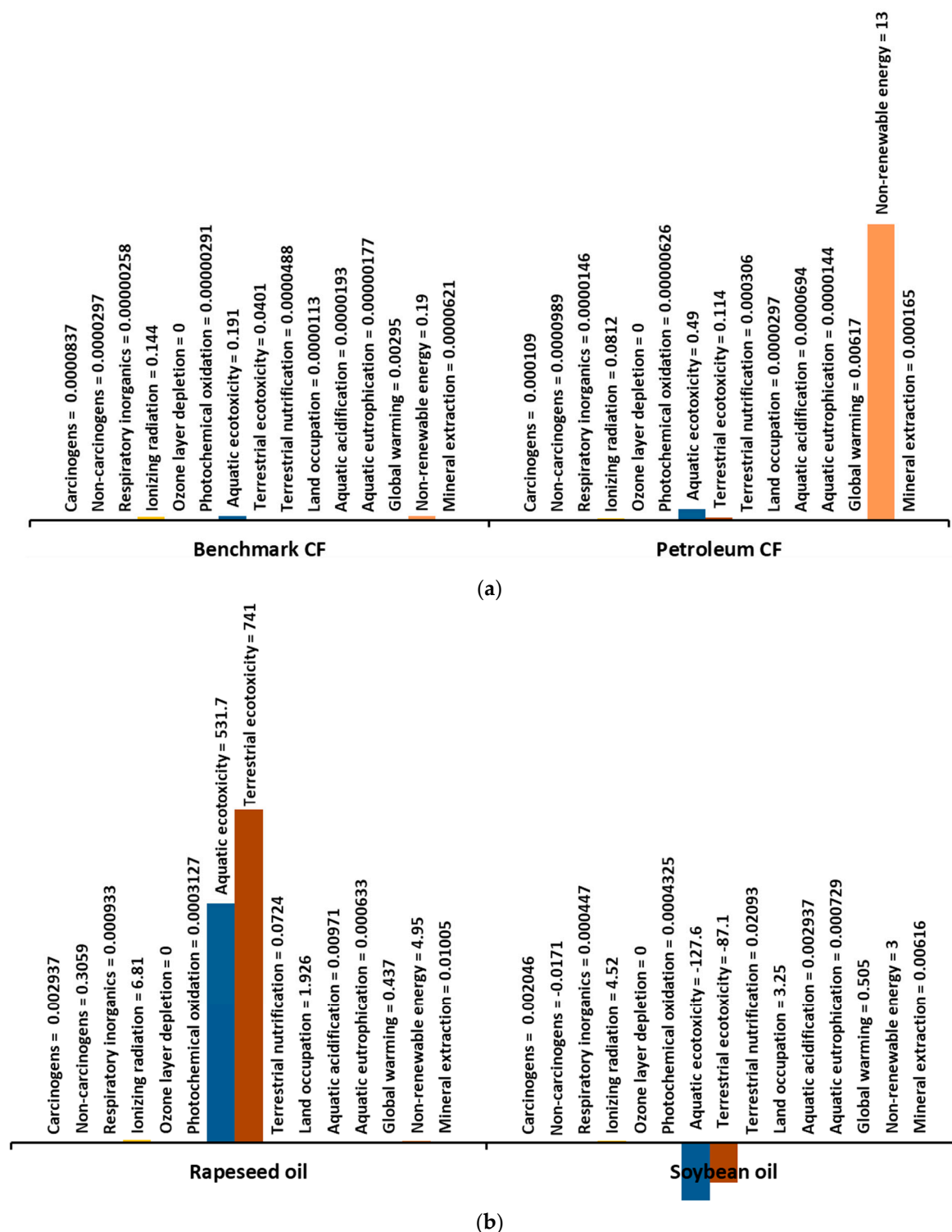
Figure 2. Midpoints impact contribution for 150 mL of (**a**) benchmark cutting fluid (CF) and petroleum CF, (**b**) rapeseed oil and soybean oil.

3.3. LCA of Nano-Cutting Fluids

LCAs of NCFs consider the impacts of base fluids (vegetable oils), nano-additive synthesis processes, and the fluid's preparation processes. Soybean oil and rapeseed oil are used as base fluids.

LCAs for base fluids have already been conducted in the previous section. LCAs for nano-additives are presented in Section 3.3.1. Four nano-additives are presented: Molybdenum disulfide (MoS_2), multi-walled carbon nanotubes (MWCNTs), and titanium dioxide (TiO_2), and aluminum oxide (Al_2O_3). NCFs' preparation was the top-down (two-step method) preparation process approach.

3.3.1. Nanoparticle Synthesis

Nanoparticle synthesis processes are available through physical, chemical, and biological methods. Detailed synthesis processes for nanoparticles were included in the presented results of the conducted SimaPro software LCAs. Information on the synthesis processes was gathered from the literature. Gathered information for synthesis processes including the processes inputs/outputs, and energy consumption.

Molybdenum Disulfide (MoS_2) Nanoparticle Synthesis

MoS_2 nanoparticle's LCA used in this paper is mainly based on the wet synthesis technique used in previous work [24]. The aqueous solution of citric acid is utilized with ammonium molybdate to result in molybdenum with the citric acid solution. Then, ammonium sulfide is added to form MoS_2. The functional unit used is 1 g of the MoS_2 powder. Inputs and outputs quantities required to obtain a 1 g of the MoS_2 powder are presented in Table 2. In addition, the electricity used during mixing, spinning, and drying processes are presented in Table 2. The chemicals and electricity supply inventory database in SimaPro software has been utilized to conduct the LCA of MoS_2 nanoparticles. Figure 3a displays the midpoint impact categories of MoS_2 nanoparticle's LCA. Aquatic ecotoxicity has the highest impact midpoint in comparison to other midpoints at 37.8 kg TEG water.

Table 2. Synthesis process inputs and output for obtaining 1 g of molybdenum disulfide (MoS_2) nanoparticles.

Inputs	Quantity
Ammonium molybdate	1.2 g
Citric acid	2.52 g
Ammonium sulfide	3.51 g
Electricity use	0.15 MJ
Output	**Quantity**
Ammonium citrate	0.27 g

Multi-Walled Carbon Nanotubes (MWCNTs) Nanoparticles Synthesis

MWCNTs nanoparticle's LCA used in this paper is based on the catalytic chemical vapor deposition (cCVD) used in previous work [42]. This synthesis process is used to obtain 99% pure organized MWCNTs. The functional unit used is the quantity of the batch production, which is 300 mg. Inputs and outputs quantities required to obtain 300 mg of MWCNTs are presented in Table 3. Inputs consist of 0.2 g ferrocene dissolving in 10 mL of toluene to form a solution. Then, a syringe pump is used to inject the formed solution into a quartz tube at a rate of 10 mL/h and at 790 °C. A quartz tube is used during the injection process and Ar and H_2 are presented at 450 sccm and 50 sccm, respectively. In addition, Table 3 displays the total energy consumption which includes energies consumed in heating the furnace, mechanical movements of the syringe pump Ar and mass H_2 flow controllers. In addition, the LCA includes the production stage of the catalyst, feedstock preparation, heating of the furnace, the reaction period, furnace cooling, and purification. Figure 3a displays the midpoint impact categories of MWCNTs nanoparticle's LCA. Aquatic ecotoxicity has the highest impact midpoint in comparison to other midpoints at 395 kg TEG water.
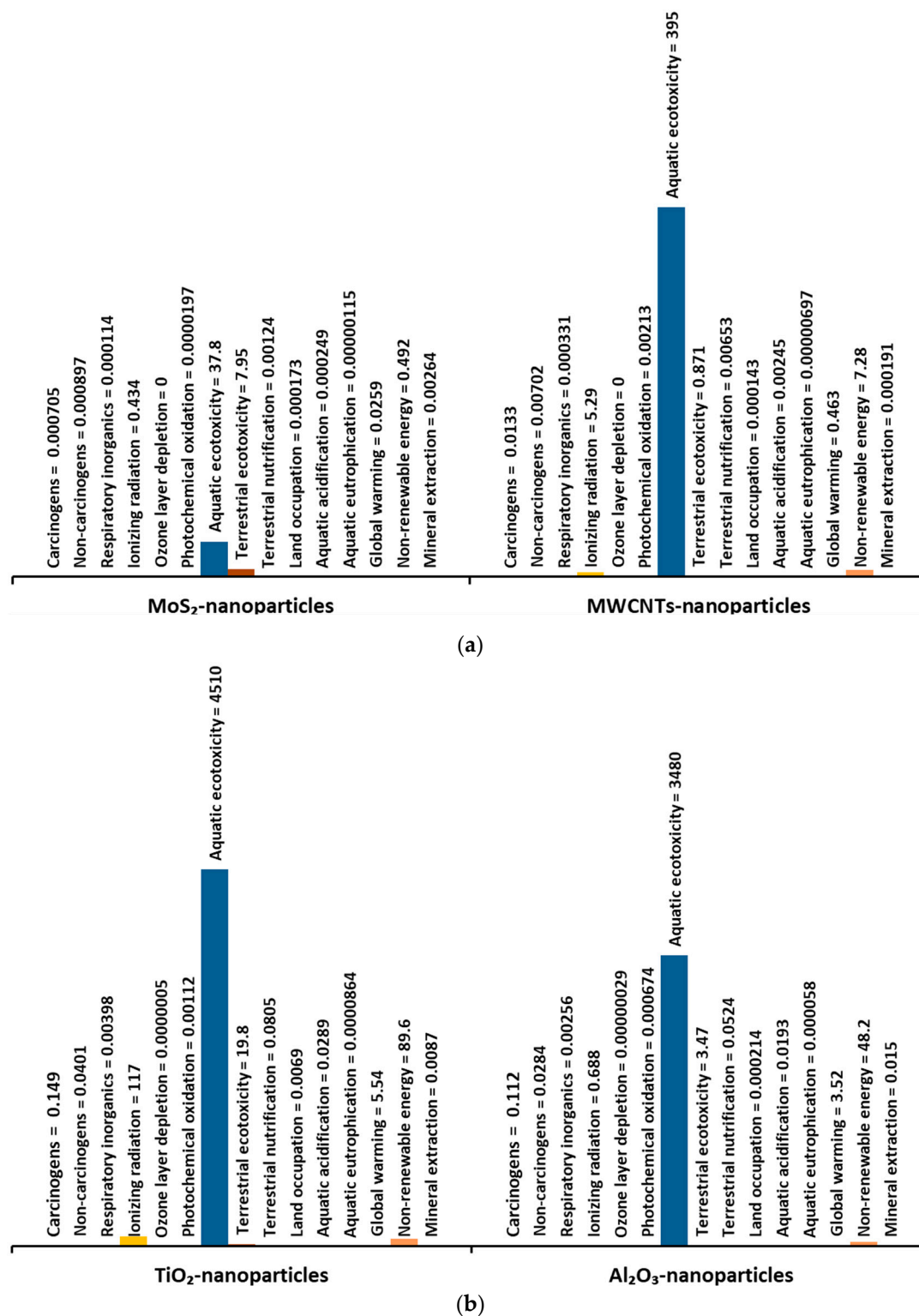
Figure 3. Midpoints impact contribution for (**a**) 1 g of MoS$_2$ nanoparticles and 300 mg of MWCNTs, (**b**) 1 kg of TiO$_2$ nanoparticles, and 1 g of Al$_2$O$_3$ nanoparticles.

Table 3. Synthesis process inputs and outputs for obtaining 300 mg of multi-walled carbon nanotubes (MWCNTs).

Inputs	Quantity
Ferrocene	0.2 g
Toluene	10 mL
Argon (stage 2, stage 3, and stage 4 for 7 h)	450 sccm for 4 h, 50 sccm for 3 h
Hydrogen (stage 3 for 1 h)	0.287 g
HCl (37% volume solution)	20 mL
Energy consumption	1.32192 kWh
Outputs	**Quantity**
Toluene	3014 mg
Benzene	496 mg
Methane	0.4 mg

Titanium Dioxide (TiO_2) Nanoparticles Synthesis

TiO_2 nanoparticle's LCA used in this paper followed the Altairnano hydrochloride synthesis processes used in previous work [43]. Like sulphate process, ilmenite ore is the main feedstock in the Altairnano hydrochloride process. Ilmenite is introduced into the unit of digestion during the existence of concentrated hydrochloric acid. Then, a small amount of iron powder is added to the mixture and the iron chloride is separated from the output steam and filtration is conducted. After filtration, the trialkyl phosphine oxide is used as solvent extraction and the sodium hydroxide is used to remove the chloride iron for the product steam. Finally, TiO_2 nanoparticles are obtained by the reaction of titanium oxychloride with water. During the synthesis of TiO_2 nanoparticles, the dehydration process consumes the highest amounts of methane. The functional unit used 1 kg of the TiO_2 nanoparticles. Inputs and outputs quantities are required to obtain 1 kg of the TiO_2 nanoparticles are presented in Table 4. Figure 3b displays the midpoint impact categories of TiO_2 nanoparticle's LCA. Aquatic ecotoxicity has the highest impact midpoint in comparison to other midpoints at 4510.

Table 4. Synthesis process inputs and output for obtaining 1 kg of titanium dioxide (TiO_2) nanoparticles.

Inputs	Quantity
Ilmenite	2.165 kg
Iron powder	0.103 kg
Hydrochloric acid	0.065 kg
Methane	0.866 kg
Steam	14.948 kg
Energy consumption	52.895 MJ

Aluminum Oxide (Al_2O_3) Nanoparticles Synthesis

Al_2O_3 nanoparticle's LCA was used in this paper followed by the sol-gel synthesis technique used in previous work [44]. The sol-gel synthesis technique is known as chemical solution deposition, it is a wet-chemical technique which widely used to produce Al_2O_3 nanoparticles. The first step to produce Al_2O_3 nanoparticles requires preparing a solution of distilled water with citric acid and aluminum nitrite. Then, the solution is placed for 2 h over the thermal plate with magnetic agitation at 60 °C. To maintain constant agitation, the solution is heated for additional 1.5 h at 80 °C. After that, an oven is utilized to evaporate the water content from the obtained gel. Finally, the produced gel is burnt for 2 h at 1000 °C. The functional unit used is 1 g of Al_2O_3 nanoparticles. Inputs and outputs quantities required to obtained 1 g of the Al_2O_3 nanoparticles are presented in Table 5. Figure 3b displays the midpoint impact categories of Al_2O_3 nanoparticle's LCA. Aquatic ecotoxicity has the highest impact midpoint in comparison to other midpoints at 3480 kg TEG water.

Table 5. Synthesis process inputs and output for obtaining 1 g of aluminum oxide (Al_2O_3) nanoparticles.

Inputs	Quantity
Aluminum nitrate	7.98 g
Citric acid	4.47 g
Water vapor	253.819 g
Electricity use	11.695 kWh

3.3.2. Preparation Process of Nano-Cutting Fluids

NCFs preparation process is the process where nano-sized particles are mixed with a base fluid. Proper execution of this process results in fluids with desirable properties such as homogeneity, physical and chemical stability, durability, and dispersibility. There are two commonly used approaches for the preparation process of NCFs: The bottom-up and the top-down approaches [45]. The bottom-up approach is known as the one-step method, while the top-down approach is known as the two-step method. NCFs presented in this paper are prepared via the two-step method, similar to the procedure followed in [18]. During the one-step method, preparation of nanoparticles and their suspension into the base fluid are executed at the same time. The two-step method is more commonly used and is cheaper, which produces NFCs in two steps. The first step involves producing nanoparticles via synthesis techniques. Then, during the second step nanoparticles are dispersed into the base fluid. There are common apparatuses that are used during the dispersion of solid nanoparticles into the base fluid, such as magnetic stirrers, ultrasonic bath, homogenizers, high-shear mixers, and bead mills.

According to the first functional unit, the preparation volume for the nano-fluids is 150 mL. This volume consists of three components: vegetable oil (base fluid), nano-additives (1 wt.%), and surfactant of sodium dodecyl sulfate (0.3 g). The purpose of using a surfactant is to increase the NCF's stability. The two steps method followed in [18] utilized an ultrasonic device (AQUASONIC-50HT) for 3 h at 60 °C. Then, a magnetic stirrer (Hot Plate Stirrer-3073-21) is used for 30 min to assure for complete dispersion of nanoparticles within the base fluid. The ultrasonic device consumed 1.5 kWh and the magnetic stirrer consumed 0.09 kWh.

3.4. LCA Comparison of Cutting Fluids

LCAs are broken down into LCAs for two conventional CFs (i.e., benchmark and petroleum oil), two vegetable oils (i.e., soybean oil and rapeseed oil), and eight NCFs (i.e., soybean-MoS_2-NCF, soybean-MWCNTs-NCF, soybean-TiO_2-NCF, soybean-Al_2O_3-NCF, rapeseed-MoS_2-NCF, rapeseed-MWCNTs-NCF, rapeseed-TiO_2-NCF, rapeseed-Al_2O_3-NCF). Figure 4 presents the damage categories in the normalized unit (µPt) for two conventional CFs, soybean vegetable oil, and four soybean vegetable oil-based NCFs. Figure 5 presents damage categories in µPt for two conventional CFs, rapeseed vegetable oil, and four rapeseed vegetable oil-based NCFs. Four damage categories are included in Figures 4 and 5, which are human health, ecosystem quality, climate change, and resources. Presented damage categories are normalized for each CF. Figures 4 and 5 indicate that benchmark CF has the lowest impacts on all damage categories, followed by petroleum oil, in comparison to the other CFs. Petroleum oil has a higher impact on the resource's category, because of its non-renewable energy sources. Soybean oil has a high impact on the ecosystem quality category, because of the high consumptions of water during soil's cultivation and fertilization. However, it has a medium level impact on the resources category, due to its impact on the non-renewable energy midpoint category as shown in Figure 2. Rapeseed oil has a higher impact on human health, ecosystem quality, and resource categories, in comparison to soybean oil, while it has a higher allocation factor. However, it has a slightly smaller impact on the climate change category, in comparison to soybean oil. In regards to NCFs, Soybean-TiO_2 has the lowest impacts on all damage categories, in comparison to the other seven NCFs, except for rapeseed-TiO_2-NCF and rapeseed-MoS_2-NCF, which have lower impact factors in the climate change category. Soybean-TiO_2 has a slightly larger impact than soybean oil CF. Moreover,

on average between all damage categories, rapeseed-NCFs have higher impacts on the damage categories than soybean-NCFs, due to the higher impact their base rapeseed oil has, in comparison to the soybean oil.
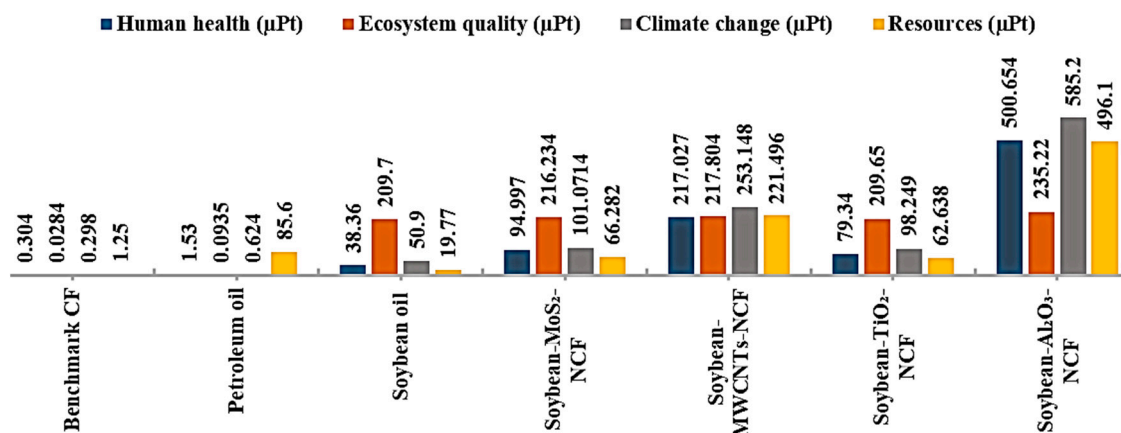

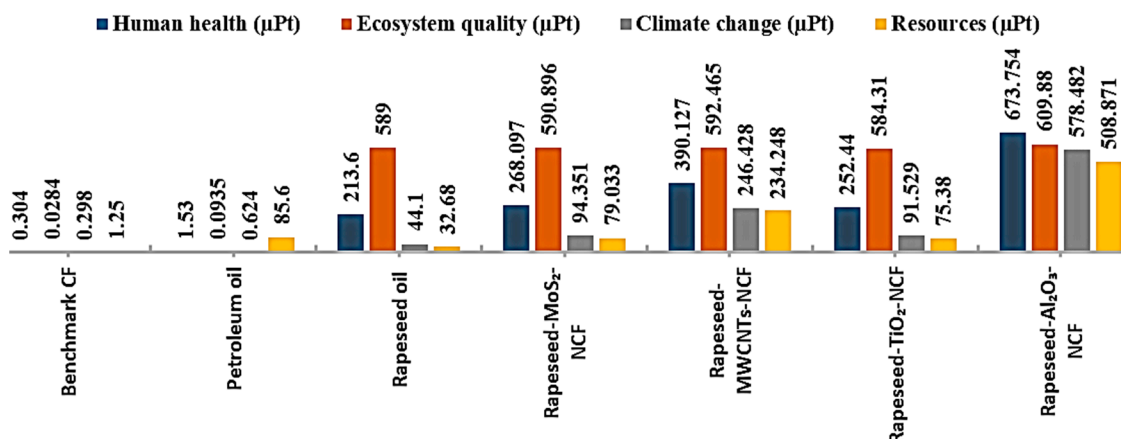**Figure 4.** Damage categories of conventional CFs and nano-CFs based on soybean vegetable oil.

Figure 5. Damage categories of conventional CFs and nano-CFs based on rapeseed vegetable oil.

Figure 6 displays a single score for each analyzed CF. Out of the 12 investigated CFs, conventional benchmark CF presents the lowest impact on the four damage categories, and rapeseed-Al_2O_3-NCF presents the highest impact. Additionally, vegetable oils have higher impact scores than conventional CFs due to due to their cultivation and the fertilization processes, where high amounts of water are used in the soil. However, in terms of the resource's category, conventional petroleum CF has a higher impact than vegetable oils, due to its extraction method from non-renewable energy sources.

In comparison with the vegetable oils, rapeseed oil has higher impact scores than soybean oil, mainly because of its higher score within the ecosystem quality category. Moreover, NCFs have impacts higher than vegetable oils that range between 41% to 470%. TiO_2 and MoS_2 NCFs impacts were lower than the MWCNTs-NCF and Al_2O_3-NCF. NCFs have the highest impacts out of all other CFs, due to their energy-intensive synthesis and preparation processes.

Nanoparticles synthesis processes are energy-intensive processes. Energy consumed by nanoparticles synthesis processes depends on three parameters: material of nanoparticles, synthesis process used, and quality of the output particles. Used synthesis processes presented a significant impact on NCFs damage impact scores. Mainly because NCFs are produced in a laboratory (small scale) setting, while conventional CFs are produced in industrial (large scale) settings. Laboratory settings mainly focus on researching and developing NCFs. Industrial settings focus on optimizing CFs production techniques which reduce the energy required per unit volume.
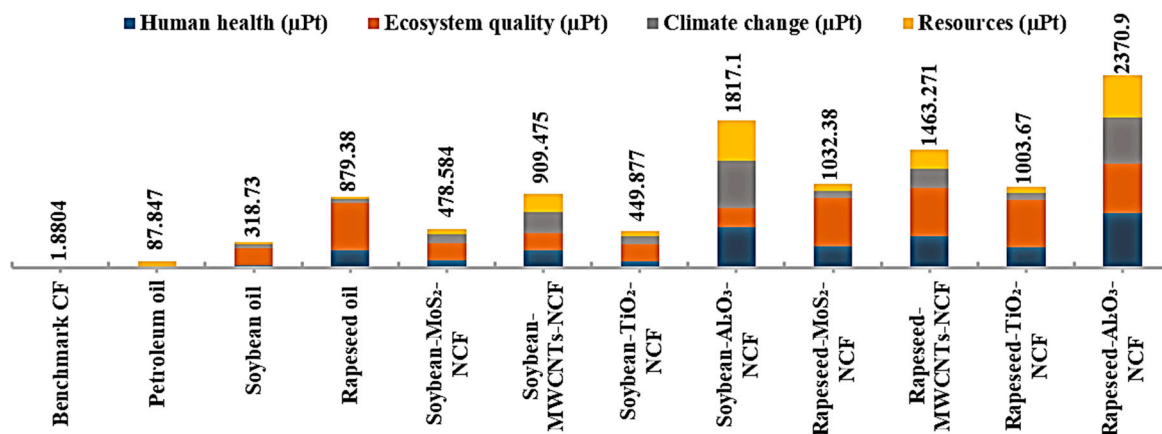
Figure 6. The single score of all damage categories for the considered cutting fluids.

3.5. LCA of Cooling Strategies

Twelve LCAs cooling techniques are presented, compared, and discussed in this section. LCAs are broken down into LCAs for TFC and MQL cooling techniques. TFC was considered for two conventional CFs (i.e., benchmark and petroleum oil). MQL cooling technique was considered for 10 CFs which are; two vegetable oils (i.e., soybean oil and rapeseed oil), and eight NCFs (i.e., soybean-MoS_2-NCF, soybean-MWCNTs -NCF, soybean-TiO_2-NCF, soybean-Al_2O_3-NCF, rapeseed-MoS_2-NCF, rapeseed-MWCNTs-NCF, rapeseed-TiO_2-NCF, rapeseed-Al_2O_3-NCF). The LCAs' functional unit that is adapted to compare cooling technique is the machining of a single M42 × 200 AISI 4043 bolt. The industrial bolt was presented and discussed, in the small to medium-sized enterprise (SME) in Western Australia [39]. Also, SME provided inputs and outputs data, which are utilized during the execution of this works LCAs. SME provided inventory information for machining a M42 × 200 AISI 4043 bolt. The information included: cutting energy, pumping energy, compressor energy, the quantity of coolant, and tool weight reduction. SME cutting energy and tool weight reduction information were excluded during the development of the presented LCAs, because their provided amounts are influenced by CFs [39] used. In regard to the pumping energy, TFC consumed 5.124×10^5 kWh per bolt, while the MQL cooling technique consumed 0.051 kWh during CFs pumping and air compressing. Although MQL uses approximately 7.6% of the amount of cutting fluid in TFC, it consumes considerably higher energy than TFC, due to the energy consumed by MQL's air compressor [39]. Figures 7 and 8 display the impacts of CF strategies on four damage categories, which are: human health, ecosystem quality, climate change, and resources. Damage categories are provided in μPt. Based on the displayed impacts, the TFC technique of benchmark CF has the lowest impact on the damage categories, followed by the TFC technique of petroleum oil. TFC of petroleum oil has a noticeably high impact on the resource category, because of the used extraction method of this type of CF. MQL technique of rapeseed oil displays a higher impact on the human health category by 14% and ecosystem quality category by 58%, than the MQL technique of soybean oil. However, in terms of climate change and resource categories both vegetable oil MQL techniques present similar impacts. Besides, there is a slight increase in the damage categories when comparing MQL-NFCs to MQL of vegetable oils. Slight increases range within: 2%–37%, 0%–10%, 3%–37%, and 3%–37% on human health, ecosystem quality, climate change, and resources categories, respectively.
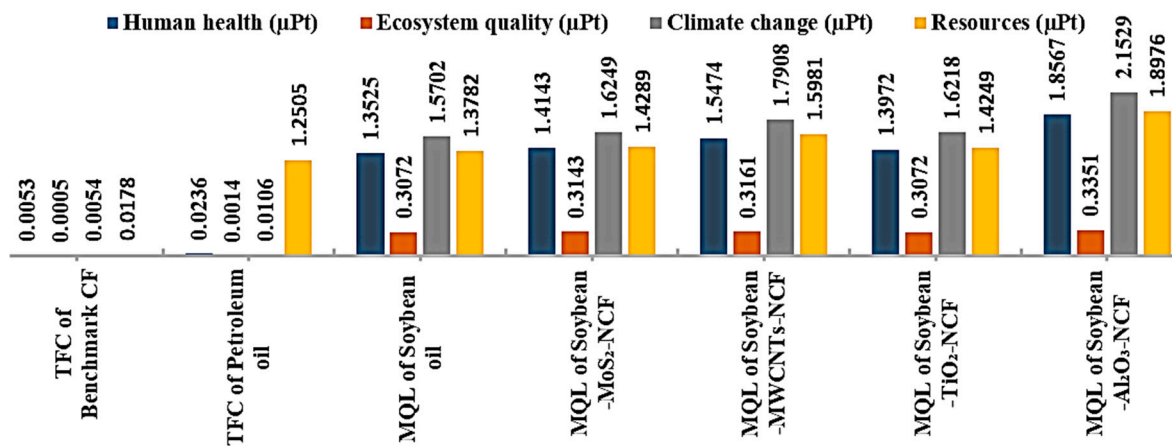
Figure 7. Damage categories of TFC of conventional CFs and MQL of nano-CFs based on soybean vegetable oil.
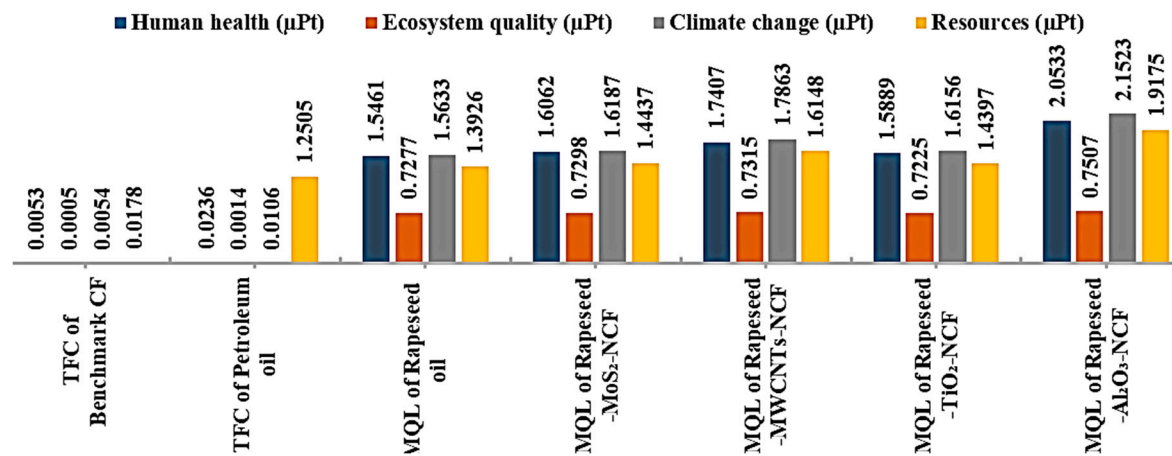

Figure 8. Damage categories of traditional flood cooling (TFC) of conventional CFs and minimum quantity lubrication (MQL) of nano-CFs based on rapeseed vegetable oil.

Figure 9 displays a single score for each analyzed cooling strategy. Out of the 12 investigated cooling strategies, TFC of benchmark CF presents the lowest impact on the four damage categories, and MQL of rapeseed-Al_2O_3-NCF presents the highest impact. Also, MQL of vegetable oils has higher impact scores than TFC of conventional CFs, even though they have similar damage impact scores on the resource category. In regard to vegetable oils, MQL of rapeseed oil has a higher impact than MQL of soybean oil by 11.9%. Additionally, damage impact scores increase by 14.13% by the introduction of nanoparticles. MQL NCFs of rapeseed oils have higher impact scores than the MQL NCFs of soybean oils, because of their base fluids impact scores. Due to the small used quantity of CFs and high used energy in MQL technique, the ecosystem quality scores are relatively small in comparison with scores of the other damage categories. Besides, it can be seen that the small quantity of cutting fluid associated with MQL reduce the increasing percentage of the total score of MQL of NFCs by the range of 3.7% to 35.4% in comparison with MQL of vegetable oils.
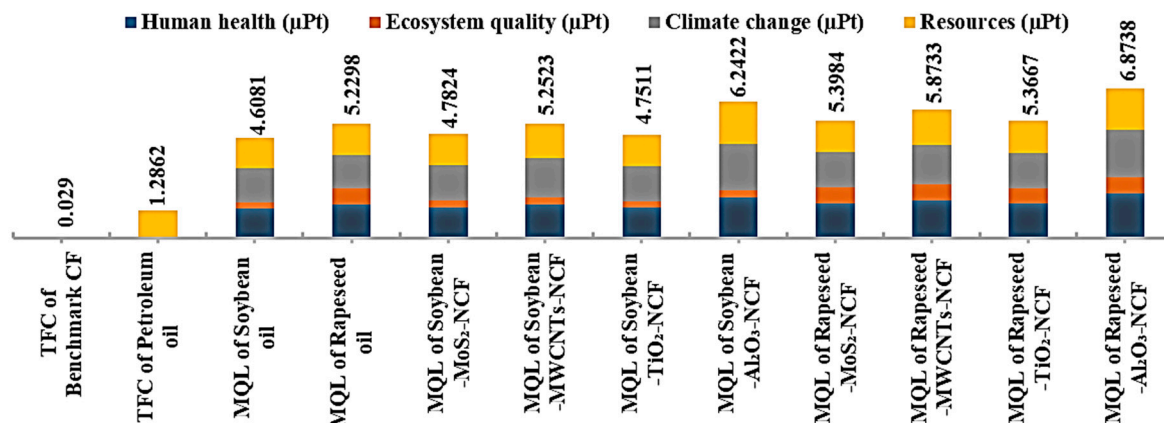
Figure 9. The single score of all damage categories for the considered cooling strategies.

4. Overall Evaluation of the Cooling Strategies

This subsection provides an overall qualitative evaluation of the considered cooling strategies. This evaluation covers the conducted cradle-to-gate LCA of cooling strategies, human health impacts during the machining process, environmental and human health impacts at end of life stage, as well as the machining performance as shown in Figure 10. The first three evaluation factors are based on the "lower-the-better criterion," while the fourth factor is based on the higher-the-better criterion. Besides, the evaluation has been conducted over three levels which are high, medium, and low.
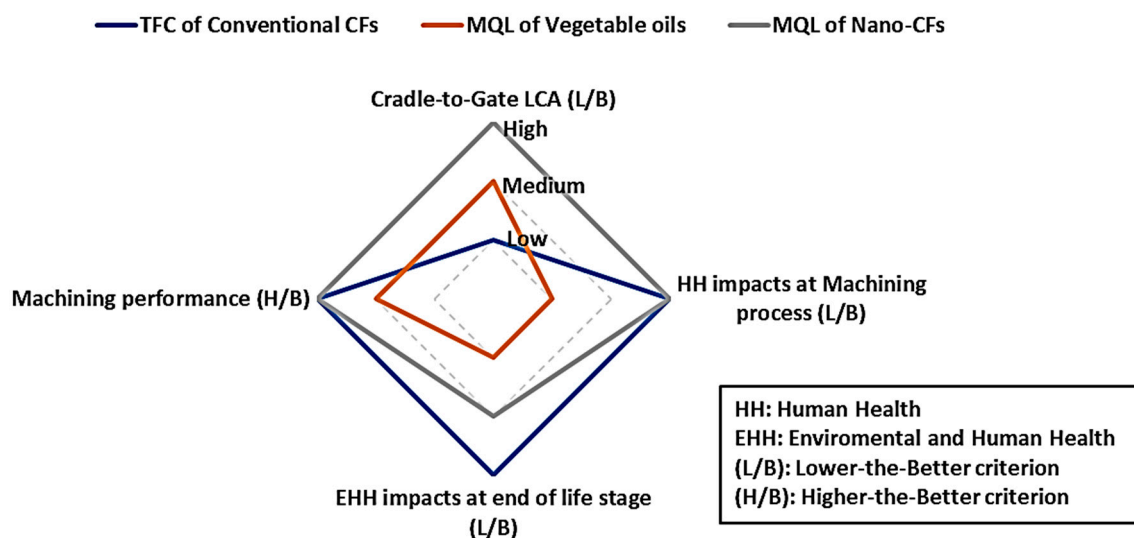

Figure 10. Schematic diagram of the overall evaluation of the cooling strategies.

Cradle-to-gate LCA: TFC of conventional CFs displayed the lowest impact on the four damage categories. Accordingly, this strategy has a low level of impact on cradle-to-gate LCA. The MQL of vegetable oils strategy achieved a medium level in this evaluation factor which presented higher impact scores compared to TFC of conventional CFs, however, they displayed close damage impact scores on the resource category. In addition, MQL of NCFs showed higher impact scores than MQL of their base fluids, and that is mainly due to the used synthesis processes. Thus, this strategy displays a high score in cradle-to-gate LCA as shown in Figure 10.

Human health impacts during the machining process: The usage of conventional CFs displays high human health impacts due to the high rates of occupational infections related to the development of cancer, respiratory distress, and skin disorders. Besides, the big quantity of the used conventional CFs in the TFC cooling strategy leads to sever impact for the human health factor for the machining performance factor as shown in Figure 10. Vegetable oils are organic products extracted from plant seeds

and consist of triglycerides, which are long chains of fatty acids combined with glycerol, and therefore, that makes the exposure of these fluids safe to the operators in the machining process. Utilizing the MQL technique for applying vegetable oils leads to low impacts of this cooling strategy. For the nano-CFs, nanosized particles are more toxic than larger particles, because nano-particles are smaller in size in comparison to human body cells, and this feature allows the body cells to capture these particles and negatively impact the human health. Although the vaporization of NCFs during MQL leads to small amounts of particles to be airborne, this cooling strategy showed a high level in human health factor at the machining process as shown in Figure 10 due to lack of information about exposure assessment of these particles.

Environmental and human health impacts at end-of-life stage: Conventional cutting fluids are made of combinations of oils, water, and other additives. Adding antimicrobial (biocides) and antifoam additives to control these problems leads to critical environmental problems due to the disposal process of these additives. Besides, the disposal of used CFs which included other additives of EP and corrosion inhibiting is only allowed in special incineration sites due to the generated toxins [2]. Consequently, the disposal of used conventional cutting fluids has been linked to pollution in water systems, air quality, and soil. Thus, TFC of conventional CFs displayed high impacts on environmental and human health impacts at end-of-life stage. Vegetable oils satisfy the aspects of CFs sustainability and are considered to be renewable, biodegradable, and can easily be degraded in soils due to their limited toxicity. Consequently, the MQL of vegetable oils achieved a low level of impact in this evaluation factor. For the NCFs, they need special types of separation and filtration processes before disposal and recycling. These processes are utilized to separate the NCF to its components of vegetable oil and nanoparticles and lead to eco-friendly disposal of the base-fluid of vegetable oils. Besides, these processes drive to reusing the separated nanoparticles instead of disposing of the whole nano-fluids. Therefore, the MQL of NCFs achieved a medium level of impact at the end of life stage.

Machining performance: The oil-based type of conventional CFs shows excellent lubrication properties which are needed at low cutting speeds machining processes. Oil-based CFs (i.e., pure petroleum oil) act as lubricants which decrease the coefficient of friction decreasing the generated forces. While the aqueous-based conventional CFs (i.e., benchmark CF) show excellent cooling properties and are preferably used in operations in which high heat is generated and relatively high cutting speeds are required. Conventional CFs offer a wide range of lubrication and cooling properties that are needed for different types of machining processes. Accordingly, the conventional CFs have a high-performance level as shown in Figure 10. Vegetable oils show desirable lubrication properties for the machining processes. Their lubrication properties come from their triglyceride structure and their long and polar fatty acid chains which are beneficial to decrease the friction between the tool-workpiece. Furthermore, vegetable oils have a higher flash point which makes vegetable oils less flammable. However, vegetable oils have their drawbacks: they are less reliable under high loads, and they have poor rust control and low thermal stability. Consequently, MQL of vegetable oils displays a medium level in machining performance. NCFs have a significant increase in the friction reduction between the contact surfaces and also reduce cutting forces and tool wear. Besides, they have many special effects such as bearing effect, mending effect, protective film effect, and polishing effect. The introduction of nanoparticles can improve the thermal conductivity of the vegetable oils, which enhance the cooling properties and thermal stability of the base oil, and allow to use a small quantity of CFs by MQL technique. Therefore, MQL of NCFs achieved a high level in the machining performance factor as shown in Figure 10.

According to the overall evaluation of the considered cooling strategies, the MQL of vegetable oils is the most sustainable cooling strategy for machining processes with associated low/medium cutting temperature. While MQL of TiO_2 and MoS_2 NCFs are the sustainable cooling strategy for machining processes associated with high cutting temperature due to their enhanced lubrication and cooling properties and small impacts of their dispersed nanoparticles. Accordingly, MQL of TiO_2 and MoS_2 NCFs cooling strategies with high personal protection procedures to the operators are considered as

sustainable strategies for machining difficult-to-cut material which have low thermal conductivity and high-speed machining processes.

5. Conclusions and Future Work

Available works in the literature have investigated the usage of MQL-NCF and presented its benefits in comparison to TFC techniques, in terms of machining process performance. However, environmental and human health impacts of NCFs and MQL have not been discussed or compared to TFC techniques. This paper presented and discussed 24 cradle-to-gate LCAs, which mainly focused on CFs and cooling strategies' impact on the environment and human personal health. Besides, it offers an overall evaluation of the considered cooling strategies through human health impacts at the machining process, environmental and human health impacts at end-of-life stage, and machining process performance. In terms of CFs, conventional benchmark CF presented the lowest impact scores on all damage categories, pure petroleum oil displayed a medium impact on the resources and very small impact on the other damage categories. Soybean and rapeseed oils showed high impacts on the ecosystem quality category. NCFs displayed higher impacts scores than their base vegetable oils that ranged between 41% to 470%, based on the used nano-additives, because of their impactful synthesis processes. TiO_2 and MoS_2 NCFs presented slightly higher impacts than the impacts of their base vegetable oils. However, TiO_2 and MoS_2 NCFs impacts were lower than the MWCNTs-NCF and Al_2O_3-NCF. Besides, NCFs of rapeseed oil displayed higher impacts than NFCs of soybean oil, because rapeseed oil had a higher impact score than soybean oil. In terms of cooling strategies, TFC of benchmark CF displayed the lowest impact on the four damage categories. The highest impact scores were displayed by MQL of rapeseed-Al_2O_3-NCF. In addition, MQL of rapeseed oil had a higher impact than MQL of soybean oil by 11.9%. MQL of NCFs had higher impact scores than MQL of their base fluids, mainly due to the used synthesis processes. MQL after adding 1 wt.% of nanoparticles to vegetable oil increased the total impact on average by 14.13%. TFC of conventional CFs displayed the lowest damage categories scores in comparison to MQL of vegetable oils and NCFs. However, TFC of conventional CFs is known to contribute to severe health problems for operators. Besides, its recycling is considered to be a challenging task. Conventional CFs offer a wide range of lubrication and cooling properties that are needed for different types of machining processes. MQL of NCFs displayed the highest damage categories scores compare to other cooling strategies, because of its energy-intensive synthesis process. Besides, operator exposure to nanosized particles can lead to respiratory distress and cancer. NCFs need special types of separation and filtering processes before disposal and recycling. MQL of NCFs achieved a high level of machining performance. MQL of vegetable oils displayed moderate impacts on the damage categories due to their cultivation and the fertilization processes. Besides, vegetable oils show a medium level of machining performance due to their low thermal stability. However, vegetable oils are considered to be environmentally friendly because they are renewable and biodegradable.

In terms of future work, the cradle-to-grave impacts of NCFs need more investigation along with developing the monitoring methodologies of the nanoparticles. Besides, research works are required to optimize the parameters of the synthesis process to reduce the energy consumption and impacts of NCFs. In addition, more attention is needed to develop new treatment techniques to eliminate the disposal problems of the NCFs to overcome their drawbacks.

References

1. Çakīr, O.; Yardimeden, A.; Ozben, T.; Kilickap, E. Selection of cutting fluids in machining processes. *J. Achiev. Mater. Manuf. Eng.* **2007**, *25*, 99–102.
2. Debnath, S.; Reddy, M.M.; Yi, Q.S. Environmental friendly cutting fluids and cooling techniques in machining: A review. *J. Clean. Prod.* **2014**, *83*, 33–47. [CrossRef]
3. Adler, D.; Hii, W.-S.; Michalek, D.; Sutherland, J. Examining the role of cutting fluids in machining and efforts to address associated environmental/health concerns. *Mach. Sci. Technol.* **2006**, *10*, 23–58. [CrossRef]
4. Sharma, V.S.; Singh, G.; Sørby, K. A review on minimum quantity lubrication for machining processes. *Mater. Manuf. Process.* **2015**, *30*, 935–953. [CrossRef]
5. Najiha, M.; Rahman, M.; Yusoff, A. Environmental impacts and hazards associated with metal working fluids and recent advances in the sustainable systems: A review. *Renew. Sustain. Energy Rev.* **2016**, *60*, 1008–1031. [CrossRef]
6. Abubakr, M.; Abbas, A.T.; Tomaz, I.; Soliman, M.S.; Luqman, M.; Hegab, H. Sustainable and Smart Manufacturing: An Integrated Approach. *Sustainability* **2020**, *12*, 2280. [CrossRef]
7. Kishawy, H.A.; Hegab, H.; Saad, E. Design for sustainable manufacturing: Approach, implementation, and assessment. *Sustainability* **2018**, *10*, 3604. [CrossRef]
8. Lawal, S.; Choudhury, I.; Nukman, Y. Application of vegetable oil-based metalworking fluids in machining ferrous metals—A review. *Int. J. Mach. Tools Manuf.* **2012**, *52*, 1–12. [CrossRef]
9. Singh, R.K.; Sharma, A.K.; Dixit, A.R.; Tiwari, A.K.; Pramanik, A.; Mandal, A. Performance evaluation of alumina-graphene hybrid nano-cutting fluid in hard turning. *J. Clean. Prod.* **2017**, *162*, 830–845. [CrossRef]
10. Lee, K.; Hwang, Y.; Cheong, S.; Choi, Y.; Kwon, L.; Lee, J.; Kim, S.H. Understanding the role of nanoparticles in nano-oil lubrication. *Tribol. Lett.* **2009**, *35*, 127–131. [CrossRef]
11. Khandekar, S.; Sankar, M.R.; Agnihotri, V.; Ramkumar, J. Nano-cutting fluid for enhancement of metal cutting performance. *Mater. Manuf. Process.* **2012**, *27*, 963–967. [CrossRef]
12. Shahnazar, S.; Bagheri, S.; Hamid, S.B.A. Enhancing lubricant properties by nanoparticle additives. *Int. J. Hydrogen Energy* **2016**, *41*, 3153–3170. [CrossRef]
13. Uysal, A.; Demiren, F.; Altan, E. Applying minimum quantity lubrication (MQL) method on milling of martensitic stainless steel by using nano MoS_2 reinforced vegetable cutting fluid. *Procedia Soc. Behav. Sci.* **2015**, *195*, 2742–2747. [CrossRef]
14. Amrita, M.; Srikant, R.; Sitaramaraju, A. Performance evaluation of nanographite-based cutting fluid in machining process. *Mater. Manuf. Process.* **2014**, *29*, 600–605. [CrossRef]
15. Sen, B.; Mia, M.; Krolczyk, G.; Mandal, U.K.; Mondal, S.P. Eco-friendly cutting fluids in minimum quantity lubrication assisted machining: A review on the perception of sustainable manufacturing. *Int. J. Precis. Eng. Manuf. Green Technol.* **2019**, 1–32. [CrossRef]
16. Benedicto, E.; Carou, D.; Rubio, E. Technical, economic and environmental review of the lubrication/cooling systems used in machining processes. *Procedia Eng.* **2017**, *184*, 99–116. [CrossRef]
17. Wusiman, K.; Jeong, H.; Tulugan, K.; Afrianto, H.; Chung, H. Thermal performance of multi-walled carbon nanotubes (MWCNTs) in aqueous suspensions with surfactants SDBS and SDS. *Int. J. Heat Mass Transf.* **2013**, *41*, 28–33. [CrossRef]
18. Hegab, H.; Umer, U.; Soliman, M.; Kishawy, H.A. Effects of nano-cutting fluids on tool performance and chip morphology during machining Inconel 718. *Int. J. Adv. Manuf. Technol.* **2018**, *96*, 3449–3458. [CrossRef]
19. Das, A.; Patel, S.; Biswal, B.; Sahoo, N.; Pradhan, A. Performance evaluation of various cutting fluids using MQL technique in hard turning of AISI 4340 alloy steel. *Measurement* **2020**, *150*, 107079. [CrossRef]
20. Rapeti, P.; Pasam, V.K.; Gurram, K.M.R.; Revuru, R.S. Performance evaluation of vegetable oil based nano cutting fluids in machining using grey relational analysis-A step towards sustainable manufacturing. *J. Clean. Prod.* **2018**, *172*, 2862–2875. [CrossRef]
21. Gupta, M.K.; Jamil, M.; Wang, X.; Song, Q.; Liu, Z.; Mia, M.; Hegab, H.; Khan, A.M.; Collado, A.G.; Pruncu, C.I. Performance Evaluation of Vegetable Oil-Based Nano-Cutting Fluids in Environmentally Friendly Machining of Inconel-800 Alloy. *Materials* **2019**, *12*, 2792. [CrossRef]
22. Sen, B.; Mia, M.; Gupta, M.K.; Rahman, M.A.; Mandal, U.K.; Mondal, S.P. Influence of Al_2O_3 and palm oil–mixed nano-fluid on machining performances of Inconel-690: IF-THEN rules–based FIS model in eco-benign milling. *Int. J. Adv. Manuf. Technol.* **2019**, *103*, 3389–3403. [CrossRef]

23. Salem, A.; Hegab, H.; Kishawy, H.; Rahnamayan, S. Multi-objective Optimization During Sustainable Machining of Difficult-to-Cut Materials. In Proceedings of the Joint Canadian Society for Mechanical Engineering and CFD Society of Canada International Congress 2019, London, ON, Canada, 2–5 June 2019.

24. Deorsola, F.; Russo, N.; Blengini, G.; Fino, D. Synthesis, characterization and environmental assessment of nanosized MoS_2 particles for lubricants applications. *Chem. Eng. J.* **2012**, *195*, 1–6. [CrossRef]

25. Krajnik, P.; Pusavec, F.; Rashid, A. Nanofluids: Properties, applications and sustainability aspects in materials processing technologies. In *Advances in Sustainable Manufacturing*; Springer: Heidelberg, Germany, 2011; pp. 107–113.

26. Campitelli, A.; Cristóbal, J.; Fischer, J.; Becker, B.; Schebek, L. Resource efficiency analysis of lubricating strategies for machining processes using life cycle assessment methodology. *J. Clean. Prod.* **2019**, *222*, 464–475. [CrossRef]

27. Mia, M.; Gupta, M.K.; Lozano, J.A.; Carou, D.; Pimenov, D.Y.; Królczyk, G.; Khan, A.M.; Dhar, N.R. Multi-objective optimization and life cycle assessment of eco-friendly cryogenic N_2 assisted turning of Ti-6Al-4V. *J. Clean. Prod.* **2019**, *210*, 121–133. [CrossRef]

28. Gupta, M.K.; Song, Q.; Liu, Z.; Pruncu, C.I.; Mia, M.; Singh, G.; Lozano, J.A.; Carou, D.; Khan, A.M.; Jamil, M. Machining characteristics based life cycle assessment in eco-benign turning of pure titanium alloy. *J. Clean. Prod.* **2020**, *251*, 119598. [CrossRef]

29. Finkbeiner, M.; Inaba, A.; Tan, R.; Christiansen, K.; Klüppel, H.-J. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* **2006**, *11*, 80–85. [CrossRef]

30. Ekvall, T.; Finnveden, G. Allocation in ISO 14041—A critical review. *J. Clean. Prod.* **2001**, *9*, 197–208. [CrossRef]

31. Ryding, S.-O. ISO 14042 Environmental management* Life cycle assessment* life cycle impact assessment. *Int. J. Life Cycle Assess.* **1999**, *4*, 307. [CrossRef]

32. Lecouls, H. ISO 14043: Environmental management· life cycle assessment· life cycle interpretation. *Int. J. Life Cycle Assess.* **1999**, *4*, 245. [CrossRef]

33. Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.; Suh, S. Recent developments in life cycle assessment. *J. Environ. Manag.* **2009**, *91*, 1–21. [CrossRef]

34. Menoufi, K.A.I. Life Cycle Analysis and Life Cyle Impact Assessment Methodologies: A State of the Art. 2011. Available online: http://hdl.handle.net/10459.1/45831 (accessed on 13 October 2020).

35. Jolliet, O.; Margni, M.; Charles, R.; Humbert, S.; Payet, J.; Rebitzer, G.; Rosenbaum, R. IMPACT 2002+: A new life cycle impact assessment methodology. *Int. J. Life Cycle Assess.* **2003**, *8*, 324. [CrossRef]

36. Padmini, R.; Krishna, P.V.; Rao, G.K.M. Effectiveness of vegetable oil based nanofluids as potential cutting fluids in turning AISI 1040 steel. *Tribol. Int.* **2016**, *94*, 490–501. [CrossRef]

37. Hegab, H. Towards Sustainable Machining of Difficult-to-Cut Materials Using Nano-Cutting Fluids. Ph.D. Thesis, University of Ontario Institute of Technology, Oshawa, ON, Canada, 2018.

38. Zhu, D.; Li, X.; Wang, N.; Wang, X.; Gao, J.; Li, H. Dispersion behavior and thermal conductivity characteristics of Al_2O_3–H_2O nanofluids. *Curr. Appl. Phys.* **2009**, *9*, 131–139. [CrossRef]

39. Ginting, Y.; Boswell, B.; Biswas, W.; Islam, M.N. Advancing environmentally conscious machining. *Procedia Cirp* **2015**, *26*, 391–396. [CrossRef]

40. Clarens, A.F.; Zimmerman, J.B.; Keoleian, G.A.; Hayes, K.F.; Skerlos, S.J. Comparison of life cycle emissions and energy consumption for environmentally adapted metalworking fluid systems. *Environ. Sci. Technol.* **2008**, *42*, 8534–8540. [CrossRef] [PubMed]

41. Sahasrabudhe, S.N.; Rodriguez-Martinez, V.; O'Meara, M.; Farkas, B.E. Density, viscosity, and surface tension of five vegetable oils at elevated temperatures: Measurement and modeling. *Int. J. Food Prop.* **2017**, *20*, 1965–1981. [CrossRef]

42. Griffiths, O.G.; O'Byrne, J.P.; Torrente-Murciano, L.; Jones, M.D.; Mattia, D.; McManus, M.C. Identifying the largest environmental life cycle impacts during carbon nanotube synthesis via chemical vapour deposition. *J. Clean. Prod.* **2013**, *42*, 180–189. [CrossRef]

43. Grubb, G.F.; Bakshi, B.R. Life cycle of titanium dioxide nanoparticle production: Impact of emissions and use of resources. *J. Ind. Ecol.* **2011**, *15*, 81–95. [CrossRef]

44. Ojeda, K.A.; Herrera, A.P.; Sierra, M.J.; Tamayo, K. Environmental impact study by life cycle assessment of the use of alumina nanoparticles as an additive in biodiesel/diesel blends. *Ing. Compet.* **2015**, *17*, 133–142.

45.   Ali, N.; Teixeira, J.A.; Addali, A. A review on nanofluids: Fabrication, stability, and thermophysical properties. *J. Nanomater.* **2018**, *2018*, 6978130. [CrossRef]

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