*lubricants*

MDPI

*Article*

# Olive Pomace Oil as a Chainsaw Lubricant: First Results of Tests on Performance and Safety Aspects

**Roberto Fanigliulo [1,*], Paolo Bondioli [2], Marcello Biocca [1], Renato Grilli [1], Pietro Gallo [1], Laura Fornaciari [1], Liliana Folegatti [3], Stefano Benigni [1], Igor Calderari [2], Francesco Gallucci [1] and Daniele Pochi [1]**

[1] Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA)—Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari (Research Centre for Engineering and Agro-Food Processing), Via della Pascolare 16, Monterotondo, 00015 Rome, Italy; marcello.biocca@crea.gov.it (M.B.); renato.grilli@crea.gov.it (R.G.); pietro.gallo@crea.gov.it (P.G.); laura.fornaciari@crea.gov.it (L.F.); stefano.benigni@crea.gov.it (S.B.); francesco.gallucci@crea.gov.it (F.G.); daniele.pochi@crea.gov.it (D.P.)

[2] ASSITOL, Associazione Italiana dell'Industria Olearia, Piazza di Campitelli 3, 00186 Rome, Italy; paolo.bondioli1956@gmail.com (P.B.); igor.calderari@assitol.it (I.C.)

[3] InnovHub, Stazioni Sperimentali Industria, Area SSOG, Via G. Colombo 79, 20133 Milan, Italy; liliana.folegatti@mi.camcom.it

* Correspondence: roberto.fanigliulo@crea.gov.it

**Abstract:** The total loss lubrication system that is typical of chainsaws is responsible for a massive dispersion in the agro-forestry environment of highly impactful pollutants, mostly of fossil origin, often well known as carcinogenic substances, which, in addition to presenting a risk to the environment, represent an important risk factor for human health, especially for chainsaw users. During its use, the chain lubricant is dispersed from the guide bar tip in the form of droplets and aerosol, or it is adsorbed on wood residues and sawdust. Then, it is subjected to drift, settles on the ground and vegetation, and can hit the operators, who, after prolonged exposures, can suffer both irritation of the respiratory tract and dermal absorption. Such a risk factor is often amplified by the widespread use of less-expensive, sometimes illegal alternatives, such as exhausted motor oils. To mitigate said negative effects, a process has been in progress for several years that is aimed at replacing conventional lubricants with synthetic or biobased oils with increasing biodegradability. As a contribution to this process, a study has been started on the possibility of using refined olive pomace oil (ROPO) as a base stock for the formulation of a totally biodegradable chainsaw lubricant. On purpose, to improve its properties of viscosity and adhesivity, such an oil was added with a biodegradable thickening agent, obtaining four formulations with different viscosity. After a lab test and a preliminary cutting test on firewood, the formulation with 2% of thickener resulted in being the best, and 3.0 g kg$^{-1}$ of *tert*-butylhydroquinone (TBHQ), a food-grade antioxidant, was then added to form the final formulation ($F_2$) to be compared, in the subsequent four test sessions, to a biodegradable commercial chain lubricant ($S_B$). The tests were carried out without changing the chainsaw setting, on different wood species, both in forest and, with the aim of increasing the repeatability of tests conditions and comparability of results, at a fixed point. The fluids' performances were mainly evaluated based both on the operators' opinions and on the measurements of the chain–bar temperatures and of saw chain wear related to a predefined number of cuts. As to the destiny of the fluid dispersed during cutting, the overall dispersion was assessed by considering the average working time, the consumption of chain lubricant, and the forest area cut down daily. Eventually, the amounts of inhalable and respirable dust particles as vectors of oil residues were quantified by means of personal air samplers worn by the operators and analyzed to determine any differences in the concentration of metallic elements. The test results evidenced chain temperatures that were 0.5, 4.9, and 12.5 °C higher with $F_2$ relating to $S_B$, respectively, in the cutting of trunks of fresh *Pinus*, *Eucalyptus*, and dry *Pinus*. They were accompanied by chain weight losses of 89.5% and 35% higher with $F_2$ relating to $S_B$, respectively, in cutting tests of Turkey oak and Poplar. Such a greater wear, however, apparently did not affect the saw chain's cutting efficiency with $F_2$, since the operators declared that they did not notice any difference between the performances of the two fluids at the time of comparison. The effects of higher wear on the chain lifetime, any deriving risks for the operator's safety, and the possibility to reduce the wear levels observed with $F_2$

check for updates

**Citation:** Fanigliulo, R.; Bondioli, P.; Biocca, M.; Grilli, R.; Gallo, P.; Fornaciari, L.; Folegatti, L.; Benigni, S.; Calderari, I.; Gallucci, F.; et al. Olive Pomace Oil as a Chainsaw Lubricant: First Results of Tests on Performance and Safety Aspects. *Lubricants* **2023**, *11*, 494. https://doi.org/10.3390/lubricants11110494

Received: 11 October 2023
Revised: 3 November 2023
Accepted: 9 November 2023
Published: 15 November 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

will be explored in a further study, e.g., through different settings of the lubricating system of the chainsaw. The results of the analyses of the air-sampled dust residues that were evidenced with $F_2$ showed lower concentrations of respirable and inhalable particles and of some metallic elements (Al, Mg, and Ca) than those with $S_B$. This behavior probably depends on the different interaction between sawdust and the two fluids, which differ according to their chemical–physical characteristics (different viscosity, composition, and additives). However, it represents a positive factor in favor of the use of the ROPO-based lubricant, emphasized by the total biodegradability of its residues that are possibly contained in the dust inhaled by the operators.

**Keywords:** chainsaw; lubrication; biodegradable oil; environmental contamination; guide bar temperature; chain wear; circular economy

## 1. Introduction

The negative impact on the environmental and the food chain contamination from mineral oil-based lubricants, fuels, and technical products becomes more evident every day. Several studies containing numerous evidence of the source of this contamination are available [1–5]. Contamination can be derived from automotive gas exhaust, oil spillage from hydraulic devices of agricultural machines, and aerosols produced by two-stroke engines in use during infield activity (air blowers, grass trimmers, branch shakers, etc.) [6,7].

One of the most impacting dispersions of pollutants in agriculture is that seen in total loss lubrication systems connected with the use of chainsaws in agro-forestry practice for green maintenance and pruning. The use of loss lubricants is needed to ensure the proper lubrication and cooling of the chains and other devices during cutting activity [8]. Modern chainsaws release the oil from the bar tip once it has traveled around the guide bar. The lubricating oil enters the environment as aerosol, as oil adsorbed on wood residues and sawdust, and directly as droplets depositing on the ground and vegetation [9]. Most petroleum-based lubricating chain oils are well-known carcinogenic substances [10,11]. In addition, prolonged exposure to oil mists due to the high speed of the chainsaw can cause irritation of the user's respiratory tract or dermal absorption. Such risk factors to workers' health could certainly be amplified by the widespread use of less-expensive, sometimes illegal alternatives, such as exhausted motor oils, as chain lubricants.

Based on these considerations, our research group started to study the possibilities of technical use of refined olive pomace oil (ROPO) with different targets:

- Promoting the use of vegetable oils with additives in concentration as low as possible as lubricants along the food chain to replace mineral oil-based lubricants.
- Contributing to the reduction of mineral oil contamination of food and the environment.
- Finding alternative uses for ROPO, a solvent extracted from dried olive residues (pomace) that is an involuntary by-product of the olive oil production chain.

The main production sites of crude olive pomace oil are in Spain, Italy, and Greece. It cannot be used as it is because of the strong dark color, bad smell, and high free acidity values. The refined product, generally prepared by physical refining, is a yellow oil with low acidity and a flat taste such as that of all refined vegetable oils. The refined oil cannot be marketed in pure form, but it must be mixed with a certain amount of extra virgin olive oil, according to European Regulation 2022/2104 [12].

When our research began, one of the driving forces was represented by the very low market price of ROPO in comparison with other refined liquid vegetable oils, such as sunflower, rapeseed, and soy. With the beginning of the Ukraine War in February 2022, the vegetable oil market underwent dramatic trouble and, at this moment, ROPO has a bulk price that is higher than its seed oil competitors. All considerations reported in this paper can obviously be translated to a number of natural vegetable oils with a similar unsaturation degree. The use of vegetable oils as substitutes for mineral oils is not an absolute novelty, but the interest in this field has been recently reinforced by the results reported in some papers about the study of contamination along the food chain, from the field to the packaging of food products [13–15].

Vegetable-based lubricants first appeared in the marketplace in Europe in the mid-1980s. The acceptance and use of these products, particularly in the European forest industry, is widespread and growing. The two main reasons for this are concerns about workers' occupational safety and health, and environmental protection. Vegetable oils have natural properties, including good lubricity, resistance to shear, a high flash point, and a high viscosity index. These qualities give the vegetable oils chain lubricant requirements similar to petroleum-based chain oils [16–18]. Our research group developed a solid background with several previous research projects; the last of them was the Agroener Project, supported by the Italian Ministry of Agriculture, leading to the design and the test of hydraulic fluids based on *Crambe abyssinica* and *Carthamus tinctorius* oils, minimally refined [19,20]. In a previous paper, the preparation and evaluation of hydraulic fluid based on ROPO was also discussed.

As mentioned before, the role of a lubricating oil for chainsaw covers different aspects, ranging from the friction reduction during use to the cooling of the moving device, until the protection of the integrity of the equipment [21]. Another less evident property, but necessary for a chainsaw oil, is the adhesiveness towards metallic surfaces, as this characteristic is fundamental to keeping the chain well-oiled during use. Considering a common chainsaw, in the tip section of the bar–chain system, where the chain completes a 180° arc to return towards the machine body, the centrifugal force is maximum and causes the outwards oil dispersion, leaving the lower part of the chain without lubricant during the cutting.

Unlike other different refined vegetable oils obtained from low-acidity crude feedstocks, ROPO comes from a starting material with a high content of free fatty acids. While acidity is easily removed, the neutralized oil contains a high concentration of partial glycerides (mainly diglycerides in a 4–7% concentration), whose molecules confer high polarity and better metal affinity to this fluid. Despite this property, in some chainsaws, we observed the spatter phenomenon during use. For this reason, a humectant–viscosifier additive was added at different doses to improve the oil performance, producing four formulations. The final formula tested was based on ROPO containing 2% of thickening biodegradable additive and 3.0 g $kg^{-1}$ of food-grade antioxidant (*tert*-buthylhydroquinone, TBHQ) to preserve the olive pomace oil from the oxidative degradation during the field tests. According to a green chemistry approach, both additives were chosen for their good characteristics in terms of both environmental and health safety and technical efficiency to obtain a fully biodegradable lubricant.

This paper describes the evolution of a study articulated in five test sessions aimed at exploring the various aspects connected to the use of ROPO-based fluid for the lubrication of saw chains. Each step of the activity provided additional information and suggestions used to set up the next step and increase our knowledge of the matter. The tests concerned the assessment of the ROPO-based fluid by comparing its performance to that of a widespread conventional lubricant for chainsaws in different operative contexts, ranging from the felling of trees in the forest to tests at the fixed point, with the aim of increasing, at each step, the repeatability of the test conditions and the comparability of the results.

Parallelly, based on previous experiences of air sampling used to determine the presence of pollutants in the dust produced during agricultural operations [22] and considering the impact that the use of chainsaws may have both on forest environments and on human health, the tests of cutting were accompanied by a series of air samplings to assess the amount of inhalable and respirable dust fractions and of metallic elements contained in the dust according to the EPA methodology [23] for essential and toxic elements in order to assess the level of exposure of the operators to wood dust and to the substances it possibly contains. According to the Directives (EU) 2019/130 [24] and (EU) 2017/2398 [25], wood dust is recognized as a carcinogenic agent that is also responsible for other pathologies of the respiratory tract; the analyses of dust emissions referred to the limit value of 2 mg $m^{-3}$

during eight hours of work [26] of hardwood dust concentration (as an inhalable fraction), as established in said directives. The gravimetric analysis of the dust residues considered inhalable and respirable fractions and the dimensional composition of the latter according to five classes. The dust concentrations were related to the detected amounts of metallic elements and to the emissions of chain lubricants to assess the relative amounts inhaled by the operators and dispersed into the environment with the assumption that the use of a highly biodegradable lubricant such as the ROPO-based fluid can help reduce the risk to both the operator's health and the environment.

## 2. Materials and Methods

The assessment of the aptitude of refined olive pomace oil (ROPO)-based fluid as chain lubricant was made by comparing its performance to that of a commercially available conventional fluid in different test sessions.

### *2.1. Chain Lubricants at Comparison*

#### 2.1.1. ROPO-Based Biolubricant

ROPO was provided by Casa Olearia (Bari, Italy). It is a refined product that is obtained via hexane extraction of dried olive oil residues, physically refined. The food destination of such a fluid requires its mandatory mixing with extra virgin olive oil.

##### Analytical Methods for ROPO Evaluation

All reported results are the average values of two independent evaluations after a repeatability requirement check. All used methods are International Standards, public, easily available, and completed by precision data.

##### Oil Additivation with Viscosifier/Humectant and Antioxidant

Considering the possibility that some ROPO characteristics, such as viscosity, moistening capacity, and adhesiveness, had to be increased to better perform the chain lubrication, an additive with suitable characteristics was identified. It was the BIOTAC, which was provided by Brad-Chem Ltd. (Leigh, Lancashire, UK) through the Italian representative URAI (Milan, Italy). According to the technical sheet, it is an additive based on natural rubbers and is therefore biodegradable and very sticky. The main features/benefits claimed by the manufacturer are as follows:

- Highly viscous, fluid.
- All components are biodegradable (90% by OECD 301B Guideline).
- Approved by the Food and Drug Administration (Sections 177.1030 and 184.1555).
- Quickly and easily dissolves in natural vegetable oils, including rapeseed oil. It is also soluble in TMP oleate and other synthetic esters.
- Enhances biodegradable vegetable properties.

Moreover, to preserve ROPO from oxidative degradation during the functional tests, a food-grade antioxidant was added at the same time.

##### Chainsaw Oil Preparation

The preparation procedure was split into two steps:

- Preparation of a mother solution. To prepare 10 L of the oil-additives blend, 1 L of ROPO was heated at 80 °C in a 2-L beaker, under stirring. Due to its very high viscosity, the BIOTAC additive also had to be preheated at 80 °C in the oven before use. When both constituents reached the set temperature, a certain amount of BIOTAC additive was added to the oil, continuing the stirring and heating until all additive was dissolved, and the mother solution was ready. During the described preparation, 3.0 g $kg^{-1}$ of *tert*-butylhydroquinone antioxidant (TBHQ—Aldrich cod. 112941, Merck Life Science srl, Milan, Italy) was added to the oil using the same procedure.

- Dilution of the mother solution in the final 10-L blend. To obtain the desired additive concentration in the final fluid, the obtained mother solution was diluted ten times to obtain the final fluid for tests.

According to this procedure, four formulations were produced: the first, $F_0$, only consisted of ROPO and TBHQ, and the other three, i.e., $F_1$, $F_2$, and $F_3$, contained, respectively, 1%, 2%, and 3% BIOTAC, with the aim of studying their behaviors as lubricants for chainsaws. The analyses were carried out according to standard methods. Each used method is reported near the measurement results in Section 3.

#### 2.1.2. Conventional Lubricant

The four ROPO-based formulations just described were compared with the oil Stihl Bioplus ($S_B$ in the following), a very popular good-quality biodegradable chain lubricant (kinematic viscosity at 40 °C: 37.19 $mm^2 \cdot s^{-1}$). It is a bio-oil, and, as such, it is less harmful to the environment than mineral lubricants.

### *2.2. Tests*

Several test sessions on different chainsaws lubricated by the fluids described in Section 2.1 were carried out under different work conditions. The aim of the tests was to observe the various aspects of ROPO use and to evaluate its attitude compared to a conventional chain lubricant on the market. The comparison was based on various criteria, such as the following:

- Evaluations expressed by the operators.
- Observation of the temperature of the chain and of the guide bar during cutting, under the hypothesis that any different lubricating capacity of the tested fluids could lead to different friction values in the interface between the bar and chain and consequent to different heating levels.
- Assessment of the wear of the chain through mass measurements before and after cutting activity.
- Quantitative and qualitative analysis of the air-borne particulate sampled during cutting with the chain lubricants used.

These criteria were progressively introduced into five test sessions, whose setup varied depending on the specific aims of each of them. Therefore, each test was indicated by a "T" followed by a number (0 to 4).

During a preliminary wood trunk-cutting test ($T_0$), two chainsaws were used with four different fluids formulated with ROPO at four different concentrations of the thickening agent (0, 1, 2, and 3%). The second test ($T_1$), lasting two days, concerned the professional felling of forest trees by three specialized workers utilizing two ROPO formulations in comparison with a commercially available biodegradable oil, which lubricated two professional chainsaws. The third test ($T_2$) provided interesting results concerning the operability of the best formulation of the vegetable fluid tested in the previous tests, in comparison with the same conventional fluid, during cutting tests at the fixed point, utilizing two different chainsaws, one of which was operated by a wireless electric motor. The fourth and the fifth tests ($T_3$ and $T_4$) regarded the same two oils and the endothermic chainsaw used in $T_2$ which were used in the intensive crosscutting of trunks at the fixed point and in the felling of a 15-year-old poplar grove, respectively.

Their general layout is summarized in Table 1, while Tables 2 and 3 report the main characteristics of, respectively, the used chainsaws and of the adopted sensors and analytical methods.

**Table 1.** Layout of the tests.

| Tests | $T_0$ | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
|---|---|---|---|---|---|
| Location | Bomarzo, Italy | Mugnano, Italy | Monterotondo (Rome), Italy | | |
| Period | October 2020 | February 2021 | June 2021 | December 2021 | February 2022 |
| Duration (days) | 2 | 2 | 1 | 1 | 1 |
| Activity | Firewood cutting | Forest cutting | Intensive cutting at a fixed point | Intensive cutting at a fixed point | Felling of a poplar grove |
| Operators | 1 worker | 3 lumberjacks | 1 worker | 1 worker | 1 worker |
| Chain lubricants | $F_0$, $F_1$, $F_2$, $F_3$ | $F_0$, $F_2$, $S_B$ | $F_2$, $S_B$ | $F_2$, $S_B$ | $F_2$, $S_B$ |
| Trunk dimensions | Variable size | Diam.: 25–40 cm | Diam.: 15–20 cm<br>Length: 2.5 m | Diam: 30–35 cm<br>Length: 2.5 m | Diam: 15–20 cm<br>Length: 12–18 m |
| Tree species | Turkey oak | Turkey oak | *Pinus*, *Eucalyptus* | Turkey oak | Poplar |
| Measurements carried out during tests | - | Diameter of cuts | Diameter of cuts | Diameter of cuts | Diameter of cuts |
| | - | Cuts number per full of oil | Number of cuts | Number of cuts | Number of cuts per full of oil |
| | Bar and chain temperature | Bar and chain temperature | Bar and chain temperature | Bar and chain temperature | - |
| | Oil temperature inside the reservoir | Internal temp. of freshly cut trunks | Internal temp. of freshly cut trunks | Internal temp. of freshly cut trunks | - |
| | Weather conditions | Weather conditions | Weather conditions | Weather conditions | - |
| | - | Air/dust sampling and analysis | Air/dust sampling and analysis | Chain wear (mass variation) | Chain wear (mass variation) |
| | - | Sampling of sawdust and analysis | Sampling of sawdust and analysis | Thermographic analysis | - |
| Other observations | Operator ratings | | | | |

**Table 2.** Chainsaws used in the tests.

| Tests | $T_0$ | | $T_1$ | | $T_2$ | | $T_3$, $T_4$ |
|---|---|---|---|---|---|---|---|
| Brand | Husqvarna | Oleomac | Husqvarna | Stihl | Stihl | Pellenc [1] | Stihl |
| Model | 353 | 952 | 372 XP | 362 C | MS 201TC | C21HD | MS 201TC |
| Engine Displacement ($cm^3$) | 51.7 | 51.7 | 70.7 | 59 | 35.2 | 45.0 [2] | 35.2 |
| Power (kW) | 2.4 | 2.5 | 3.9 | 3.5 | 1.8 | 2.0 | 1.8 |
| Max recom. engine speed ($min^{-1}$) | 13,000 | 13,000 | 13,500 | 10,000 | 10,500 | 6200 | 10,500 |
| Fuel reservoir volume (L) | 0.50 | 0.50 | 0.77 | 0.60 | 0.30 | - | 0.30 |
| Oil reservoir volume (L) | 0.28 | 0.27 | 0.40 | 0.32 | 0.22 | 0.25 | 0.22 |
| Oil pump type | Adjustable flow | | | | | | |
| Chain pitch (mm) | 8.0 | 9.5 | 9.5 | 9.5 | 9.5 | 6.35 | 9.5 |
| Guide bar length (mm) | 460 | 460 | 450 | 500 | 350 | 280 | 350 |
| Ac. pressure, dB (A) | 102 | 101 | 103 | 106 | 100 ± 2.5 | 85 | 100 ± 2.5 |
| Ac. power, dB (A) | 113 | 113 | 115 | 117 | 113 ± 2.5 | 100 | 113 ± 2.5 |
| Vibration front/rear ($mm \cdot s^{-2}$) | 3.1/3.2 | 5.2/5.5 | 3.5/4 | 3.5/3.5 | 3.5/3.1 | 2.5/2.5 | 3.5/3.1 |
| Mass without cutting group (kg) | 5.0 | 5.4 | 6.1 | 5.95 | 3.7 | 2.55 | 3.7 |

[1] Electric wireless chainsaw. [2] Displacement of an internal combustion engine chainsaw with equivalent performance, according to the datasheet.

**Table 3.** Sensors and analytical methods used in the tests.

| Type of Measurement | Parameters | $T_0$ | $T_1$ | $T_2$ | $T_3$ | $T_4$ |
|---|---|---|---|---|---|---|
| Atmospheric conditions | Temperature, R.H., Wind speed, Atm. pressure | Local bulletin https://www.ilmeteo.it/meteo/Bomarzo (accessed on 22 October 2020) | Portable weather station Kestrel® 4500 (R-P-R Ltd., Lymington, UK) | | | |
| Measurements during cutting activity | Trunk length and diameter | - | Manual measurement | | | |
| | Oil temp. (in the tank) | Salmoiraghi Digital thermometer 301H + | - | - | - | - |

**Table 3.** *Cont.*

<table>
<tr><th colspan="2">Type of Measurement</th><th>Parameters</th><th>$T_0$</th><th>$T_1$</th><th>$T_2$</th><th>$T_3$</th><th>$T_4$</th></tr>
<tr><td colspan="2" rowspan="4">Measurements during cutting activity</td><td>Chain/bar temperature</td><td>RTD PT100 probe (Resolution: 0.1 °C; Accuracy: ±0.1%)</td><td colspan="2" rowspan="2">Infrared thermometer Mestek IR01D (Range of measurement −50 °C/800 °C; Accuracy: ±0.5 °C)</td><td rowspan="2">FLIR E54 thermal imaging camera (IR res. 320 × 240 pixels. Thermal sens. <40 mK at 30 °C Accuracy: ±2 °C</td><td>-</td></tr>
<tr><td>Internal wood temperature</td><td></td><td></td></tr>
<tr><td rowspan="2">Air sampling</td><td>-</td><td>-</td><td>-</td><td>Five-stage impactor SKC Sioutas (Dorset, BSI DT11 8ST, UK) + L12 37 mm diameter, PTFE filters Merck (Darmstadt, Germany)</td><td>-</td></tr>
<tr><td colspan="4">Isokinetic personal air sampler Zambelli Egoplus-TT (Bareggio MI, Italy) + 37 mm diameter, PTFE filters Merck (Darmstadt, Germany)</td><td></td></tr>
<tr><td rowspan="6">Laboratory measurements</td><td colspan="2">Kinematic visc. @ 40 °C<br>Kinematic visc. @ 100 °C<br>Viscosity index (V.I.)</td><td colspan="5">Ubbelohde Viscometers for 40 °C in thermostatic bath (ASTM D445)<br>Ubbelohde Viscometers for 100 °C in thermostatic bath (ASTM D445)<br>Calculated from $V_{40}$ and $V_{100}$ (ASTM D2270)</td></tr>
<tr><td>Humidity</td><td>Sawdust</td><td colspan="4">Oven Bicasa—MFA (Bernareggio, MB, Italy)</td><td>-</td></tr>
<tr><td rowspan="2">Gravimetric analyses</td><td>Sawdust on the chain</td><td>-</td><td colspan="3">Precision balance Sartorius CP 622 (Resolution 0.01 g; Min. weight: 0.1 mg; Max. weight: 622 g)</td><td>-</td></tr>
<tr><td>Filters</td><td>-</td><td colspan="3">Analytical balance Sartorius ME5 (Resolution 0.001 mg; Max. weight: 5.1 g)</td><td>-</td></tr>
<tr><td rowspan="2">Chemical analyses</td><td>Filter mineraliz.</td><td>-</td><td colspan="4">Microwave Assisted Acid Digestion of Sediments, Sludges, and Oils (U.S. EPA Method 3051A)</td></tr>
<tr><td>Metallic elements</td><td></td><td colspan="2">ICP-MS, method UNI EN ISO 16967:2015 (CREA Lab.)</td><td>ICP-MS, method U.S. EPA 6020B:2014 (INNOVHUB Lab.)</td><td>-</td></tr>
</table>

All cutting activities were carried out by professional operators who were provided with all personal protective equipment (PPE) required by the current laws and followed all required safety procedures.

### 2.2.1. Preliminary Test ($T_0$)

The layout of $T_0$ is reported in Table 1. This test aimed at collecting the first opinions of a professional operator on the intensive cutting of about 2000 kg of seasoned oak (*Quercus robur* L.) firewood (2019 felling) of various sizes (diameter between 5 and 60 cm), as shown in Figure 1. On purpose, the operator was provided with 2 L of each of the formulations $F_0$, $F_1$, $F_2$, and $F_3$, to refill the two chainsaws described in Table 2. The equipment belongs to two different categories of use. The most important difference lies in the engine rotation speed: the Husqvarna chainsaw works at a much higher speed and is therefore intended for professional use (e.g., forestry companies), while, given its lower speed, the Oleo-Mac chainsaw is more suitable for mainly hobby users. Samples of just-cut sawdust were taken to determine the wood's humidity according to the mass difference between the wet and oven-dried samples. In addition to the operator's opinions, the data on atmospheric conditions, as well as the temperature of the guide bar and of the lubricant in the tank, were also collected, as indicated in Table 3.

**Figure 1.** Oak firewood used in $T_0$.

### 2.2.2. Felling in Turkey Oak Forest ($T_1$)

To deepen the information on the behavior of the ROPO-based chain lubricant, the formulations $F_0$ (without thickener) and $F_2$ (2% of thickener) were supplied to a company specialized in the forest cutting to be tested in real conditions of use represented by the felling of Turkey oak (*Quercus cerris* L.) trees and trunk limbing. The test setup and the professional chainsaws involved are described, respectively, in Tables 1 and 2. On the first day of the test, both chainsaws were equipped with new chains. The Husqvarna 372 XP was tested with the abovementioned $F_0$ and $F_2$ ROPO-based formulations, while the chainsaw Stihl 362-C was used with the conventional fluid $S_B$. The test consisted of the felling (and limbing) of trees during the time interval required to use up the full volume of oil. At this time, the number of cuts per full volume of oil was counted, and each cut diameter was manually measured. Moreover, the main weather parameters and the temperature of the chain and of the freshly cut wood (inside trunk temperature) were measured by the sensors and instruments reported in Table 3. Two of the three operators forming the cutting team were equipped with isokinetic personal air samplers mounting PTFE filters with the aim of collecting the air-suspended sawdust particulate and obtaining information on the potentially inhaled amount of particulate and on its quality via a gravimetrical and chemical analysis of the residues. Table 3 reports the main characteristics of the air samplers and filters and the method adopted for the analyses. The sampling airflow was set at the value of 1.7 $L \cdot min^{-1}$, which is suitable to collect the respirable fraction of particulate. Samples of sawdust were collected to determine the humidity via the difference between the wet and oven-dried mass of samples (Table 3). A third air sampler (same model) was used upwind, a few hundred meters from the cutting site, to collect particulate samples as blank. From the second day of the test, the team underwent its cutting activity by lubricating both chainsaws with $F_0$ until using up the supplied quantity (10 L) to achieve the opinions of the operators after a period spent in normal working conditions. Eventually, the operators were interviewed to find out the opinions derived from the use of the ROPO-based lubricant compared to conventional oil and the details of the work carried out daily (actual working time, duration, and number of oil fills in a day, average area of wood cut down daily, average duration of a chain, etc.).

### 2.2.3. Trunks Cutting at Fixed Point ($T_2$)

$T_2$ was thought to apply intensive workloads to the chainsaws and to improve the control of test conditions, with respect to $T_1$, to increase the comparability of the performances of the two chain lubricants. The general test layout is described in Table 1, while Table 2 shows the main characteristics of the two chainsaws used in this case: the Stihl MS 201TC with an internal combustion engine (ICE) and the Pellenc Selion C21HD with wireless electric motor (WEM). Due to the absence of exhaust gas emissions, the WEM chainsaw was considered helpful in the evaluation of the substances contained in the dust residues of the air samplings which came only from the cutting. In $T_2$, each chainsaw carried out

100 crosscuts on a log continuously, with each lubricant. The test was made using trunks of Pine (*Pinus radiata* L.) and *Eucalyptus* (*Eucalyptus globulus* Labill.) with similar sizes (Table 1). To refer all observed data to similar starting conditions, all cuts were executed by the same operator, replacing the chain before each new trunk cutting. Figure 2 shows the details of the test setups.

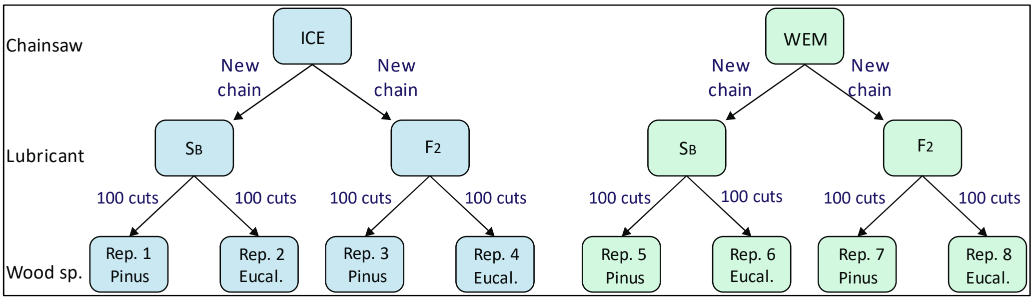



**Figure 2.** The planned $T_2$ layout included two chainsaws, two chain lubricants, and two wood species. Each test line started with a new chain.

The operator was also equipped with two isokinetic personal air samplers with their associated PTFE filters. As in $T_1$, one sampler was used for the collection of total dust, while the second mounted a Dorr-Olivier sampling head for the collection of the respirable fraction. The filters underwent a gravimetric analysis to determine the concentration of dust in the air (Table 3). A third air sampler was used upwind, a few hundred meters from the cutting site, to collect particulate samples as blank. During trunk cutting, the weather conditions were monitored, and the temperature of the chain was measured every 10 cuts. The sensors used are shown in Table 3, together with the methods adopted for the analyses which were carried out by the CREA laboratory.

#### 2.2.4. Cutting of Turkey Oak Trunks at Fixed Point ($T_3$)

All data relating to the setup of $T_3$ to the used chainsaw and to the sensors, instruments, and analytical methods are reported in Tables 1–3, respectively. The general purpose of $T_3$ was the same as $T_2$, i.e., to create controlled work conditions which allowed us to better compare the performance of the chain lubricants, $F_2$ and $S_B$. $T_3$ was focused on the application of a very severe workload consisting of the intensive crosscutting of Turkey oak trunks. The test involved one ICE chainsaw used in three repetitions of 100 cuts with each oil (total of 300 cuts), on trunks with a diameter of about 20 cm. A new chain was used with each oil. As in $T_2$, the operator featured two personal air samplers with PTFE filters to collect the sawdust particulate with reference to the inhalable fraction and the respirable fraction of sawdust particulate. The air-sampling activity was improved in this test by introducing a 5-stage impactor, positioned 2 m away from the cutting place, with the aim of characterizing the particulate matter produced with each lubricant. The impactor works at a 9 $L \cdot min^{-1}$ flow rate and provides the number of particles in the following dimensional classes: >2.5 µm, 1.0 µm, 0.5 µm, 0.25 µm, and <0.25 µm, mostly relating to the respirable fraction. All filters underwent gravimetric and chemical analyses for the determination of the concentration of the dust and of metallic elements in the air. The temperature of the chain and of the internal wood (just cut) was monitored by using a thermal image camera to identify the most stressed section of the chain–bar system and observe the level of temperature reached. Eventually, after the test, both chains were disassembled and accurately cleaned and weighted to measure their mass variation as a wear indicator.

#### 2.2.5. Felling of a Poplar Grove ($T_4$) at CREA

The test took place at the CREA experimental farm (Rome, Italy) and consisted of the felling of a 15-year-old poplar grove (*Populus alba* L., clone AF8) that was grown without an artificial irrigation system and fertilization. The test setup is summarized in Table 1. The aim of the test was to achieve additional information on any difference in the wear of the chains lubricated with ROPO-based fluid ($F_2$) and conventional fluid ($S_B$). The felling was carried out by means of the chainsaw reported in Table 2. Two plots were defined, and in each plot, one of the lubricants was used for comparison and a new chain was used. The assessment of chain wear was made by using the difference between the mass of the new chain and of the same chain after the felling (Table 3).

2.2.6. Chemical Analyses

All analytical methods used to characterize the refined olive pomace oil were standardized, and the complete list is reported, along with the measured property, in the tables discussed in Section 3.

The chemical analyses for the determination of the metallic elements in the air were carried out at the LASER-B laboratory of CREA according to the EPA methodology for the detection of essential and toxic elements [23]. The metal content was determined on filters used in personal samplers that were pretreated by a microwave mineralization process. An aliquot of each sample was transferred to special Teflon containers and subjected to an acid attack, using a microwave digester (model Start D, Milestone, Sorisole, BG, Italy). The determination of the metal content was carried out by ICP-MS (Inductively Coupled Plasma–Mass Spectrometer model 7700, Agilent, Santa Clara, CA, USA). The etching mixture used was composed of 6 mL of $HNO_3$ (65% $v/v$) and 3 mL of $H_2O_2$ (30% $v/v$). The calibration of the instrument was carried out using multi-element standards (standard mix, concentration 10 ppm in metal) prepared in an aqueous solution acidified with 1% of $HNO_3$ (65% $v/v$).

## 3. Results and Discussion

### *3.1. Results of Laboratory Activity*

Table 4 shows the fatty acid composition of ROPO. The typical pattern of olive oil was confirmed, with the fatty acids being represented by oleic, palmitic, and linoleic acids. No changes were detected after additivation.

**Table 4.** ROPO fatty acid composition according to ISO 12966-2:2017 (methyl esters prepared according to cold method with KOH) and ISO 12966-4:2015.

| Fatty Acid | %Area |
|---|---|
| Myristic | 0.02 |
| Pentadecanoic | 0.01 |
| Palmitic | 11.17 |
| Palmitoleic | 0.85 |
| Heptadecanoic | 0.07 |
| Heptadecenoic | 0.11 |
| Stearic | 2.91 |
| Oleic | 72.38 |
| Linoleic | 10.71 |
| Eicosanoic | 0.47 |
| Eicosenoic | 0.34 |
| Linolenic | 0.59 |
| Docosanoic | 0.22 |
| Erucic | <0.01 |
| Tetracosanoic | 0.10 |

To assess the effects of the additivation described in Section 2.1.1 on the physical–chemical ROPO properties, lab analyses were carried out on ROPO as it is and the formulation $F_2$ (ROPO + 3.0 g $kg^{-1}$ TBHQ + 2% BIOTAC). The results of the characterization are reported in Table 5. The listed parameters are typical of refined food oils. Considering the specific application related to this study, both the kinematic viscosity and the behavior of the oil when cold are of particular importance because they could represent a limit to the conservation and use of the oil in the winter period.

**Table 5.** Main physical–chemical properties of the ROPO as it is and the formulation $F_2$.

| Parameters | Methods | Units | ROPO | $F_2$ |
|---|---|---|---|---|
| Density @ 15 °C | ISO 12185:1986 | $kg \cdot m^{-3}$ | 914.8 | 914.8 |
| Acidity | ISO 660:2020 | % Oleic Acid | 0.16 | 0.18 |
| Acid value | ISO 660:2020 | $mg \cdot KOH \cdot g^{-1}$ | 0.31 | 0.36 |
| Peroxide value | ISO 3960:2017 | $m_{Eq} \cdot O_2 \cdot kg^{-1}$ | 11.70 | 15.72 |
| Kinematic viscosity @ 40 °C | ASTM D445-06 | $mm^2 \cdot s^{-1}$ | 40.12 | 47.05 |
| Kinematic viscosity @ 100 °C | ASTM D445-06 | $mm^2 \cdot s^{-1}$ | 8.52 | 10.02 |
| Viscosity index | ASTM D2270-10 | - | 197 | 207 |
| Copper corrosion (50 °C, 3 h) | ASTM D 130 | Class | 1 | 1 |
| Rancimat Induction Time | ISO 6886:2016 | Hours | 4.95 | 25.18 |
| Slip point | ISO 6321:2021 | °C | −3 | n.a. |
| Limpidity point | ISO 6321:2021 | °C | 0 | n.a. |
| Pour point | ISO 3016:2019 | °C | −9 | −9 |
| Sulfur | ISO 20846:2019 | $mg \cdot kg^{-1}$ | 7.6 | 8.3 |
| Phosphorous | ISO 10540-3:2002 | $mg \cdot kg^{-1}$ | 0.3 | 4.5 |
| Potassium | EPA 6010D:2014 | $mg \cdot kg^{-1}$ | <1 | 15 |
| Tin | EPA 6010D:2014 | $mg \cdot kg^{-1}$ | 2 | 4 |
| Monoglycerides | EN 14105:2020 | $\% \, m \cdot m^{-1}$ | 0.25 | 0.25 |
| Diglycerides | EN 14105:2020 | $\% \, m \cdot m^{-1}$ | 6.68 | 6.68 |
| Ashes | ISO 6884:2008 | $\% \, m \cdot m^{-1}$ | 0.003 | 0.003 |
| Conradson carbon residue | ISO 10370:2014 | $\% \, m \cdot m^{-1}$ | 0.26 | 0.26 |

The comparison between the parameter values of ROPO as it is and $F_2$ shows the strong impact of the additivation on the kinematic viscosity and Rancimat Induction Time, while the impact on the acidity and phosphorous and sulfur content seems negligible. Other parameters, such as the mono- and diglyceride content and the cold properties, were not affected by the additivation. The considerable presence of monoglycerides (0.25% $m \cdot m^{-1}$) and diglycerides (6.68% $m \cdot m^{-1}$) confirms what is reported in the Introduction, and for this specific application, it could be advantageous thanks to the greater interaction of these molecules with metal surfaces. Also, the analysis of trace elements such as aluminum, silver, barium, boron, cadmium, calcium, chromium, iron, magnesium, manganese, molybdenum, nickel, lead, silica, sodium, titanium, vanadium, and zinc did not show changes, as all element concentrations remained under the detection limit, with the only exceptions being potassium (from <1 to 15 $mg \cdot kg^{-1}$) and tin (from 2 to 4 $mg \cdot kg^{-1}$). A further lab test was carried out to deepen the information on the impact of different concentrations of BIOTAC on the viscosity of the four formulations defined in Section 2.1.1. The results are shown in Table 6.

**Table 6.** Effects of the additivation of the thickening agent BIOTAC on the viscosity and viscosity index of the mixture of ROPO plus 3.0 mg $kg^{-1}$ of TBHQ as oxidant.

| Formulation | Composition | Kinematic Viscosity @ 40 °C ($mm^2 \cdot s^{-1}$) | Kinematic Viscosity @ 100 °C ($mm^2 \cdot s^{-1}$) | Viscosity Index |
|---|---|---|---|---|
| $F_0$ | ROPO+TBHQ (3 g $kg^{-1}$) | 40.92 | 8.68 | 198 |
| $F_1$ | ROPO+TBHQ+BIOTAC (1%) | 44.36 | 9.36 | 201 |
| $F_2$ | ROPO+TBHQ+BIOTAC (2%) | 47.05 | 10.02 | 207 |
| $F_3$ | ROPO+TBHQ+BIOTAC (3%) | 50.28 | 10.57 | 207 |

As expected, the additive has a strong effect on a 40 °C kinematic viscosity, which increased from 40.92 in $F_0$ to 50.28 $mm^2 \cdot s^{-1}$ in $F_3$. Also, a 100 °C kinematic viscosity improves accordingly (from 8.68 to 10.57 $mm^2 \cdot s^{-1}$), while the maximum viscosity index occurs in $F_2$ with 2% of BIOTAC. A further thickener addition causes a reduction in the viscosity index. Before starting with the in-field tests, an overview of the products available on the market was carried out, by means of Web research on MSDS and technical sheets, as summarized in Table 7.

**Table 7.** Comparison between $F_2$ and several chainsaw lubricant oils available on the market (from the Web).

| Lubricants | Density @ 15 °C ($kg \cdot m^{-3}$) | Kinematic Viscosity @ 40 °C ($mm^2 \cdot s^{-1}$) | Viscosity Index | Flash Point (°C) | Pour Point (°C) | Remarks |
|---|---|---|---|---|---|---|
| $F_2$ | 915 | 47 | 207 | >280 | −9 | Vegetable-based |
| ENI | 884 | 100 | 99 | 252 | −18 | Mineral product |
| ENI Forest | 885 | 105 | 100 | 240 | −14 | Mineral product |
| Papillon | 925 | 42 | - | >280 | −3 | Vegetable-based |
| UNISPAD | 920 | 60 | 180 | 300 | −10 | Vegetable-based |
| VPM | 920 | 45 | n.a. | >230 | 5 | Vegetable-based |
| TAMOIL Blue B. | 880–890 | 95–110 | >98 | >240 | −9 | n.a. |
| MOL-LUB D.F. | 875–895 | 100 | 92 | 260 | −27 | Mineral product |
| STIHL Bioplus | 920–930 | 32–42 | n.a. | >230 | n.a. | Vegetable-based |
| BIOD ENG 100% | 1090 (20 °C) | 40–55 | n.a. | 350 | −40 | Vegetable-based |

In general, the data indicate that mineral-based products have a kinematic viscosity that is higher than vegetable-based products. The latter have a viscosity of around 40 $mm^2 \cdot s^{-1}$, with two exceptions at 32 and 60 $mm^2 \cdot s^{-1}$. According to the relating technical datasheets, the listed vegetable-based fluids are not pure vegetable oils but blends with products of other origin (mainly mineral) and unidentified specific additives.

### *3.2. Tests of ROPO-Based Fluids in Chainsaws*

#### 3.2.1. Preliminary Test ($T_0$)

$T_0$ was performed on 24 October 2020 and 25 October 2020, under the atmospheric conditions reported in Table 8.

**Table 8.** Atmospheric conditions during the $T_0$ test.

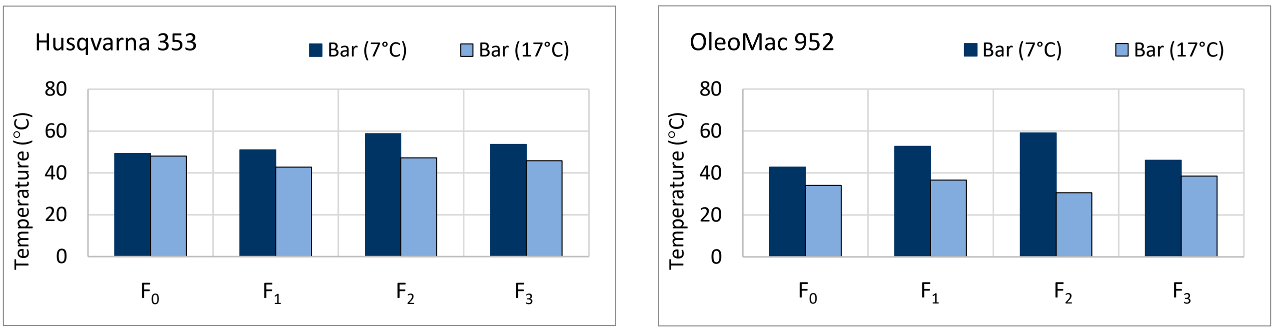
| Ambient Conditions | Day 1 | Day 2 |
|---|---|---|
| Temperature (°C) | 17 | 7 |
| R.H. (%) | 68 | 88 |
| Wind speed ($km \cdot h^{-1}$) | 25 | 0 |
| Atmospheric pressure (mbar) | 1018 | 1018 |

The first check carried out in the context of $T_0$ was an empirical practice commonly adopted by expert operators to visually assess the adhesion of the fluid to the chain to evaluate its fluidity and the need for flow rate adjustment by acting on the lubrication pump. It consisted of pointing the chainsaw bar towards a clean section of the trunk and operating the machine at maximum rotation speed, observing how the oil sprayed by centrifugal force was distributed on the surface. The check was repeated for the four ROPO-based formulations. When observing Figure 3, no significant differences can be observed in the appearance of the four trunk sections "sprayed" with ROPO added at increasingly thickener concentrations.

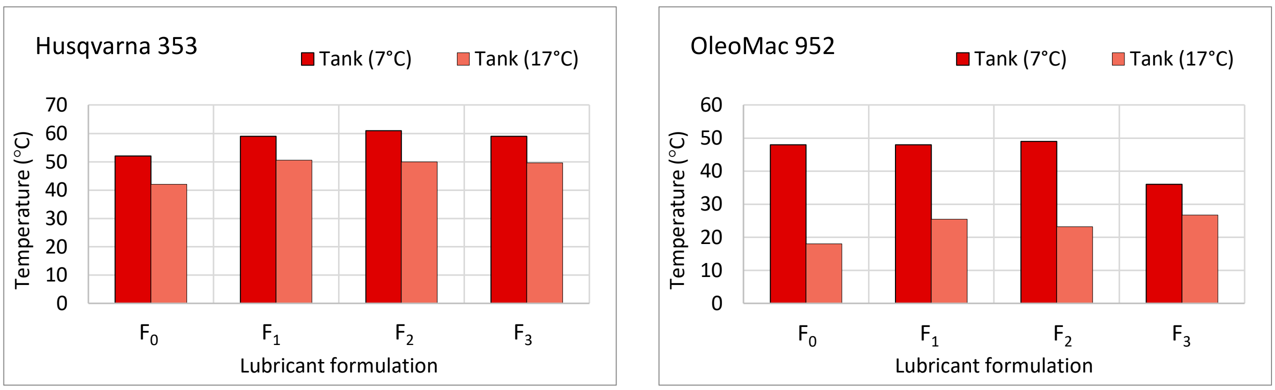
(**a**) (**b**) (**c**) (**d**)

**Figure 3.** Empirical test adopted to visually verify the correctness of the oil distribution on the chain and quantify its dispersion: (**a**) formulation $F_0$, (**b**) formulation $F_1$, (**c**) formulation $F_2$, and (**d**) formulation $F_3$.

Then, the ROPO-based formulations, $F_0$, $F_1$, $F_2$, and $F_3$, were tested in both chainsaws, which are already described in Table 2, in the intensive cutting of the oak firewood, whose average humidity, determined on the sawdust samples taken during the test, resulted in being 37.6%. During the cutting with each fluid–chainsaw combination, at an interval of 30 cuts, the operator carried out measurements of the temperature at the center of the guide bar (by contact) and of the lubricant within the oil tank (by immersion). The averages of said measurements are reported in Figure 4.




(**a**) (**b**)




(**c**) (**d**)

**Figure 4.** Results of $T_0$ test. Temperatures were observed during cutting with the four ROPO-based formulations used in two chainsaws. (**a**,**b**) Temperatures of the guide bar. (**c**,**d**) Temperature of the oil in the tank.

The first information provided is that the temperatures observed on the second day, at 08.00 h in the morning, with an ambient temperature of 7 °C, were higher than on the first day, at 17 h in the afternoon, with an ambient temperature of 17 °C. According to the operator, this behavior was determined by the fact that most of the activity took place in the morning of the second day, which caused the equipment to heat up more regardless of the outside temperature. However, it may have been emphasized by the lower relative humidity and higher wind speed observed in the afternoon of the first day (Table 8) which favored heat dissipation despite the higher ambient temperature. As for the cutting test, Figure 4 shows that the bar temperature never exceeded 60 °C. The chainsaw Husqvarna 353 worked at higher temperatures than the Oleo-Mac 952 both at the bar–chain level and in the oil tank, likely due to the considerably higher engine speed in the Husqvarna 353. Moreover, on both test days, higher chain temperatures occurred with $F_2$. It is difficult to draw conclusions from these data on the different behaviors of the four formulations, considering the heterogeneous dimensions of the material to be cut and the consequent variability of the test conditions that may have heavily influenced the temperature of the guide bar. However, at the end of the test, the ratings of the operator were largely positive, as he said that he did not notice any substantial difference among the four ROPO-based formulations and between these and the conventional chain lubricants. These positive opinions also concerned the oil's behavior at low temperatures and the absence of oil-sawdust residues and/or incrustations on the moving parts after a prolonged stop of the machines, verified by leaving both chainsaws unused for about a month, at the end of which, they restarted without any inconvenient. The positive results of $T_0$ encouraged the execution of the study but also evidenced, above all, the need to carry out the tests in such a way that makes it possible to reliably compare the performance of ROPO-based fluids to that of conventional chain lubricants. Furthermore, in addition to the technical performance of the fluids, the opportunity emerged to investigate other aspects of their use, such as the quantity and quality of the sawdust dispersed in the environment and its inhalable fraction, to evaluate any exposure risks for the operators. Considering the results of $T_0$ and that, in the preliminary test, $F_2$ and $F_3$ showed the highest I.V. (207), which indicates greater resistance to thermal stress, it was decided to continue the study using only the $F_2$, whose viscosity, is lower than that of $F_3$ (Table 6), involves less dissipation of energy in the sliding of the chain along the bar and is nearer to the viscosity of $S_B$.

#### 3.2.2. Felling in Turkey Oak Forest ($T_1$)

Table 9 reports the main data relating to the cutting collected on the first day of the test. The measurements refer to the time required, in each replicate, to use up the full amount of oil. Considering the different capacity of the reservoir of the two chainsaws used in the test, for a better comparison, Table 9 also shows the data relating to the full use of oil and the data calculated referring to the oil unit ($dm^3$), according to the hypothesis that the statistical indicators remained constant.

Based on the results reported in Section 3.1, $F_2$ was chosen for this test among the four ROPO-based formulations because of its higher viscosity index (Table 6), which theoretically should have given the oil greater stability. $S_B$ was used in the Stihl chainsaw in two repetitions. Then, $F_2$ was used in the Husqvarna chainsaw by a second operator, in two repetitions. Eventually, $F_2$ was replaced by $F_0$ in the same chainsaw in a further repetition. The variability in tree size is confirmed by the very different values of the statistical indicators of cutting diameter observed among the repetitions. The average diameter varies from 9.97 cm (Rep. 3) up to 18.53 cm (Rep. 4), and the maximum diameter varies from 19.00 cm (Rep. 5) up to 60.00 cm (Rep. 4). The generally high values of standard deviation and CV testify the high variability in cutting diameter within each repetition, as well as among repetitions. The results of Mann–Whitney test (Table 10) on the data of diameters indicate that all repetitions significantly differ from each other regardless of the chainsaw and/or chain lubricant used.

**Table 9.** Data collected on the first day of $T_1$ concerning the cutting.

| Repetitions<br>Chain Lubricant<br>Chainsaw | Parameters | Rep. 1<br>$F_2$ | Rep. 2<br>$F_2$<br>Husqvarna 372 XP | Rep. 3<br>$F_0$ | Rep. 4<br>$S_B$ | Rep. 5<br>$S_B$<br>Stihl 362 C | Average |
|---|---|---|---|---|---|---|---|
| Values per full of oil | Cutting time (s) | 1860 | 1740 | 1500 | 1161 | 1500 | 1552.20 |
| | Cuts number (N) | 414 | 242 | 300 | 238 | 414 | 321.60 |
| | Time per cut (s·cut$^{-1}$) | 4.5 | 7.2 | 5.0 | 4.9 | 3.6 | 5.04 |
| | Cut frequency (N·min$^{-1}$) | 13.4 | 8.3 | 12.0 | 12.3 | 16.6 | 12.51 |
| Values per dm$^3$ | Cutting time (s·dm$^{-3}$) | 4650 | 4350 | 3750 | 4644 | 6000 | 4679 |
| | Cuts number (N·dm$^{-3}$) | 1035 | 605 | 750 | 952 | 1656 | 1000 |
| Cut diameter | Average (cm) | 10.10 | 11.50 | 9.97 | 18.53 | 10.80 | 12.18 |
| | Max (cm) | 28.00 | 50.00 | 35.00 | 60.00 | 19.00 | 38.40 |
| | Min (cm) | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| | St. dev. (cm) | 4.31 | 8.68 | 6.82 | 8.38 | 5.63 | 6.77 |
| | CV (%) | 42.69 | 75.49 | 68.43 | 45.20 | 52.16 | 56.79 |
| | St. error | 0.21 | 0.56 | 0.39 | 0.54 | 0.33 | 0.41 |
| | Sum of diameters per full of oil (cm) | 4087 | 2784 | 2990 | 4410 | 3240 | 3502 |
| | Sum of diameters per liter of oil (cm·dm$^{-3}$) | 10,218 | 6960 | 7475 | 17,640 | 12,960 | 11,051 |
| Cut section | Average (cm$^2$) | 94.71 | 162.93 | 114.43 | 324.52 | 116.45 | 162.61 |
| | Max (cm$^2$) | 615.75 | 1963.50 | 962.11 | 2827.43 | 283.53 | 1330.46 |
| | Min (cm$^2$) | 19.63 | 19.63 | 19.63 | 19.63 | 19.63 | 19.63 |
| | St. dev. (cm$^2$) | 89.58 | 327.68 | 190.18 | 316.17 | 104.73 | 205.67 |
| | CV (%) | 94.57 | 201.12 | 166.19 | 97.43 | 89.94 | 129.85 |
| | St. error | 4.40 | 21.06 | 10.98 | 20.49 | 6.05 | 12.60 |
| | Sum of sections per full of oil (cm$^2$) | 38,839 | 39,429 | 34,330 | 77,236 | 34,935 | 44,954 |
| | Sum of sections per liter of oil (cm$^2$·dm$^{-3}$) | 98,029 | 98,571 | 85,824 | 308,944 | 192,838 | 156,842 |
| Chain temperature | Average (°C) | 49.39 | 55.94 | 50.15 | 54.58 | 42.96 | 50.61 |
| | Max (°C) | 57.70 | 60.00 | 55.60 | 57.70 | 60.90 | 58.38 |
| | Min (°C) | 32.00 | 45.00 | 46.60 | 32.00 | 39.20 | 38.96 |
| | St. dev. (°C) | 10.05 | 2.72 | 4.35 | 6.34 | 7.06 | 6.10 |
| | CV (%) | 20.35 | 4.86 | 8.67 | 11.61 | 16.43 | 12.38 |
| | St. error | 0.49 | 0.17 | 0.25 | 0.41 | 0.41 | 0.35 |
| Temperature of freshly cut wood (°C) | | | | 5–7 | | | |

**Table 10.** Results of the Mann–Whitney test for equal medians.

| U\p (Same) | Rep. 1 | Rep. 2 | Rep. 3 | Rep. 4 | Rep. 5 |
|---|---|---|---|---|---|
| Rep. 1 | - | $4.52 \times 10^{-1}$ | $1.86 \times 10^{-5}$ | $4.23 \times 10^{-47}$ | $1.25 \times 10^{-1}$ |
| Rep. 2 | 48,425 | - | $1.82 \times 10^{-3}$ | $1.59 \times 10^{-29}$ | $6.54 \times 10^{-1}$ |
| Rep. 3 | 50,740 | 30,770 | - | $1.13 \times 10^{-38}$ | $6.25 \times 10^{-2}$ |
| Rep. 4 | 17,009 | 12,071 | 12,650 | - | $1.00 \times 10^{-4}$ |
| Rep. 5 | 58,000 | 35,500 | 41,100 | 13,040 | - |

The differences in tree size affect the presence of branches and, consequently, the proportion between felling cuts and limbing cuts and the number of cuts per liter of oil. The latter is maximum in Rep. 5 (1656 cuts·dm$^{-3}$). Here, we observed a relatively low average cutting diameter and the minimum value of the maximum cutting diameter, which, together with a low variability (relative to the other repetitions), indicate the prevalence of limbing cuts performed with the highest cutting frequency and the maximum chain temperature (60.9 °C) observed in $T_1$. On the other hand, higher average temperatures of the chain were observed in Rep. 2 and Rep. 4, where the size of the trees was such as to determine larger sections of cut, with more prolonged and less frequent cuts, a sign that the width of the cutting section and the cut frequency are probably the factors that are most responsible for the thermal and mechanical stress of the chain and therefore must be considered in tests on the evaluation of the quality of chain lubricants. Figure 5 shows the results of the air sampling carried out during $T_1$ by means of the personal sampler set, as described in Section 2.2.2.

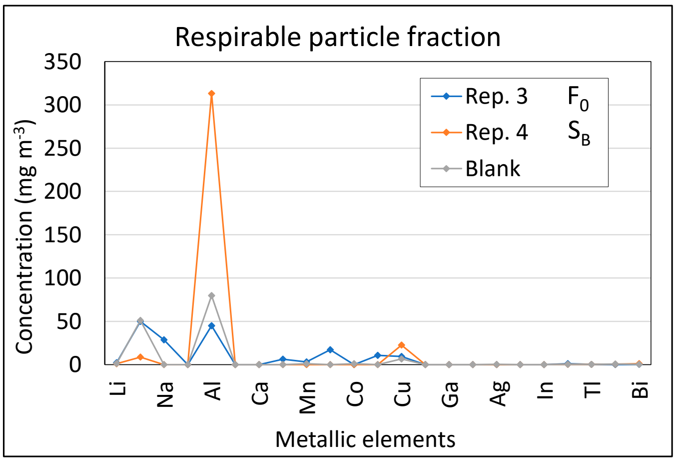



**Figure 5.** Metallic elements contained in the respirable particle fraction retained by the filters during $T_1$ air samplings. The value 0.00 was used instead of <LoQ (limit of quantifiability).

The total air volume sampled was normalized according to the reference temperature of 20 °C, and all determinations concerning the residues on the PTFE filters referred to the normalized volume. The results of the ICP-MS analyses on the residues on the PTFE filters show different concentrations of several metallic elements in Rep. 3, Rep. 4, and Blank. Their values seem relevant considering the relatively short sampling time (about 30 min). The main observations concern elements used in metallic alloys subject to wear. They are reported as follows:

- Boron (B), aluminum (Al), and copper (Cu): high concentrations of the three elements appear in all three filters. It can be noticed that they are unexpectedly high also in the blank filter, thus suggesting that an accumulation of these elements in the forest could have occurred during the felling activity carried out in the days preceding the test. Consequently, the quantities detected in $T_1$ are probably strongly affected by the previous deposits, making it difficult to discern their origins. For instance, the level of Al detected in Rep. 4 is very high compared to that of Rep. 3, where, however, it is not neglectable. It would be interesting to quantify the rate of Al coming from the previous deposits. Similar considerations can be made for B and Cu.
- Sodium (Na), chromium (Cr), manganese (Mn), iron (Fe), nickel (Ni), and barium (Ba): These elements are present in Rep. 3, sometimes in high concentrations (Na, Cr, Fe, and Ba), while in Rep. 4 and in Blank, they have low concentrations or are undetected.

Beyond the anomalous amount of Al, these data suggest the presence in Rep. 3 of a more severe wear process on the system Husqvarna 372 XP—$F_0$. About the origin of the above metallic elements, we must consider that both chainsaws are operated by internal combustion engines whose exhaust gas emissions could contain a relevant part of them. The analysis of the exhaust gases could help clarify this point. To this purpose, considering the engine speeds reported in Table 2, more severe solicitations should occur on the Husqvarna 372 XP chainsaw, which works at a 13,500 $min^{-1}$ engine speed and probably undergoes greater wear than the Stihl 362 C, whose engine works at 10,000 $min^{-1}$. Despite the willingness of the cutting team to collaborate in the test, its execution was somewhat conditioned, besides the great variability in the trees size, by the need not to excessively interfere with the normal felling activity, determining the impossibility to carry out the test with an inverted chainsaw–lubricant combination.

However, $T_1$ provided some insight into the behavior of the chain lubricants. As regards the cutting data, no relationships were found between the five repetitions, where the variability of the dimensions of the trees was the main cause of the variation in the temperature of the chain. No noticeable effects seemed to be due to the lubricants used, which, from this point of view, can be considered equivalent. On this note, the operators also declared not to have noticed any differences among $F_0$, $F_2$, and $S_B$ concerning the cutting efficiency, the duration of the full of oil, the chain sharpening intervals, etc. The only observation concerned the excessive viscosity of all three tested fluids. The operators reduced it by adding a small amount of fuel according to a questionable, albeit widespread practice. The levels of temperature reached in all repetitions can be considered physiologic. Considering the relatively low ambient temperature recorded the night before the test, the inside wood temperatures were low as well, ranging from 5 to 7 °C (Table 9), and contributed to the heating of the chains. The temperature of the chain is affected by the combination of the cutting section and the cutting frequency. The study of the relationship between the characteristics of the sawdust emissions (inhalable fraction and contents of metallic elements) and the use of different chain lubricants is made difficult in an environment probably contaminated by previous activity and by the exhaust gases' emissions from internal combustion engines. These indications were used to improve the study of the performance of chain lubricants by designing a test setup that is capable of reducing the typical variability of forestry work sites. Eventually, the operators of the cutting team provided some data that helped quantify the activity they normally perform. These data are shown in Table 11.

**Table 11.** Assessment of the oil dispersion in the environment during cutting activity based on the technical characteristics of the chainsaws used in $T_1$ (Table 2), on the measured working times, and on the information provided by the operators involved about the daily actual working time and surface covered.

| Parameters | Units Measure | Values |
|---|---|---|
| Volume of the chain lube reservoir | $dm^3$ | 0.376 |
| Duration of full oil | h | 0.47 |
| Actual working time | h $day^{-1}$ | 6 |
| Hourly oil consumption | $dm^3$ $h^{-1}$ | 0.80 |
| Daily oil consumption | $dm^3$ $day^{-1}man^{-1}$ | 4.80 |
| Cutting team composition | men | 3 |
| Team daily oil consumption | $dm^3$ $day^{-1}$ | 14.4 |
| Area covered by the team daily | ha $day^{-1}$ | 0.5 |
| Oil dispersed per unit area | $dm^3$ $ha^{-1}$ | 28.8 |
| | $cm^3$ $m^{-2}$ | 2.88 |

Based on them, it was possible to assess that the chain lubricant dispersed in the environment per surface unit is 28.8 $dm^3$ $ha^{-1}$. This value represents a heavy burden for a delicate environment such as a forest and underlines the need to proceed with the introduction of increasingly eco-sustainable products.

#### 3.2.3. Trunks Cutting at Fixed Point ($T_2$)

The felling of the trees (*Pinus* and *Eucalyptus*) of $T_2$ was carried out by an external contractor. To improve the comparability among the different combinations of chainsaw/lubricant/wood, trunks were required to have a diameter of 15–20 cm and length of 2 m, which would allow us to make the planned 100 continuous cuts per trunk. At the moment of the test, the trunks of *Pinus*, despite their sufficient size homogeneity, resulted in being partly of fresh wood and partly of dry wood. Figure 6 shows the test site, the operator equipped with PPE, the two personal air samplers at breast level, and the measurement of the chain temperature. The measurement of the chain temperature was made every ten cuts until the end of each repetition, whose duration varied, as above said, from each other.

##### Cutting

In Figure 6, the wooden disks produced by the cutting activity are visible on the ground. Some of them were sampled to characterize the test material with reference to each of the nine repetitions. The results are shown in Figure 7, which shows the plant species the average values of wood humidity and the trunks' diameters.

(**a**) (**b**) (**c**)

**Figure 6.** (**a**) Test site with a trunk of *Eucalyptus* ready for the test. (**b**) The operator during the cutting of a trunk of *Pinus*, equipped with PPE and two personal air samplers (applied on the breast). (**c**) Measuring chain temperature during the cutting by means of a laser thermometer.

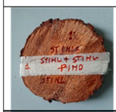
| ICE chainsaw | | WEM chainsaw | |
|---|---|---|---|
|  | Rep. 1 and Rep 5<br>Pinus – Fresh wood<br>- Diameter: 20.25 cm<br>- Humidity: 48.6% |  | Rep. 7<br>Pinus – dry wood<br>- Diameter: 15.25 cm<br>- Humidity: 13% |
|  | Rep. 2<br>Eucalyptus<br>- Diameter: 19.0 cm<br>- Humidity: 56.2% |  | Rep. 8<br>Eucalyptus<br>- Diameter: 15.25 cm<br>- Humidity: 53.7% |
|  | Rep. 3 and Rep 6<br>Pinus – Dry wood<br>- Diameter: 18.65 cm<br>- Humidity: 14.5% |  | Rep. 9<br>Eucalyptus<br>- Diameter: 15.5-16.0 cm<br>- Humidity: 55.1% |
|  | Rep. 4<br>Eucalyptus<br>- Diameter: 20.65 cm<br>- Humidity: 57.1% | The temperature of internal wood, measured at the moment of the cutting, varied in the interval 26-28°C | |

**Figure 7.** Some characteristics of the trunks used in the six repetitions carried out with the Stihl MS201 chainsaw and the three repetitions with the Pellenc Selion C21 HD.

It can be noted that the presence of dry wood, with humidity values from 13% to 14% in some *Pinus* trunks, is confirmed, alongside trunks of fresh wood with a humidity level from 48% to 56%. The presence of dry wood combined with the intensity of cutting made it necessary to adapt the test layout to the new conditions. Figure 8 shows the layout applied. The differences between the actual layout and the planned one (shown in Figure 2) are explained by the data reported in Table 12.

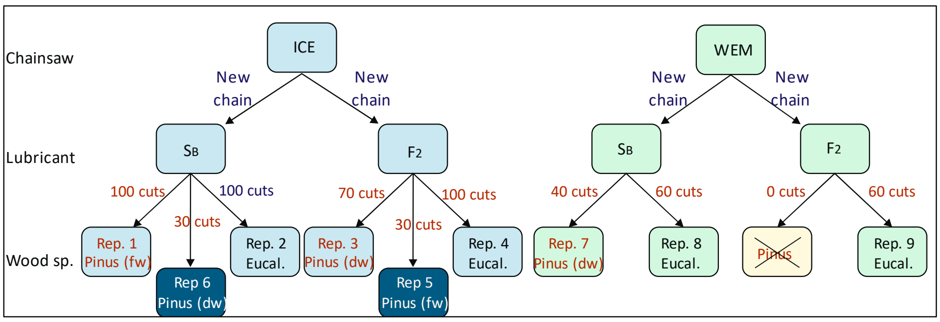



**Figure 8.** Actual test layout of $T_2$. The repetitions are numbered by order of execution. Due to contingent reasons that occurred during the test, the planned one shown in Figure 2 had to be modified. fw: fresh wood. dw: dry wood. The dark blue boxes represent additional repetitions, Rep. 5 and Rep. 6. The yellow box indicates that the repetition was canceled.

**Table 12.** Chain temperatures (°C) observed during the cutting test schematized in Figure 6 and statistical indicators. The temperature was measured every ten cuts.

| **Chainsaws** | | **ICE** | | | | | | **WEM** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Chain lubricant | | | $S_B$ | | | $F_2$ | | $S_B$ | | $F_2$ |
| Repetition | | Rep. 1 | Rep. 6 | Rep. 2 | Rep. 5 | Rep. 3 | Rep. 4 | Rep. 7 | Rep. 8 | Rep. 9 |
| Wood | | *Pinus* (fw) | *Pinus* (dw) | *Eucal.* | *Pinus* (fw) | *Pinus* (dw) | *Eucal.* | *Pinus* (dw) | *Eucal.* | *Eucal.* |
| Trunk diameter (cm) | | 20 | 18.5 | 19 | 20 | 18.5 | 20.5 | 15.3 | 15.3 | 15.8 |
| Unit measure | | °C | °C | °C | °C | °C | °C | °C | °C | °C |
| Number of cuts | 10 | 39.2 | 63.8 | 49.1 | 44.1 | 67.9 | 56.6 | 64.4 | 44.4 | 42.7 |
| | 20 | 49.1 | 80.1 | 51.9 | 43.6 | 98.3 | 57.2 | 73.2 | 43.4 | 45.9 |
| | 30 | 47.1 | 88.8 | 52.6 | 49.1 | 104.2 | 54.4 | 77.6 | 43.3 | 46.9 |
| | 40 | 49.1 | - | 54.7 | - | 113.2 | 56.1 | 72.1 | 41.2 | 46.9 |
| | 50 | 48.8 | - | 53.7 | - | 112.6 | 52.6 | - | 42.2 | 46.8 |
| | 60 | 42.1 | - | 55.6 | - | 112.6 | 53.8 | - | 42.1 | 46.9 |
| | 70 | 45.9 | - | 54.2 | - | 109.7 | 53.6 | - | - | - |
| | 80 | 45.3 | - | 53.7 | - | - | 53.3 | - | - | - |
| | 90 | 45.2 | - | 52.5 | - | - | - | - | - | - |
| | 100 | - | - | 52.6 | - | - | - | - | - | - |
| Statistical indicators (All data) | Min | 39.2 | 63.8 | 49.1 | 43.6 | 67.9 | 52.6 | 64.4 | 41.2 | 42.7 |
| | Max | 49.1 | 88.8 | 55.6 | 49.1 | 113.2 | 57.2 | 77.6 | 44.4 | 46.9 |
| | Mean | 45.8 | 77.6 | 53.1 | 45.6 | 102.6 | 54.7 | 71.8 | 42.8 | 45.7 |
| | St. dev. | 3.4 | 12.7 | 1.8 | 3.0 | 16.3 | 1.7 | 5.5 | 1.2 | 1.6 |
| | St. err. | 1.1 | 7.3 | 0.6 | 1.8 | 6.1 | 0.6 | 2.7 | 0.5 | 0.6 |
| | CV | 7.3 | 16.4 | 3.4 | 6.7 | 15.8 | 3.1 | 7.6 | 2.7 | 3.4 |
| Statistical indicators (30 cuts) | Min | 39.2 | 63.8 | 49.1 | 43.6 | 67.9 | 54.4 | 64.4 | 43.3 | 42.7 |
| | Max | 49.1 | 88.8 | 52.6 | 49.1 | 104.2 | 57.2 | 77.6 | 44.4 | 46.9 |
| | Mean | 45.1 | 77.6 | 51.2 | 45.6 | 90.1 | 56.1 | 71.7 | 43.7 | 45.2 |
| | St. dev. | 5.2 | 12.7 | 1.9 | 3.0 | 19.5 | 1.5 | 6.7 | 0.6 | 2.2 |
| | St. err. | 1.7 | 5.2 | 0.6 | 1.2 | 7.4 | 0.5 | 2.7 | 0.2 | 0.9 |
| | CV | 11.6 | 16.4 | 3.6 | 6.7 | 21.6 | 2.6 | 9.4 | 1.4 | 4.9 |

The chain temperatures were measured during every ten cuts. The intensive cutting determined the heating of the chainsaws. The heating level seemed to be increased in the repetitions with dry wood (*Pinus* dw), and the cutting had to be interrupted in Rep. 3 before the planned 100 cuts. The electric chainsaw particularly suffered from overheating to the point that, several times, it stopped working due to the activation of the thermal protection device. Consequently, the planned cutting of the trunk of *Pinus* (Rep. 7 in Figure 2) had to be canceled. To consider the unforeseen variable fresh wood vs. dry wood, the residual parts of the fresh and dry trunks from the first four repetitions (planned) were used in two further repetitions, which were carried out after Rep. 4 (Rep. 5 and Rep. 6 in Figure 8) before starting to cut with the electric chainsaw. The residual parts of trunks used in Rep. 5 and Rep. 6 only sufficed for 30 cuts. However, they allowed us to obtain data from all combinations of chainsaw/lubricant/wood, albeit in different numbers. The data of the chain temperatures observed during $T_2$ are summarized in Table 12. The following indications are provided:

- The planned 100 cuts were executed only in Reps. 1, 2, and 4 with fresh wood, whose high humidity contributed to the cooling of the chain. In all three repetitions, after 50–60 cuts, the temperature stabilized at relatively low values which, however, seem lower with *Pinus* (fw) (average: 45.7 °C) than with *Eucalyptus* (53.1 and 54.4 °C in Rep. 2 and Rep. 4, respectively).
- In Rep. 3, with lubricant $F_2$, the cutting of dry wood *Pinus* trunks caused the raising of the chain temperature up to 113 °C, which indicated that we needed to stop the test after 70 cuts. The data for the first 30 cuts of Rep. 3 seem significantly higher than those of Rep. 6 and indicate the possibility of a minor efficiency of $F_2$ as lubricant under these conditions.
- Considering Rep. 2 and Rep. 4, respectively (100 and 80 cuts on *Eucalyptus*), the chain temperature values resulted in being higher in Rep. 4 in the presence of the $F_2$ lubricant. This could be partly due to the higher starting temperature in Rep. 4 (56.6 °C) than in Rep. 2 (49.1 °C), caused by the chain overheating that occurred in Rep. 3. Slightly higher temperatures of the chain occurred, again with $F_2$, in Rep. 5, compared to the values of the first 30 cuts of Rep. 1 with $S_B$, in the cut of *Pinus* fresh wood.

- Reps. 7 to 9 concerned the electric chainsaw. Its electric motor overheated and stopped working after 40 cuts in Rep. 7 (with *Pinus* dry wood and chain temperatures which raised up to 77 °C) and after 60 cuts in Reps. 8 and 9 (both with *Eucalyptus* and chain temperatures relatively low), indicating that this type of machine is not suitable for continuous cutting tasks. As regards the behavior of the two lubricants, the comparison between Rep. 8 and Rep. 9, both on *Eucalyptus*, shows that lower chain temperatures occurred with $F_2$.

The series of values of chain temperature reported in Table 12 underwent two-sample tests (Mann–Whitney) and two-sample paired tests (t-test), which always confirmed the significance of the differences in their means and medians. The additional repetitions, Rep. 5 and Rep. 6, were not considered because of the scarcity of material to be cut and of pre-weighted PTFE filters.

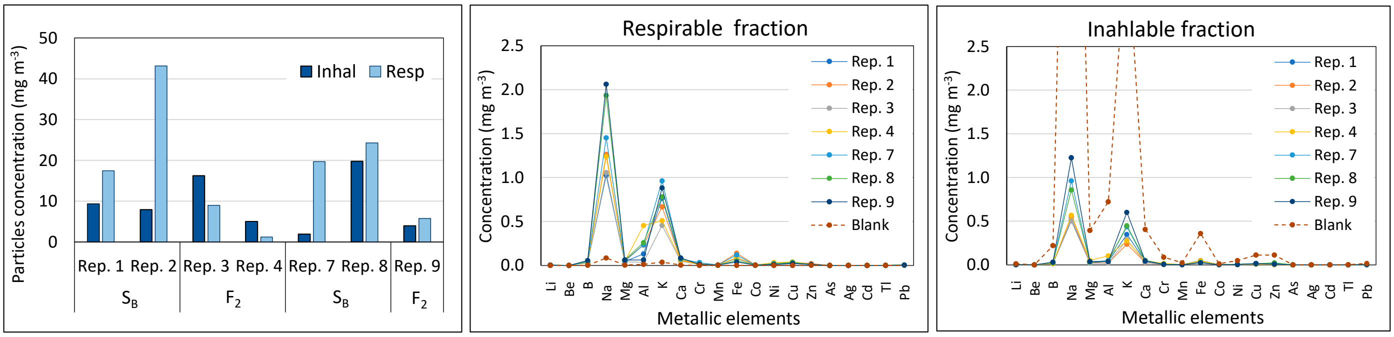
Air Sampling

The residues retained by PTFE filters of the two personal air samplers in the cutting operations with the two fluids were analyzed in the laboratory to determine the following: (1) the mass (mg) of particles relating to the inhalable fraction (>2.5 μm) and respirable fraction (<2.5 μm) by means of gravimetric analysis; and (2) the mass (mg) of metallic elements in the same fractions, by means of ICP-MS. Based on the sampled air volumes, all amounts are referred to by the unit of air volume and expressed as mg $m^{-3}$. The results are shown in Table 13.

**Table 13.** Results of the gravimetric analysis of the PTFE filter with the residues of the total inhalable dust and of the respirable dust fraction (<4 μm) relating to the air samplings carried out during the seven repetitions.

| **Chainsaws** | **Particles** | **ICE** | | | | **WEM** | | |
|---|---|---|---|---|---|---|---|---|
| **Chain Lubricants** | | **$S_B$** | | **$F_2$** | | **$S_B$** | | **$F_2$** |
| **Repetitions** | | **Rep. 1** | **Rep. 2** | **Rep. 3** | **Rep. 4** | **Rep. 7** | **Rep. 8** | **Rep. 9** |
| Wood | | *Pinus* (fw) | *Eucal.* | *Pinus* (dw) | *Eucal.* | *Pinus* (fw) | *Eucal.* | *Eucal.* |
| Wood Humidity | | 48.6 | 56.2 | 14.5 | 57.1 | 48 | 53.7 | 55.1 |
| Diameter (cm) | | 20.25 | 19 | 18.65 | 20.65 | 15.25 | 15.25 | 15.75 |
| Number of cuts | | 90 | 100 | 70 | 80 | 40 | 60 | 60 |
| Concentration of powder as it is | Inhalable (mg $m^{-3}$) | 18.17 | 18.11 | 19.00 | 11.75 | 3.70 | 42.62 | 8.83 |
| | Respirable (mg $m^{-3}$) | 33.99 | 98.50 | 10.51 | 2.92 | 37.95 | 52.45 | 12.90 |
| Concentration of dust (d.s.) | Inhalable (mg $m^{-3}$) | 9.34 | 7.93 | 16.25 | 5.04 | 1.93 | 19.73 | 3.97 |
| | Respirable (mg $m^{-3}$) | 17.47 | 43.14 | 8.99 | 1.25 | 19.73 | 24.28 | 5.79 |
| Differences $S_B$—$F_2$ (dust as it is) | | Rep. 1–Rep. 3 | | Rep. 2–Rep. 4 | | - | Rep. 8, Rep. 9 | |
| | Inhalable (mg $m^{-3}$) | −0.83 | | 6.36 | | - | 33.79 | |
| | Respirable (mg $m^{-3}$) | 23.48 | | 95.58 | | - | 39.55 | |
| Differences $S_B$—$F_2$ (dust d.s.) | Inhalable (mg $m^{-3}$) | −6.91 | | 2.89 | | - | 15.77 | |
| | Respirable (mg $m^{-3}$) | 8.48 | | 41.89 | | - | 18.49 | |

The concentration of respirable particles shows very large variations among the repetitions, with values that seem dramatically high in Rep. 2 (98.50 mg·$m^{-3}$) and Rep. 8 (52.45 mg·$m^{-3}$) and suggest they can be outliers, maybe a consequence of contamination. To evaluate the percent humidity (H) of the wood that produced the dust, the concentrations of the powder as it were divided by the factor (1-H/100) calculated for each repetition, obtaining the concentration of the powder's dry substance. The values provided by this calculation resulted in the reduced amplitude of the variations between repetitions to the point that the possible outliers could be considered reliable values. Moreover, they confirmed the same trend of the powder as it is concerning the concentration of respirable fraction vs. inhalable fraction. Table 13 also shows the differences between the concentrations of dust observed with $S_B$ and with $F_2$ in the cutting of the same wood species. The differences resulted in being negative only in the cutting of *Pinus* wood with the ICE chainsaw. In this case, however, the cutting was carried out for $S_B$ on fresh wood and for $F_2$ on dry wood, which is supposed to be capable of generating more dust. In all other cases, the differences were largely positive. The reason for this trend is not clear. It could be connected to differences in the granulometry of the sawdust induced using $S_B$ vs. $F_2$, which would imply that the two fluids interact differently with the bar–chain system. This could also explain why, in the repetitions with $F_2$, the respirable fraction is lower (or slightly higher) than the inhalable one. Further investigations may confirm or deny this hypothesis. After the gravimetric analysis, the residues on the PTFE filters underwent a chemical analysis to determine the contents of metallic elements in the sampled air volume. Their concentration is expressed as mg·m$^{-3}$. This analysis regarded both the respirable and inhalable dust fraction. The results are shown in Figure 9, where, to visualize the proportion between metallic elements and total dust, we also show the concentrations of the inhalable and respirable fractions calculated on the dry substance of dust, as already reported in Table 13.




(**a**) (**b**) (**c**)

**Figure 9.** Results of the analyses on the residues from air samplings carried out in the seven repetitions of Table 13. (**a**) Concentrations in the air of inhalable and respirable sawdust particles. (**b**) Concentrations in the air of metallic elements in the respirable fraction. (**c**) Concentrations in the air of metallic elements in the inhalable fraction. The values below the detectability threshold (<LoQ) were considered to be 0 in the diagrams.

The red dashed lines in Figure 9 represent the blank concentrations in the two fractions. In the inhalable fraction, the trend of the blank is anomalous probably due to a contamination of the filter. As observed for the inhalable and respirable fractions of dust (Figure 9a), the concentrations of several metallic elements resulted in being very high and, in some cases, approached the limit values. Figure 9b,c show some peaks in the concentrations of specific elements, which occur in all repetitions, albeit to a different degree. They particularly concern Na, Al, K, and Fe, and, to a lesser extent, they concern B, Mg, Ca, Cr, Ni, and Cu. As for the results of the gravimetric analysis, the metal concentrations are always higher in the respirable fraction, indicating that said elements, probably originating from the wear of components made of metal alloys, are mostly contained in smaller particles. Observing how the concentrations of the single elements vary between the repetitions, in general, it seems that, in those with $F_2$ (Rep. 3, Rep. 4, and Rep. 9), the concentrations are lower than in the corresponding repetitions with $S_B$ (Rep. 1, Rep. 2, and Rep. 8, respectively), except for Al, which resulted in being higher in Rep. 4 (cutting of *Eucalyptus*). As regards Al, it could also be noticed that its concentration is higher mostly in the repetitions carried out on *Eucalyptus*, i.e., in Rep. 2 and Rep. 8, beyond that in Rep. 4.

The comparison between Figures 9b and 5 shows that, in $T_1$ and $T_2$, the elements involved are substantially the same, albeit notable differences can be noticed in their concentrations, particularly concerning Na and K, which, in $T_2$, reach very high levels (respectively, 2 mg·m$^{-3}$ and 1 mg·m$^{-3}$) probably linked to the test conditions adopted, to the very high concentrations of wood dust observed, and to the different wood species used with respect to $T_1$. However, beyond the evaluation of the chainsaw's cutting performance, the data confirm that the test method adopted in $T_2$ is also useful in the assessment of the quality of the air through the detection of the particles emitted. The method must be suitably improved as regards the uniformity of the material to be cut in order to provide more accurate and comparable data. Eventually, considering the values of the concentrations of respirable and inhalable wood dust fractions (Table 13) and of metallic elements (Figure 9), the comparison between the data of Reps. 1 to 4 with the ICE chainsaw and those of Reps. 7 to 9 with the WEM chainsaw does not show evident differences that are attributable to the presence/absence of exhaust gas emissions.

#### 3.2.4. Cutting of Turkey Oak Trunks at Fixed Point ($T_3$)

Test of Cutting

The test site setup is visible in Figure 10, with the five-stage impactor and the thermal imaging camera placed near the cutting place.


(**a**) (**b**) (**c**)

**Figure 10.** Test site of $T_3$. (**a**) Five-stage impactor (I) and operator equipped with two air samplers, (AS) on the breast. (**b**) Thermal imaging camera (TI) is filming the cutting of a trunk. (**c**) Some thermal images: the temperature values displayed at the top left refer to the point of the chain where the camera was pointed.

The operator features the two air samplers and the PPE. Two further air samplers were placed a few hundred meters away from the test site for blank samplings of both inhalable and respirable particles. Figure 10 also shows two thermal images taken during the test. Table 14 summarizes the main test results and the main statistical indicators.

As the test site was under a porch, it was partly protected from the wind. The humidity of the wood, measured on the samples of sawdust taken during the test, varied between 32 and 36%. The internal wood temperature was in the range of 6.3–8.2 °C. As to the dimensions of the six trunks, their length was 2.5 m, while their average diameter varied in the range of 15.6–23.2 cm. Since the test required three repetitions for $F_2$ and three for $S_B$, the trunks used with each fluid were chosen to obtain two groups (of three trunks) as homogeneous as possible. The table also reports the average section of each trunk and the total cut surface resulting from the 100 cuts of each repetition. The total cut surfaces resulted in being equal for $F_2$ and $S_B$. Conversely, the total cutting time was different for $F_2$ and $S_B$. The ANOVA on the values of the total cut sections and cutting times observed in the six repetitions showed that the differences between the two fluids were not significant for the former, while they were significant for the latter (Table 15).

**Table 14.** Main data observed during the cutting of Turkey oak trunks using the lubricants $S_B$ and $F_2$.

| Fluids | Rep. / Stat. Ind. | Environ. Temp. °C | R.H. % | Wood Hum. % | Wood Intern. Temp. °C | Cuts N | Cutting Time s | Time per Cut (Mean) s cut$^{-1}$ | Diameter (Mean) cm | Section Surface (Mean) cm$^2$ | Total Cut Surface m$^2$ | Max Chain Temp. [1] °C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $S_B$ | 1 | 8.9 | 63.3 | 33.6 | 6.3 | 100 | 670 | 6.7 | 20.4 | 325.9 | 3.30 | 84.9 |
| | 2 | 11.83 | 59.2 | 35.7 | 8.2 | 100 | 965 | 9.7 | 23.2 | 424.1 | 4.20 | 122.3 |
| | 3 | 12.17 | 60.9 | 32.0 | 7.4 | 100 | 489 | 4.9 | 15.6 | 191.1 | 1.90 | 62.2 |
| | Total | - | - | - | - | 300 | 2124 | - | - | - | 9.40 | - |
| | Average | 10.97 | 61.1 | 33.8 | 7.3 | - | 708 | 7.1 | 19.7 | 313.7 | 3.1 | 89.80 |
| | Dev. St. | 1.80 | 2.06 | 1.86 | 0.95 | - | 240 | 2.4 | 3.9 | 117.0 | 1.16 | 30.35 |
| | St. error | 1.04 | 1.19 | 1.07 | 0.55 | - | 139 | 1.4 | 2.2 | 67.5 | 0.67 | 17.52 |
| | CV | 16.39 | 3.37 | 5.51 | 13.1 | - | 34 | 33.9 | 19.6 | 37.3 | 36.99 | 33.80 |
| $F_2$ | 4 | 10.1 | 66.3 | 33.1 | 7 | 100 | 497 | 5.0 | 15.6 | 191.1 | 1.90 | 78.1 |
| | 5 | 10.57 | 66.2 | 35.7 | 7.9 | 100 | 1341 | 13.4 | 26.1 | 535.1 | 5.40 | 104.6 |
| | 6 | 10.4 | 66.2 | 32.3 | 8.20 | 100 | 555 | 5.6 | 16.2 | 207.0 | 2.10 | 112.8 |
| | Total | - | - | - | - | 300 | 2393 | - | - | - | 9.40 | - |
| | Average | 10.36 | 66.2 | 33.7 | 7.7 | - | 798 | 8.0 | 19.3 | 311.1 | 3.13 | 98.50 |
| | Dev. St. | 0.24 | 0.05 | 1.8 | 0.62 | - | 471 | 4.7 | 5.9 | 194.2 | 1.97 | 18.14 |
| | St. error | - | 0.14 | 1.0 | 0.36 | - | 272 | 2.7 | 3.4 | 112.1 | 1.13 | 10.47 |
| | CV | - | 2.30 | 5.3 | 8.11 | - | 59 | 59.1 | 30.5 | 62.4 | 62.73 | 18.41 |

[1] Monitoring chain temperatures with the thermal imaging camera was aimed at exploring the potential of the device and was not performed systematically. The values shown are the maximum temperatures observed by the operator and are only indicative.

**Table 15.** ANOVA results for the values of the cutting time and average section surface to verify the presence of significant variability in such parameters between the two fluids.

| Test for Equal Means | | | | | | |
|---|---|---|---|---|---|---|
| **Parameters** | **Variability Factors** | **Sum of Squares** | **Df** | **Mean Square** | **F** | **P (Same)** |
| Cutting time | Between groups | 12,060.2 | 1 | 12,060.2 | 0.3183 | 0.6294 |
| | Within groups | 559,953 | 4 | 139,988 | - | - |
| | Error | 75,770.3 | 2 | 37,885.2 | - | 0.7503 |
| | Between subject: | 484,182 | 2 | 242,091 | - | - |
| | Total | 572,013 | 5 | - | - | - |
| Average section surface | Between groups | 10.67 | 1 | 11 | 0.0014 | 0.9737 |
| | Within groups | 10.28 | 4 | 25,691.2 | - | - |
| | Error | 15,390.3 | 2 | 7695.17 | - | 1 |
| | Between subject: | 87,374.3 | 2 | 43,687.2 | - | - |
| | Total | 102,775 | 5 | - | - | - |

The different behaviors of the values of the cut section surface (equal in $F_2$ and $S_B$) and of the related total cutting time (different in $F_2$ and $S_B$) can be explained by a non-linear relationship between the two parameters. With reference to the data reported in Table 14, the diagram of Figure 11 shows that increasing the trunk section causes a more than proportional increase in the cutting time.

The six points are interpolated by an exponential function with a high $R^2$. Increasing the trunk section determines the augmented surface of contact between the chain and wood, resulting in increased friction, a higher engine load, and a lower engine speed. This tendency is likely to be accentuated as the hardness of the wood and its cut resistance increase. The relationship between the cutting time and the trunk section is probably linked to the magnitude of chain wear. A new chain was used with each fluid to carry out the abovementioned 300 cuts, which resulted in a total cut surface of 9.4 m$^2$ for both fluids, while the total cutting times were 2124 s and 2393 s, respectively, for $S_B$ and $F_2$. The chain wear was evaluated according to the differences between the mass of the new chain and the mass measured after the 300 cuts, after it was accurately cleaned. Table 16 shows the measurements made on the two chains in the tests with $S_B$ and $F_2$.

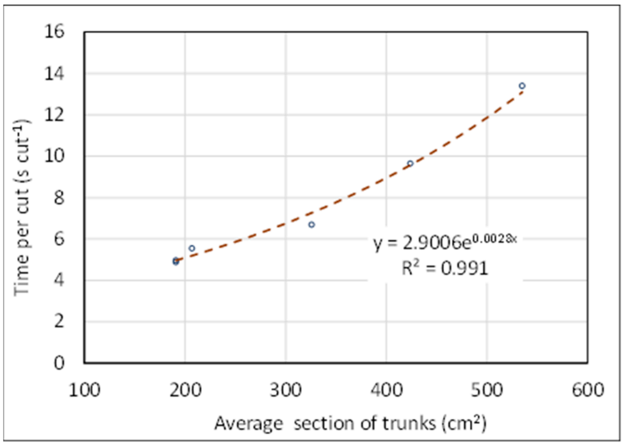



**Figure 11.** Variation in the cutting time as a function of the trunk section.

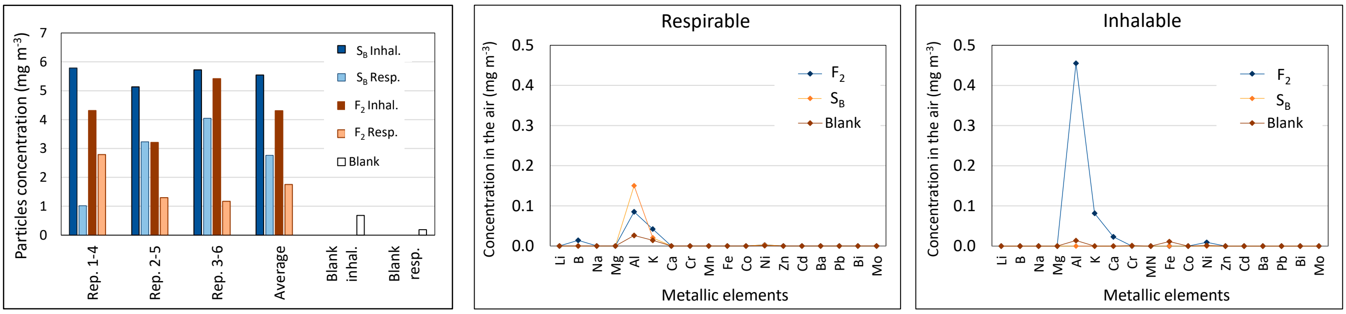
**Table 16.** Evaluation of the wear of the chains after the test with $S_B$ and $F_2$ in $T_3$.

| Lubricants | State of the Saw Chain | Masses | | | Specific Chain Wear | | |
|---|---|---|---|---|---|---|---|
| | | Chains g | Residues mg | Losses mg | Per surf. Unit mg m$^{-2}$ | Per Cut mg cut$^{-1}$ | Diff. % |
| $S_B$ (viscosity @ 40 °C: 42 mm$^{-2}$·s$^{-1}$) | New | 172.25 | - | - | - | - | - |
| | End of test: dirty chain | 173.74 | 1490 | - | - | - | - |
| | End of test: cleaned chain | 172.06 | - | 190 | 20.21 | 0.63 | - |
| $F_2$ (viscosity @ 40 °C: 47 mm$^{-2}$·s$^{-1}$) | New | 172.36 | - | - | - | - | - |
| | End of test: dirty chain | 174.29 | 1930 | - | - | - | - |
| | End of test: cleaned chain | 172.00 | - | 360 | 38.30 | 1.20 | 89.47 |

It can be noticed that the mass reduction observed with $F_2$ (360 mg) was nearly double (1.89 times) compared to $S_B$ (190 mg). At the same time, the mass of the residues detached from the chain by cleaning operations was higher in the chain lubricated with $F_2$. Here, the residues had a vitrified aspect, and the cleaning resulted in being more difficult. Various factors could have contributed to determine the differences in the levels of chain wear observed with the two fluids. With the same total surface area cut with the two fluids, it must be considered that the trunk with the largest section (535 cm$^2$) was cut with $F_2$ in Rep. 5 (Table 14), where the cutting times expanded according to the exponential function of Figure 11 and resulted in being much greater than in the other five repetitions. The mechanical and thermal stress conditions that occurred on the chain in Rep. 5 probably were used to make the entire $F_2$ test, on average, more demanding and to determine the observed higher chain wear with respect to $S_B$ test. As regards the thermal stress with the two fluids, albeit the chain temperatures reported in Table 14 are only indicative and the higher value was observed in Rep. 2 instead of Rep. 5, they seem to confirm that, with $F_2$, the average thermal level of the chain was higher than with $S_B$, thus indicating the probable occurrence of a higher friction. Considering the magnitude of the differences between the two wear levels, alongside the considerations reported in the previous point, the greater wear observed with $F_2$ could partly be derived from an insufficient lubrication, which was highlighted by the severe test conditions, and contributed to the increase in both the friction (between chain parts and guide bar) and the chain temperature [21]. Since new saw chains were used in $T_3$ and were never sharpened, the observed mass reductions should interest mostly their lubricated parts, like the rivets, the drive links, and the tie straps, while the wear of the cutters caused by the friction with the wood should be limited and similar with both fluids. This point should be verified. The two fluids were used on the chainsaw without modifying the preset flowrate of the chain lubricant. Despite the positive impressions of the operators, who always affirmed that they did not notice any differences in the performance of the chainsaw after replacing $S_B$ with $F_2$, and considering the higher viscosity of $F_2$ (Table 7), it is possible that some changes in the flow rate of the lubricant (in the chainsaw, when possible) and/or in the formulation of the fluid led to a reduction in wear, bringing the performance of $F_2$ closer to that of $S_B$.

Air Samplings

As in $T_2$, the residues on the filters of the two air samplers were analyzed to quantify the fractions of inhalable and respirable sawdust and the concentration of metallic elements. Figure 12a shows that the limit of 2 mg·m$^{-3}$ established by the Directive (EU) 2019/130 [24] was always exceeded, except for with the respirable fraction with $F_2$. Despite the fact that these data relate to a particular context (intensive cutting at fixed point in a restricted area), they seem compatible with the mean concentrations observed during daily chainsaw running in hardwood coppice (*Quercus petraea* and *Fagus sylvatica*) [26].

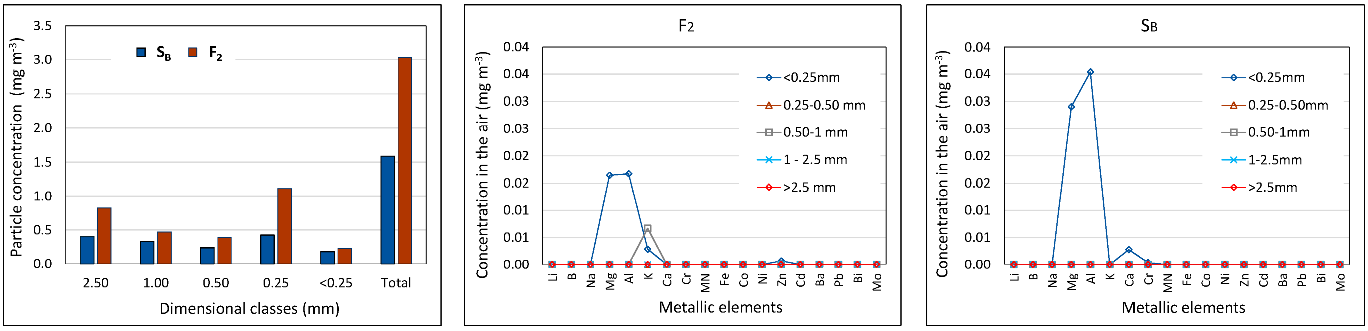



(**a**) (**b**) (**c**)

**Figure 12.** Results of the analyses on the residues from air samplings. (**a**) Concentrations in the air of inhalable and respirable particles. (**b**) Concentrations in the air of metallic elements in the respirable fraction. (**c**) Concentration in the air of metallic elements in the inhalable fraction.

The data relating to $S_B$ and $F_2$ are compared following the same sequence of repetitions adopted for each fluid: Rep. 1 vs. Rep. 4; Rep. 2 vs. Rep. 5; and Rep. 3 vs. Rep. 6. According to this sequence, the concentrations of both inhalable and respirable particles resulted in being higher with $S_B$ than with $F_2$ (except in Rep. 1 vs. Rep. 4 for the respirable fraction). The trend is confirmed by considering the average concentration: in both fractions, the mean values resulted in being clearly higher with $S_B$. This reflects the results of the air samplings made in $T_2$, albeit there were much higher particle concentrations observed. The reasons why the particle concentration is higher with $S_B$ than with $F_2$ are not clear. Due to their characteristics, the fluids could interact differently with the sawdust particles, influencing their dispersion in a different way. This will be the subject of further investigation. The concentrations of metallic elements, as reported in Figure 12b,c, are of the same order of magnitude observed in $T_1$ (Figure 5) during the felling of the Turkey oak wood. Relevant peaks are visible only for Al, whose highest value is observed for $F_2$ in the inhalable fraction. In the respirable fraction, the Al concentration is higher for $S_B$. Small increases in K, Ca, Fe, and Ni were observed in both fractions. In general, following the trend of the gravimetric analysis, the concentrations observed in $T_3$ resulted in being significantly lower than those observed in $T_2$. Figure 13a provides some information on the dimensional composition of the respirable fraction according to the classification provided by the five-stage impactor. In this case, only one sampling was carried out for each fluid, which lasted the time of the three repetitions.

The total particle concentrations are of the same order of magnitude shown in Figure 12a. Here, the values with $F_2$ are higher than those with $S_B$ in all classes, conversely to what was observed with the personal air samplers. As described in Section 2.2.4, the five-stage impactor was positioned about 2 m away from the cutting place, while the personal sampler was worn by the operator and therefore was close to the cutting point. Therefore, possible different interactions of $S_B$ and $F_2$ with the sawdust particles could have affected the dynamics of their dispersion as a function of the distance from the cutting point, causing the different trends of Figures 12a and 13a. The presence of metallic elements in the five classes is shown in Figure 13b for $F_2$ and in Figure 13c for $S_B$. Most of them resulted in being below the detectable threshold and were considered to be 0. It can be noticed that, with $F_2$, the detected elements were Mg, Al, K, and Zn. The concentrations of Al and K are about 20% of the values in Figure 12b,c. With $S_B$, the highest concentrations were those of Al and Mg, but the presence of Ca was also observed. All said elements were in the lower dimensional class (<0.25 µm), except for K, which was also in the class 0.5–1 µm.




(**a**) (**b**) (**c**)

**Figure 13.** Results of the analyses on the residues retained by the 5-stage impactor in the relating dimensional classes. (**a**) Particle gravimetric analysis for both fluids. (**b**) Concentration of metallic elements observed after the test with $F_2$. (**c**) Concentration of metallic elements observed after the test with $S_B$.

### 3.2.5. Felling of a Poplar Grove at CREA

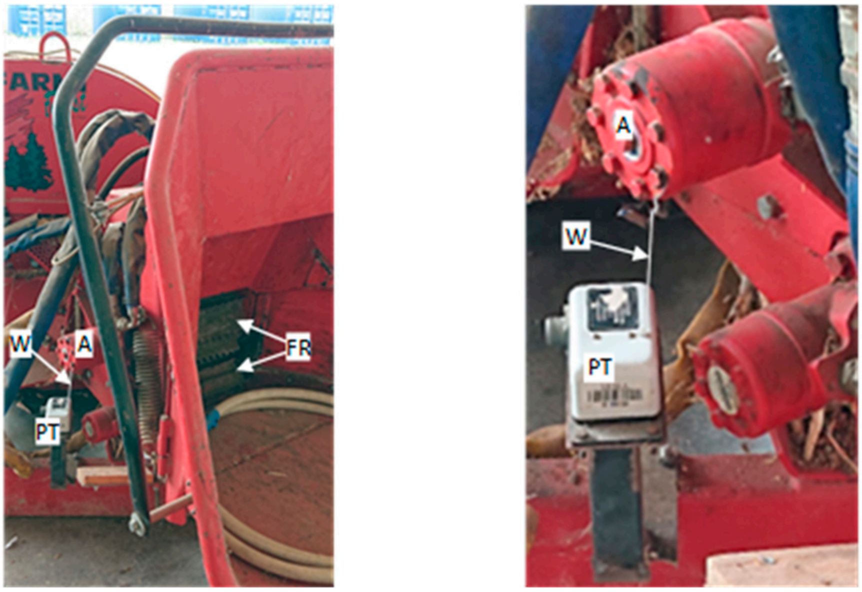
This test was carried out in another study concerning the dynamic and energetic requirements of the felling and chipping of a poplar grove. Such an activity represented a chance to gain additional information on the behavior of the ROPO-based fluid, with particular attention paid to the wear of the chain. Therefore, the same ICE chainsaw and the same chain lubricants, $S_B$ and $F_2$, used in $T_2$ and $T_3$ were used in $T_4$. The poplar grove was divided into two plots, and each plot was felled using one of the two lubricants and a new saw chain. The results of $T_4$ are reported in Table 17.

**Table 17.** Evaluation of the wear of the chains after the felling of the poplar grove ($T_4$).

| Lubricants | State of the Saw Chain | Masses | | | Cutting Data | | | Specific Chain Wear | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Chains g | Residues mg | Losses mg | Trees N | Section Mean Area [1] cm² | Total Cut Area m² | per Surf. Unit mg m⁻² | per Cut mg cut⁻¹ | Diff. % |
| $S_B$ | New | 171.98 | | | | | | | | |
| | End of test: dirty chain | 172.59 | 0.86 | 250 | 294 | 153.72 | 4.5 | 0.85 | 55.32 | |
| | End of test: cleaned chain | 171.73 | | | | | | | | |
| $F_2$ | New | 172.04 | | | | | | | | |
| | End of test: dirty chain | 172.88 | 1.13 | 290 | 252 | | 3.9 | 1.15 | 74.86 | 35.33 |
| | End of test: cleaned chain | 171.75 | | | | | | | | |

[1] The mean section was calculated based on the mean diameter of 13.99 cm (average of total cut diameters).

Besides the wear of the two chains consequent to the felling of the respective poplar tree plot, Table 17 also shows some useful data for interpreting the wear itself, like the number of cuts carried out and the mean cut section area. The latter was calculated from the mean diameter resulting from the cut diameters of a sample of 60 trunks taken randomly among the total trunks felled in the two plots. The diameters were measured during the chipping by means of a potentiometric transducer installed on the feed rollers of the chipper (Figure 14) to continuously measure the variation in the diameter of the trunk as it proceeds into the machine towards the chipping organs.




(a) (b)

**Figure 14.** (**a**) Wire potentiometric transducer, PT, installed on the chipper. (**b**) Detail of the wire transducer. PT is fixed to the chipper frame. The end of its wire (W) is connected to the shaft (A) of the upper feed roller (FR), which is pushed upwards, while the lower FR remains stationary, when the log enters the machine due to the rotation of both FR. Through the elongation of the wire, the PT continuously monitors the variations in the distance between the two FRs, thus providing the variation in the trunk diameter along the entire length.

The data of the diameters of the 60 trunks were recorded and processed, selecting, for each trunk, the maximum value, which refers to the cut section. This elaboration provided a mean diameter of 13.99 cm, with a standard deviation of 25.9 cm and a coefficient of variation of 18.5%, which indicates the high variability of the parameter. By hypothesizing that the variability of the diameters (and areas of the sections) of the sample are uniformly distributed between the two plots, multiplying the mean area of cut section by the number of cuts of each plot provides the total cut area. This and the cut number were used to calculate, respectively, the specific chain wear per unit of surface (mg $m^{-2}$) and the specific chain wear per cut (mg $cut^{-1}$). Despite the fewer cuts made, the chain used with $F_2$ suffered a higher mass reduction. The data of specific wear emphasize the difference between the two observed wear levels. The difference can be quantified as 35.33%-higher wear for $F_2$ in relation to $S_B$. The differences in the wear levels observed with $F_2$ and $S_B$ are lower in $T_4$ than in $T_3$ (Table 16) due to the different hardness values of the wood species used in the cutting tests (respectively, Poplar and Turkey oak). However, both test results indicate that the saw chains lubricated by $F_2$ underwent higher wear than those lubricated with $S_B$. The generally higher levels of temperature observed with $F_2$ in all tests, probably caused by higher frictions, seem to confirm this trend.

## 4. Conclusions

### *4.1. Lubricants and Chainsaws Performance*

The results shown in this paper provide a positive indication about the possibility of using refined olive pomace oil as a base stock for lubricant for chainsaws, though some aspects concerning its performance should be deepened and improved. The comparison between the ROPO-based formulation (containing 2% thickener and 3 g·$kg^{-1}$ of antioxidant) and the market-available Stihl Bioplus was made without any modification to the flow rate on the lubrication pump and evidenced, with the former, higher temperatures, probably caused by higher friction both among the various elements of the saw chain and between these and the guide bar, which resulted in higher chain wear than with the latter [27]. This wear does not seem to affect the efficiency of wood cutting, as testified by the positive opinions of the skilled operators involved in the tests who never noticed any difference between biobased and conventional fluid. However, it would be advisable to check whether it could in any way jeopardize the life of the chain (linked to the wear of the teeth following sharpening) and, consequently, the operator's safety conditions. Based on the experiences described above, a further series of comparative tests would help to clarify doubts about the suitability of ROPO as a lubricant for chains, suggesting a way to improve its performance by bringing it closer to that of the conventional fluid. These tests should be focused on the "systematic" acquisition of the following data:

- Measurement of the temperature of the fluids within the reservoir during the cutting.
- Measurement of the temperature of the saw chain/guide bar system and of the wood by means of the thermal imaging camera during the cutting with both fluids.
- Saw chain lubricant consumption during cutting with both fluids and evaluation of any differences. e.g., $F_2$, used from $T_1$ to $T_4$, is more viscous than $S_B$, and its consumption should therefore be lower and cause more friction, heating, and wear of the chain.
- Based on the results of the previous point, an ROPO-based formulation with a different viscosity could be tested to reduce the difference in chain wear relating to the commercial lube. Another possibility to investigate is to change the flow rate setting of the pump in the chainsaw's lubrication system in order to optimize the lube distribution on the chain.
- Evaluation of the long-term stability of the biofluid, both in the storage phase and after sitting for a long time in the unused chainsaw.

To compare the results provided by the lubricants, the data should come from tests at a fixed point, which would allow us to maximize the repeatability of conditions like trunk dimensions, ambient temperature, and relative humidity; and to standardize the dust sampling and the thermal monitoring of the chain, lube, and wood.

### *4.2. Lubricants and Sawdust Emissions*

The results of the air samplings and analyses of the residues revealed that the concentrations in the air of the inhalable and respirable fraction of wood dust particles both often exceed the limit of 2 mg·m$^{-3}$ established by the Directive (EU) 2019/130 and, thus, may increase the risk of cancer from workers exposure to this material. It was also found that dust particles contain variable amounts of metallic elements (like Al, K, Ca, Cu, and Zn), and these resulted in also being present in the respirable fraction. These concentrations were found to be lower with the ROPO-based fluid than with the conventional fluid, and the reason for this needs to be clarified: it could depend on some different interaction of the wood dust particles with the dispersed fluids droplets. The sawdust also acts as a vector of chain lubricant and other substances (like metallic elements) dispersed by the chainsaw during cutting, the presence of which in the respirable fraction makes them potentially dangerous for the health of the operators, increasing the risk deriving from exposure to mere sawdust. In a study on the dispersion of chainsaw oil based on the use of radiotracers, it was determined that 21.9% falls onto the ground, 8.3% is soaked into the cut trunk's surface and into the immediately surrounding area, about 5% remains in the air as aerosol, and, finally, 64.4% of the total lubricant consumption is retained by sawdust [9]. Therefore, wood dust particles, as the lighter part of the sawdust, will also probably contain oil that is capable of deeply penetrating the respiratory system. Its amount could be assessed by combining the just-cited data and some results of our study. For example, relating to the results of $T_1$, the assessed amount of oil dispersed per surface unit is 28.8 L ha$^{-1}$ of felled forest. Of these, according to the aforementioned percent distribution, 1.6 L ha$^{-1}$ would be in aerosol form, and 20.2 L ha$^{-1}$ would be incorporated in the mass of sawdust. Considering the number of cuts per hectare, the mean area of cut section, the thickness of the cut (Table 9), and a mean specific gravity of 900 g L$^{-1}$ for the wood of Turkey oak, the mass of sawdust can be assessed at around 3145 kg ha$^{-1}$, with a resulting mean concentration of oil in sawdust of 0.32%. Hypothesizing that this remains constant in the dust wood particles, in the case of a concentration of respirable fraction of around 3 mg m$^{-3}$ (Figure 12a, $S_B$), the oil it contained would be 9.65 mg m$^{-3}$. This value probably underestimates the actual respirable oil amount because it does not comprehend the aerosol fraction, and, most of all, the operators constantly work near the cut point, where the wood dust concentration is higher. As regards the effects of these values on workers' health, the Directive (EU) 2019/130 refers to hardwood dust as a carcinogenic risk factor. Other substances present in wood dust, like metallic elements (arsenic, lead, cadmium, and nickel), could increase the risk from exposure to simple wood dust [22,28].

From this point of view, the risk is probably affected by the presence of the exhausts of two-stroke-engine chainsaws, which are characterized by the presence of mutagenic substances due to the combustion of the gasoline–lubricant mix [6]. According to the same approach and data used to assess the concentration of chain lubricant in sawdust, the consumption of mix per surface unit is 52.5 L ha$^{-1}$, which contains 1.6 L ha$^{-1}$ oil (at 3% in the mix). However, the results of $T_2$ did not evidence the influence of exhausts in the concentration of wood dust and metallic elements. It would be interesting to investigate the presence, in the residues from air sampling, of organic substances relevant to the health of the operators, their origins (from chain lubricant, additives, combustion exhausts, etc.), and any synergistic effects with those of wood dust. To this purpose, the use of WEM chainsaws and ICE chainsaws of comparable performance in specifically designed tests would be helpful and would allow us to improve the knowledge of the quality of the emissions with conventional and biobased lubricants. In any case, the use of highly degradable lubricants for saw chains would reduce the contribution of this factor to the global risk of exposure to all emissions from the use of chainsaws. Lubricating the saw chains with biobased lubricants like ROPO would ensure a high level of biodegradability, which should be safeguarded through a correct choice of additives, as in the case of the antioxidants adopted in our tests. Most of these considerations can be extended to the aspect of the impact of the activities based on the use of chainsaws on the environment—in particular, forests, which receive a high load of pollutants per surface unit.

The above-described process should lead to the realization of a chain lubricant that is technically valid and environmentally sustainable. Its introduction into the operative reality will depend on future market trend. The present study began in 2021, before the start of the Ukrainian war (22 February 2022), which is still ongoing and has caused, among other things, strong disruptions in the market of all vegetable oils, whose prices have increased dramatically. In relation to our study, the ROPO, previously considered a by-product, acquired new value as edible oil, and its price increased from 1.90 EUR kg$^{-1}$ in January 2022 to 3.10 EUR kg$^{-1}$ in October 2022 [29] and to 3.40 EUR kg$^{-1}$ in October 2023 [30], making it non-competitive with conventional chain lubricants. The desirable end of the war could help restore market conditions and make them more favorable to the use of products such as ROPO in non-food applications.

The results obtained in this research on ROPO can be transferred to other vegetable oils with a similar fatty acid composition, such as high-oleic sunflower oil and rapeseed oil, when the price and/or availability of ROPO oil should be critical. The only remarkable difference for the discussed applications stands in the diglyceride content of these refined oils, as the acidity of the corresponding crude oils is lower.

**Author Contributions:** Conceptualization, P.B., I.C., D.P. and R.F.; methodology, D.P. and R.F.; software, M.B.; validation, R.F., P.B. and D.P.; formal analysis, L.F. (Laura Fornaciari) and F.G.; resources, L.F. (Liliana Folegatti); data curation, D.P., L.F. (Liliana Folegatti) and P.G.; writing—original draft preparation, P.B. and R.F.; writing—review and editing, D.P., R.G. and M.B.; visualization, F.G. and S.B.; supervision, I.C.; project administration, I.C.; funding acquisition, P.B. and I.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by INNOVHUB, grant number 22/2021 of 10/03/2021; and by the Italian Ministry of Agriculture (Mi.P.A.A.F.), under the AGROENER project (D.D. n. 26329, 1 April 2016)—http://agroener.crea.gov.it/ (accessed on 27 September 2023).

**Data Availability Statement:** The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to privacy restrictions.

**Acknowledgments:** The authors thank Franco Bernardini, Gino Brannetti, Cesare Cervellini, and Sandu Lazar (CREA) for their collaboration in the realization of the tests at a fixed point.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Lopez-Blanco, R.; Gilbert-Lopez, B.; Rojas-Jimenez, R.; Robles-Molina, J.; Ramos-Martos, N.; Garcia-Reyes, J.F.; Molina-Diaz, A. Evaluation of processing factors for selected organic contaminants during virgin olive oil production: Distribution of BTXES during olives processing. *Food Chem.* **2016**, *199*, 273–279. [CrossRef]
2. Moret, S.; Conchione, C.; Srbinovska, A.; Lucci, P. Microwave-based technique for fast and reliable extraction of organic contaminants from food, with a special focus on hydrocarbon contaminants. *Foods* **2019**, *8*, 503. [CrossRef] [PubMed]
3. Barp, L.; Moret, S.; Purcaro, G. Monitoring and occurrence of heavy PAHs in pomace oil supply chain using a double-step solid-phase purification and HPLC-FLD determination. *Foods* **2022**, *11*, 2737. [CrossRef] [PubMed]
4. Dennis, M.J.; Massey, R.C.; Cripps, G.; Venn, I.; Howarth, N.; Lee, G. Factors affecting the polycyclic aromatic hydrocarbon content of cereals, fats and other food products. *Food Addit. Contam.* **1991**, *8*, 517–530. [CrossRef] [PubMed]
5. Šimko, P. Determination of polycyclic aromatic hydrocarbons in smoked meat products and smoke flavouring food additives. *J. Chromatogr. B* **2002**, *770*, 3–18. [CrossRef]
6. Magnusson, R.; Nilsson, C.; Andersson, K.; Andersson, B.; Rannug, U.; Östman, C. Effect of Gasoline and Lubricant on Emissions and Mutagenicity of Particles and Semivolatiles in Chain Saw Exhaust. *Environ. Sci. Technol.* **2000**, *34*, 2918–2924. [CrossRef]
7. Ålander, T.; Antikainen, E.; Raunemaa, T.; Elonen, E.; Rautiola, A.; Torkkell, K. Particle Emissions from a Small Two-Stroke Engine: Effects of Fuel, Lubricating Oil, and Exhaust Aftertreatment on Particle Characteristics. *Aerosol Sci. Technol.* **2005**, *39*, 151–161. [CrossRef]
8. Stanovský, M.; Schürger, J.; Jankovský, M.; Messingerová, V.; Hnilica, R.; Kučera, M. The effect of lubricating oil on temperature of chainsaw cutting system. *Croat. J. For. Eng.* **2013**, *34*, 83–90.
9. Skoupy, A.; Pechlák, B.; Sejkora, P.A. Contribution to the understanding of oil dispersion at the work with a chain saw by means of the radiotracer method. *Lesnictví* **1990**, *36*, 937–946.
10. Nowak, P.; Kucharska, K.; Kamiński, M. Ecological and health effects of lubricant oils emitted into the environment. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3002. [CrossRef]
11. Webb, E.; Bushkin-Bedient, S.; Cheng, A.; Kassotis, C.D.; Balise, V.; Nagel, S.C. Developmental and reproductive effects of chemicals associated with unconventional oil and natural gas operations. *Rev. Environ. Health* **2014**, *29*, 307–318. [CrossRef] [PubMed]
12. *EUR-Lex—32022R2104—EN—EUR-Lex*; Commission Delegated Regulation (EU) 2022/2104 of 29 July 2022 Supplementing Regulation (EU) No 1308/2013 of the European Parliament and of the Council as Regards Marketing Standards for Olive Oil and Repealing Commission Regulation (EEC) No 2568/91 and Commission Implementing Regulation (EU) No 29/2012. European Union: Brussels, Belgium, 2023.
13. Gòmez-Coca, R.B.; Pérez-Camino, M.; Moreda, W. The Mineral Oil Hydrocarbon Paradox in Olive Pomace Oils. *Food* **2023**, *12*, 434. [CrossRef] [PubMed]
14. Brühl, L. Occurrence, determination, and assessment of mineral oils in oilseeds and vegetable oils. *Eur. J. Lipid Sci. Technol.* **2016**, *118*, 361–372. [CrossRef]
15. Ursol Menegoz, L.; Conchione, C.; Peroni, D.; Carretta, A.; Moret, S. A study of the impact of harvesting operations on the mineral oil contamination of olive oils. *Food Chem.* **2023**, *406*, 135032. [CrossRef] [PubMed]
16. Garrett, S. Vegetable Oil for Lubricating Chain Saws. In *Fire Management Tech Tips*; United States Department of Agriculture Forest Service: St. Paul, MN, USA, 1998.
17. Cecilia, J.A.; Ballesteros Plata, D.; Alves Saboya, R.M.; Tavares de Luna, F.M.; Cavalcante, C.L., Jr.; Rodríguez-Castellón, E. An overview of the biolubricant production process: Challenges and future perspectives. *Processes* **2020**, *8*, 257. [CrossRef]
18. Pochi, D.; Fanigliulo, R.; Bisaglia, C.; Cutini, M.; Grilli, R.; Fornaciari, L.; Betto, M.; Pari, L.; Gallucci, F.; Capuzzi, L.; et al. Test rig and method for comparative evaluation of conventional and bio-based hydraulic fluids and lubricants for agricultural transmissions. *Sustainability* **2020**, *12*, 8564. [CrossRef]
19. Fanigliulo, R.; Pochi, D.; Bondioli, P.; Grilli, R.; Fornaciari, L.; Folegatti, L.; Malaguti, L.; Matteo, R.; Ugolini, L.; Lazzeri, L. Semi-refined Crambe abyssinica (Hochst. EX R.E.Fr.) oil as a biobased hydraulic fluid for agricultural applications. *Biomass Convers. Biorefinery* **2023**, *13*, 1859–1871. [CrossRef]

20. Ugolini, L.; Matteo, R.; Lazzeri, L.; Malaguti, L.; Folegatti, L.; Bondioli, P.; Pochi, D.; Grilli, R.; Fornaciari, L.; Benigni, S.; et al. Technical performance and chemical-physical property assessment of safflower oil tested in an experimental hydraulic test rig. *Lubricants* **2023**, *11*, 39. [CrossRef]
21. Orawiec, A.; Suryan, L.; Parmigiani, J. An evaluation of the performance of chainsaw lubricants. *Croat. J. For. Eng.* **2020**, *41*, 325–332. [CrossRef]
22. Pochi, D.; Biocca, M.; Fanigliulo, R.; Gallo, P.; Pulcini, P. Sowing of seed dressed with thiacloprid using a pneumatic drill modified for reducing abrasion dust emissions. *Bull. Insectol.* **2015**, *68*, 273–279.
23. States Environmental Protection Agency (EPA). *Method 6010D (SW-846): Inductively Coupled-Plasma Atomic Emission Spectrometry, Revision 4*; States Environmental Protection Agency (EPA): Washington, DC, USA, 2014.
24. European Union. Directive (EU) 2019/130 of the European Parliament and of the Council of 16 January 2019 amending Directive 2004/37/EC on the protection of workers from the risks related to exposure to carcinogens or mutagens at work. *Off. J. Eur. Union* **2019**, *30*, 112–120.
25. European Union. Directive (EU) 2017/2398 of the European Parliament and of the Council of 12 December 2017 amending Directive 2004/37/EC on the protection of workers from the risks related to exposure to carcinogens or mutagens at work. *Off. J. Eur. Union* **2017**, *345*, 87.
26. Marchi, E.; Neri, F.; Cambi, M.; Laschi, A.; Foderi, C.; Sciarra, G.; Fabiano, F. Analysis of dust exposure during chainsaw forest operations. *iForest* **2017**, *10*, 341–347. [CrossRef]
27. Otto, A.; Parmigiani, J. Velocity, depth-of-cut, and physical property effects on saw chain cutting. *BioResources* **2015**, *10*, 7273–7291. [CrossRef]
28. Dimou, V.; Malesios, C.; Chatzikosti, V. Assessing chainsaw operators' exposure to wood dust during timber harvesting. *SN Appl. Sci.* **2020**, *2*, 1899. [CrossRef]
29. Camera di Commercio di Bari—Borsa Merci—Commissione Olio—Listino Olio 2022. Available online: https://www.ba.camcom.it/info/listino-olio-2022 (accessed on 30 October 2023).
30. Camera di Commercio di Bari—Borsa Merci—Commissione Olio—Listino Olio 2023. Available online: https://www.ba.camcom.it/info/listino-olio-2023 (accessed on 30 October 2023).


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.