POPFREE FINAL REPORT

Promotion of PFAS-free alternatives

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Final report

POPFREE – Promotion of PFAS-free alternatives was a collaboration project that aimed at contributing to the promotion of marketable PFAS-free products by developing competitive alternatives with reduced environmental footprint and creating a market pull. The project started in November 2017 and ended in March 2020. The project, with financing from Vinnova and the project partners, had a total budget of about 25 MSEK. More information about the project can be found on www.popfree.se .

Project team:
RISE Research Institutes of Sweden, Nouryon, BillerudKorsnäs AB, BIM Kemi AB, Carrington Workwear Ltd, Chemex AB, COOP Danmark A/S, Dafo fomtec AB, Fidra, Fristads AB, Försvarets Materialverk (FMV), H&M Hennes & Mauritz GBC AB, Haglöfs AB, Helly Hansen AS, Icebug AB, Klättermusen AB, Mammut Sports Group AG, Mid Sweden University (Mittuniversitetet), Naturskyddsföreningen, Nordic Paper Seffle AB, Organoclick AB, Paragon Nordic AB, Peak Performance Production AB, Peak Region Science Park (Peak Innovation), Red creek Sweden AB, RISE IVF, Swix Sports AS, TPC Textile AB, Vasaloppet SÄLEN-MORA

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1. Executive summary

Per- and polyfluorinated alkyl substances (PFAS) is a wide group of substances originating from the 1930's; the OECD has as of today identified more than 4730 PFAS substances that have a CAS number. These molecules have found a lot of application in industries and are used in many consumer products because of their unique properties such as oil and water repellence, low surface tension allowing excellent film-forming ability or high thermal stability. However, several of these man-made chemicals are bioaccumulating, biomagnifying and non-biodegradable and are now classified as Persistent, Bioaccumulative and Toxic (PBT) according to the classification, labeling and packaging regulation CLP. PFASs have been found in many contaminated sites in urban areas but also in remote areas: significant levels of PFASs have been measured in the blood of polar bears in the arctic region.
The wide spreading of PFAS is largely due to their extensive production and use as well as persistent nature. PFAS are commonly found in impregnation sprays for shoes and textiles, firefighting foams for chemical fires or within the military sector, food packaging and food contact materials, ski waxes, decorative cosmetics, hydraulic fluids, metal plating, surface coatings, or electronics for example.

The POPFREE project has worked to minimize the use of PFAS-containing products to prevent further release of these substances. The project was capitalizing on a pull and push approach to achieve a systemic change: the pull was created by increasing consumer awareness of the issues related to PFAS while the push was obtained through development of alternative chemical solutions and products with a better health- and environmental impact.
The project was built as a matrix with six different product-related case studies running across the work packages. A visual representation of the matrix is presented in Figure 1. The six case studies selected for the project were: food contact materials, textile and leather, cosmetics, ski wax, film-forming products and firefighting foams.
In the first work package, the function of the PFASs in the different product categories was investigated to set up technical criteria that the alternative must fulfill. In the textile case, it was for example established that the essential function was durable water repellency for outdoor textiles, while dirt repellency such as repellency towards burning hydrocarbon fuel or to maintain a surface clean, was critical for personal protective equipment and to preserve high visibility. Based on the established criteria, potential alternative solutions were identified and tested in lab scale. We evaluated both commercially available and non-commercially available PFAS-free solutions. Several alternative surfactants have been tested as a direct replacement of PFAS. For some products, a direct substitution was not possible and the introduction of, for instance, nanoparticles was needed. The project has also developed new methods to evaluate our alternatives as the standards methods were not always suitable for the new types of chemistries used. In the ski wax case, a lab method based on contact-angle measurement was for example established to allow for faster screening of alternative waxes without the need for time consuming field tests. In the firefighting foam case, a special foam generating device was used and modified to generate in lab scale a foam as similar as possible to the foam used for evaluation and certification of firefighting foams.
In parallel to the technical evaluation of alternatives, risk assessments were conducted on the most promising alternatives as it was essential for the project to avoid "regrettable substitution",

i.e an alternative with equally problematic or worse hazard profile. These assessments were performed using the ingredient lists and evaluating the health and environmental impacts of the specific ingredients, according to data obtained from safety datasheets and databases. As legislation of PFASs and other substances is constantly evolving in EU, a continuous monitoring of existing and upcoming legislation was performed to ensure the developed alternatives are viable. Both work performed at the EU level within REACH and ECHA as well as within the Stockholm Convention or OECD was followed and actively engaged in.

Based on the results from these three parallel activities (screening of alternatives, risk assessment and legislation), some alternatives were further evaluated at prototype level or in larger scale. Several prototype runs were for example performed for food contact materials, film-forming products and firefighting foams. Full life cycle assessments were also performed on several products that had shown promising results in lab and pilot tests.

In parallel to the technical development, the project has intensively worked with communication. The communication has been directed towards partners in the different value chains as well as consumers. In the value chain, a textile guideline has for example been developed to support textile retailers and manufacturers in their dialog with suppliers. A dialogue was established with several authorities and joint activities such as breakfast seminars or conferences were organized directed towards specific sectors.

Several surveys were sent out to better understand consumer needs and behavior, for example with respect to handling of school uniforms with different DWR treatments. The project also had a booth in Mora during the Vasaloppet's winter week both in 2019 and 2020 to reach private persons as well as the whole cross-country sector.

In the ski wax case, the international dimension of the challenge due to competition and the need for global regulation emerged early in the project. Therefore, the POPFREE Ski goes Global project was initiated and conducted with financing from Vinnova to establish a road map for a potential phase-out of PFAS. POPFREE Ski Goes Global arranged a workshop "*Competitive skiing without fluorinated ski waxes?"* in August, 2019 and together with stakeholders from the ski sports, a common roadmap was drafted with actions and time needed to move towards PFAS-free competitive skiing. On 23rd of November the Council of the International Ski Federation decided on a total fluorine ban in all skiing disciplines from next season (2020/2021).

2. Structure of the project

The POPFREE project was built as a matrix with six different case studies related to different product categories running across the different work packages (Figure 1). The different product categories had different starting points and needs and therefore all the product categories were not involved in the work-packages 1 – 4 to the same extent.

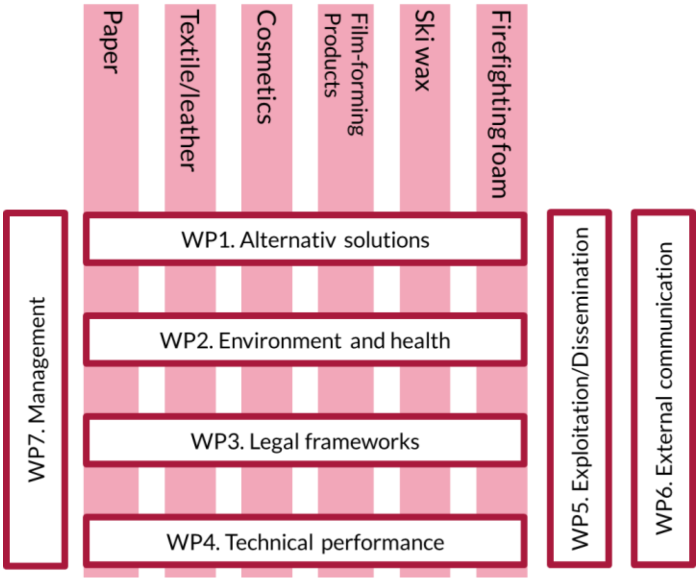


Figure 1. The POPFREE project

To achieve a systemic change, POPFREE capitalized on a push-pull approach where the push is created by the launch of new PFAS-free products and the pull results from higher demands from consumer and customers for PFAS-free alternatives (Figure 2*)*.

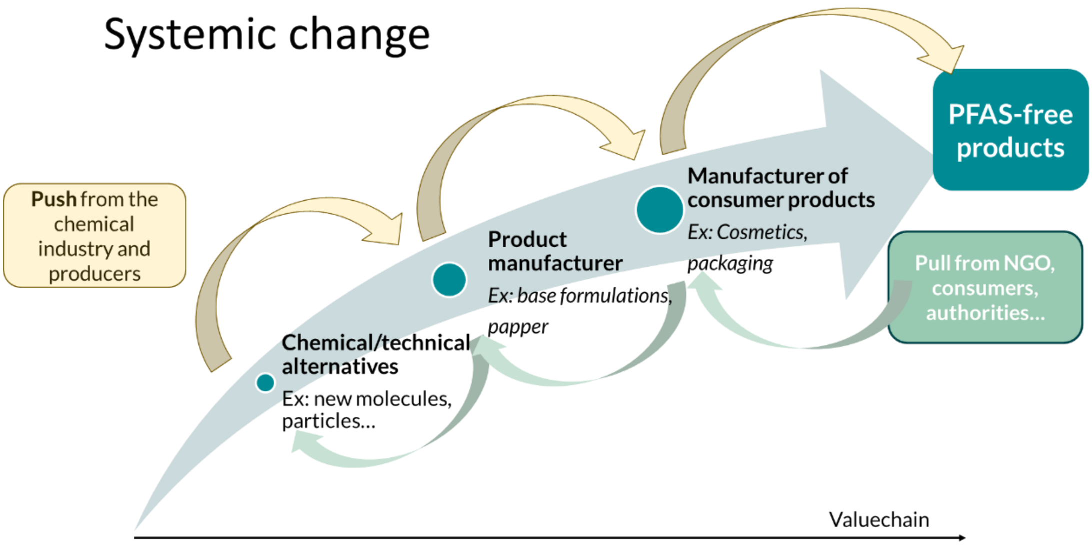


Figure 2. Illustration of the push-and-pull model.

3. POPFREE's substitution model

In POPFREE, a new substitution model was established and evaluated (Figure 3). The process consists of several steps:

- Initially, the function of the PFAS in the products was determined and essential criteria that the alterative must fulfil were established. Thereafter, potential alternatives were identified and screened at lab scale. In parallel, a risk assessment of the different alternatives with respect to health and environmental aspects was conducted. The compliance of the selected alternatives to existing and upcoming regulations was also controlled.
- If the performance, risk assessment and regulatory aspects were approved, the alterative was further evaluated at pilot scale and/or using industrial standards. When relevant a full life cycle assessment was performed.
- If the evaluation of the technical performances and LCA were approved, the alternative was considered for exploitation.
- The alternatives to be exploited will further be scaled up and tested in real environment before commercialization. This step was however not included in the project but will be part of the stage 3 project.

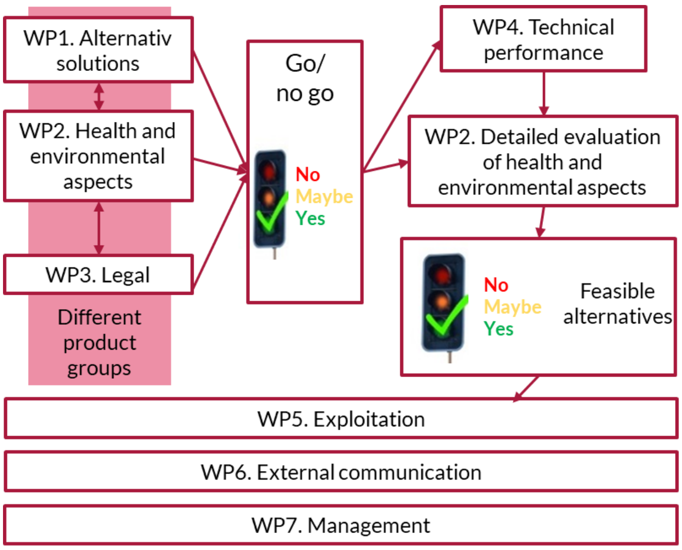


Figure 3 The POPFREE substitution model

4. Brief description of the cases and involved partners

4.1 Case paper

Partners involved: Billerud Korsnäs, BIM Kemi, COOP, Fidra, RISE, RISE IVF
Background: PFAS are used in a wide range of packaging and food contact paper to provide barrier properties against grease and oil while maintaining breathability. In the project, it was decided to focus on food contact materials FCM (for example fast food paper) and grease proof paper rather than packaging.
Sometimes FCM treated with polyfluorinated ethers are addressed as PFAS free. These polyfluorinated ethers are used as replacements in the paper industry to diPAPs to make FCM grease proof. Polyfluorinated ethers are also used as emulsifiers (surfactants) for the production of PTFE.
Aim: To develop alternatives to PFAS for food contact materials and increase awareness on the use of PFAS in packaging.

4.2 Case textile and leather

Partners involved: Carrington workwear Ltd, Fidra, Fristads Kansas, FMV, Haglöfs, Helly Hansen, Icebug, Klättermusen, Mammut, Organoclick, Paragon Nordic, Peak Innovation, Peak Performance, TPC Textile, RISE IVF, RISE.
Background: In textile and leather use, PFAS are widely used in water-, dirt- and grease repellent finishing treatments. The repellence properties obtained can be used in several ways, including waterproofing, stain release and chemical splash protection in protective textiles. The textile case, with 16 partners, thus has had the most diverse requirements of all POPFREE cases, ranging from fashion textile where currently available alternatives work as direct drop-in solutions for water repellence, to workwear and military textiles where combinations of demands for water and oil repellence in combination with other treatments and standards/legal frameworks make substitution a big challenge.
Aims: To develop more efficient testing methodology, assessing the properties of new formulations and textile systems in new ways, to make screening of new alternatives both faster and more accurate. Another aim was to develop and assess alternatives and to enable better chemicals management work in the supply chain.

4.3 Case cosmetics

Partners involved: H&M, The Swedish Society for Nature Conservation, RISE
Background: PFAS are used in decorative cosmetics where they bring properties such as anticaking, film forming, moisture/fat stability (i.e. the colour of the foundation is not affected by sweat or fat from the skin).
Aim: To substitute PFAS in cosmetic products and communicate with the cosmetic sector on the environmental risks associated with PFAS to encourage a phase out.

4.4 Case film-forming products

Partners involved: Chemex, RISE
Background: Film-forming products can be e.g. paints or protective coatings (e.g. anti-graffiti coatings or car care). In these products PFAS can be present for two reasons: either as so-called levelling agents to assure that an absolutely flat surface is formed when the applied formulation dries on its substrate, or as an additive to make the film water-, oil- and dirt-repellent. Fluorinated surfactants and polymers (PFBS derivatives or fluorotelomer derivatives) are currently used in these applications due to the low surface energy and oleophobicity of the fluorinated groups.
Aim: To replace PFAS in several formulations.

4.5 Case ski wax

Partners involved: BRAV (SWIX), Paragon Nordic, Peak Innovation, Red Creek, RISE, Sports Tech Research Center, Vasaloppet.
Background: PFAS are used in fluorinated ski waxes to provide a ski surface with high water and dirt repellence to achieve extremely low friction against snow and good glide. Fluorinated ski waxes have the greatest effect in higher snow temperatures (around zero degrees) and wet conditions. There is a direct risk of exposure to PFAS during ski waxing as vapour emissions and particles are released into indoor air when melting wax and scraping/brushing the skis, see Figure 4. Far from all ski waxers use proper safety equipment in their preparation work (proper face mask, protection clothing and gloves).
Aim: To develop a test method for faster performance assessment in alternative waxes, independent of weather conditions. To test some existing high-performance alternatives entering the market as well as prototype substances for possible development. To raise awareness amongst the skiing community about health and environmental risks associated with fluorinated waxes to increase the demand for fluorine-free waxing.

Figure 4. Photo showing the direct risk of exposure to PFAS (and dust/particles in general) during ski waxing.

4.6 Case firefighting foams

Partners involved: Dafo Fomtec, Nouryon, RISE
Background: Firefighting foams containing PFAS are normally designated Aqueous Film Forming Foam (AFFF) or Film Forming Fluoro Protein foams (FFFP). These foams are used in chemical fires by e.g. the municipal Fire and Rescue Services (FRS), the petroleum and chemical industry, airports, the military, and by the maritime and offshore sector. As a result of the environmental impact related to these foams, the foam industry has developed foam concentrates without fluorochemicals, which are normally referred to as Fluorine Free Foam (FFF). However, there is currently a great concern about the efficiency of FFF compared to existing AFFF and FFFP.
Aim: To increase the performance level of fluorine-free alternatives and improve their compatibility with current equipment.

5. Technical development and evaluation

5.1 Case paper

BIM Kemi has been working on the development of alternative formulations to be used for food contact paper. The exact composition of the formulation is a company secret and could not be shared with all partners.

5.1.1 Evaluation of formulations in lab tests

Greaseproof papers from NordicPaper and Billerudkorsnäs (A4 size) were selected and coated with three prototype formulations from BIM Kemi and two fluor-containing commercial formulations, at three different coat weight (low; aim 4-5 g/m^2, medium: 7-8 g/m^2 and high: 12-13 g/m^2). The fluor-containing formulations were used as benchmark. The coated papers were analysed using a series of standard industrial tests: KIT Test, NFA test and Total Organic Fluor measurements.

KIT Test: This is a conventional method in industry to determine the oil repellency of treated papers. In this method, 12 different test solutions with different surface tension are prepared from mixtures of three chemicals (Castor oil, toluene and n-Heptane) in specific ratio. A drop of the test solutions is then released from a height of about 10 mm onto the surface of the test piece, and the drop is quickly removed after 15 s. The surface of the test specimens is immediately examined to see any darkening of any part of the paper, indicating wetting and penetration of the test solution into the paper. The 12 test solutions are tested in a specific order corresponding to decreasing surface tension. Finally, the last test solution that does not exhibit an endpoint (i.e. penetration) indicates the KIT rate, which is given by the number of the solution, 12 being the highest possible value.
The KIT test is a cheap, easy, quick and reproducible method and it is a suitable technique for process and quality control. However, solvents used in this technique do not simulate real cases (fats & oils) and the test is performed at room temperature which is not always representative of product use (greaseproof papers for oven use or wrapping of warm food).
The treated papers and untreated papers were examined by KIT test at two different occasions during the project (Nov. 2018 and Apr. 2019) and all treated papers were given high KIT rate (10-12), while, all untreated papers were failed in the KIT test (i.e. an end-point was already visible after exposure to the first test solution). Surprisingly, the fluor-containing treated papers had lower KIT values than non-fluorinated formulations from BIM Kemi.

NFA test: NFA test is an alternative to the KIT test. In this technique, which was developed by the Solvay company, fatty acids are used to simulate the composition of naturally occurring fats and oils, and the test is performed at 60 ^oC to speed up the penetration effect. It was shown that there is a correlation between the NFA rating and end-use performances that are assessed during the quality control in production. In this method 11 different test solutions are prepared from mixtures of three chemicals (Castor oil, oleic acid and octanoic acid) in specific ratios. The solutions are kept in oven at 60 ^oC. A drop of the test solutions is then released from a height of about 10 mm onto the surface of the test piece, and the drop is removed from the surface after 5 min. The surface is immediately examined to see any darkening of any part of the paper. Finally, the test solution with the highest number that does not exhibit an endpoint is considered as NFA rate. The NFA results showed that, although most of the treated papers got very high rank at KIT test (i.e. at room temperature), NFA rates varies from 1 (lowest rate) to 11 (highest rate) for the tested specimens using higher temperature and test solutions closer to real fat/grease.

Total organic fluor measurement: Total organic fluor and total extractable organic fluor content of treated and untreated papers were also measured in collaboration with an American lab. The results did not show organic fluor coming from the prototype treatment formulations in the treated papers. Small background levels of fluor could be detected in all samples, highlighting the need of setting a reasonable limit in upcoming regulations.

5.1.2 Evaluation of formulations in pilot testing

From the three formulations prepared by BIM Kemi and evaluated in lab scale, two of the formulations showed interesting KIT and NFA values (formulations BIM 550 and BIM 570). These two formulations were selected for further evaluation at prototype level in collaboration with BillerudKorsnäs.

In April 2019 BillerudKorsnäs arranged a pilot coater test at Voith in Heidenheim, Germany. The pilot coater runs at normal full-scale production speed but with a smaller width of only 800mm. One of the paper machines at BillerudKorsnäs, Skärblacka, is equipped with the same coater, Speed sizer, as was used on the pilot coater, which ensure the relevance of the pilot testing made in Germany. BIM Kemi supplied formulation BIM 550 and 570.
BIM 550 showed good runnability on the pilot coater. However, when BIM 570 was used, the paper web was very unstable, which resulted in web breaks. Even though paper draws were changed it was not possible to improve and stabilize the paper web. Paper with BIM 570 felt smooth and wax-like and this low friction caused the paper web to move and resulted in web breaks. The paper was coated only on one side using the formulations of BIM Kemi.

Papers with BIM 550 or 570 were tested for Gurley porosity and with the Palm kernel oil test. The Gurley porosity measures the time it takes for a certain volume of air to flow through a paper and the Palm kernel oil test gives the time for the oil to break through to the other side of the paper. Tests of the barrier properties showed that the BIM 570 resulted in a more closed structure of the paper with 4050 Gurley seconds. BIM 550 showed values above 2730 Gurley seconds.
The oil penetration test showed that when the oil was applied on the barrier side, breakthrough was at 175 ± 22 min for BIM 550 and 338 ± 88 min for BIM 570. If the oil was applied on the uncoated side, breakthrough was at 284 ± 89 min for BIM 550 and 224 ± 186 min for BIM 570. The initial pilot tests run with the formulation from BIM Kemi showed promising results. However, further optimization of the formulations is necessary to achieve the desired properties. It was unfortunately not possible to run other pilot test during the project period due to unavailability of the equipment.

5.2 Case textile and leather

As the first task in the textile/leather case, a starting point survey was sent out to the industry partners to assess their needs. From this data and follow-up questions, a “Performance testing matrix” with criteria for alternative solutions was compiled and completed with known test methodologies.

In the survey, known alternatives on the market were listed and added to the Performance testing matrix. A few additional alternative solutions (i.e. more innovative approaches) were identified, which gave leads to further investigations. A PFAS reference (C6) and a benchmark alternative were chosen for further comparisons with new substances developed by project partners.

5.2.1 Preparation of fabrics

Fabrics representing a set of common outdoor and workwear textile structures and textile fibres were chosen for further testing of the alternative formulations and reference formulation. Materials including polyester, polyamide and polyester-cotton blend were tested, in both finer and heavier weaves. Each fabric was treated in a foulard process with each of the tested formulations, forming an evaluation matrix for tests.

The selected samples (maximum sample size: 33 x 43 cm) were immersed in selected chemical formulations of defined concentrations, including the prototype formulations provided by BIM Kemi. The samples were squeezed in a foulard (pressurized reels) to remove the excess liquid. The samples were dried in a horizontal position/flat in a heating cabinet (to evaporate the water) and were then pinned up on both ends on a frame, using the same force in each case. The samples on the frames were dried and cured in a stenter, directly after passing through the foulard. The whole process was done in lab scale but has a lot of resemblance to the common industrial pad-dry-cure process.

5.2.2 Evaluation of fabric properties in lab scale

Determination of resistance to surface wetting (Spray test), EN ISO 4920:2012: Provides a first indication of the repellent properties of a textile material. A well-defined volume of water is sprayed on the material through a standard nozzle. The material is mounted in a holder, inclining 45% towards the horizontal plane. The water repellence of the material is determined visually to a level 1 – 5, by comparing the samples with images of standard materials within a set time after exposure.

Determination of water repellence of fabrics by the Bundesmann rain-shower test, ISO 9865:1991: The samples are mounted on cups and exposed to a standard rain- shower under defined conditions. The method provides information about absorbed and penetrated water (by weighing the sample, after a short centrifugation, and measuring the volume of water in the cup) as well as the repellence by visual assessment of the surface, i.e. like the Water spray rate method.

Oil repellence – Hydrocarbon resistance test, ISO14419:2010: Drops of standard test liquid hydrocarbons with different surface tensions were placed on a textile surface and observed. The oil repellence grade is the highest numbered test liquid which is not absorbed by the textile material. The highest numbered test liquid has the lowest surface tension.

Determination of water repellence by contact angle measurement: Static and dynamic water contact angle were measured on treated textiles and on untreated textiles (control samples) based on sessile drop method. A water droplet was placed on the textile surface and the angle between the droplet and the surface was measured (static contact angle, SCA). Additionally, advancing (ACA), receding contact angles (RCA), and roll-off angle (ROA) were also measured by tilting method. The method can be used as primary test for evaluating the water repellence of the treated fabrics. Higher ACA and RCA, and lower CAH (contact angle hysteresis) and ROA indicate that the surface is more water repellent.

Work of adhesion-CA measurement between formulations and plane substrates: Work of adhesion is defined as the work which must be done to separate two adjacent phases 1 and 2 of a liquid-liquid or liquid-solid phase boundary from one another. For a liquid-solid phase boundary, it can be calculated from the contact angle using the Young-Dupré equation. CA was measured between different formulations and plane model substrates (with the same chemistry as textiles) in order to calculate the work of adhesion for a specific formulation and a textile. Higher work of adhesion for a formulation-textile interface can be expected as it is more difficult to apply the formulations to the textile. Combining the Work of adhesion data with the surface tension of the formulation would help to design the application system more efficiently.

Wetting/spreading measurement with sessile drop technique: During the project, a technique to evaluate the wetting/spreading rate of formulation on a specific textile has been developed. Droplets of a formulation were placed on a textile, and CA and droplet volume changes were measured as a function of time. The measurement outcome is an indication of how different formulations can wet and penetrate a specific textile. Combination of these test results and the surface tension of the formulations can be used for process development.

Liquid uptake measurement with texture analyser equipment: In this in-house developed technique, the textile is fixed in a sample holder and is immersed in selected chemical formulations using texture analyser equipment. The liquid uptake is then measured as a function of time and saturation level and time is characterized. This method is developed to simulate foulard application technique (part 4b) and to find out the best formulation for a specific textile, in terms of maximum wetting and minimum application time in order to reach the saturation level.

5.2.3 Plasma polymerization trials

Since no alternative chemistry has yet succeeded in matching workwear requirements, plasma polymerization with perfluorohexane (PFH) was evaluated as an alternative to wet chemistries. The aim was to investigate if plasma deposition of fluorinated chemicals could provide oleophobicity and high durability with very low amounts of fluorinated chemicals, minimizing chemical use and emission in production.

Four workwear-relevant textile samples with different material mixes and construction were coated and tested for oil repellence. The plasma polymerization trials took place in one of RISE in-house constructed reactors, see Figure 5. The vapor of the precursor, PFH, is introduced into the plasma chamber. Under the influence of an externally applied electromagnetic field the PFH vapor is then excited to a plasma, fragmented and deposited on the sample substrate as an ultra-thin coating. Discharge frequency was always 13.56 MHz. Two different electrode couples, upper and lower, were used during the trials. Electrode configuration is an important parameter as it affects the distribution and homogeneity of the plasma in the reactor.

Figure 5: Two of RISE small plasma reactors, upper electrode

The plasma trials were performed in three rounds with six different plasma conditions in each, varying discharge power (20-300 W), deposition time (5-20 minutes), pressure (50-140 mtorr) and electrode couple configuration. Oil repellence tests were performed on the plasma-coated textile samples at RISE IVF in Mölndal after each round, using standard method *Oil repellence – Hydrocarbon resistance test, ISO14419:2010*.
Oil repellence requirements for workwear were established in dialogue with Fristads, in relation to the Personal Protection Equipment (PPE) directive and its application in high-visibility workwear, where oil/dirt repellence is demanded. There, a level 3 of oil repellence is the required level after 10 washes, indicating that initial oil repellence has to be at least 4 or 5 to compensate for the ageing/wash process.

With the plasma treatment, a grade 3 oleophobicity was the maximum attained for all samples. Since oil repellence in no sample exceeded the required level for washed fabrics, the conclusion was made that this setup for plasma polymerization would not reach an accepted performance level after washes, and the plasma trials were ended.

5.2.4 Industry Partner-led developments

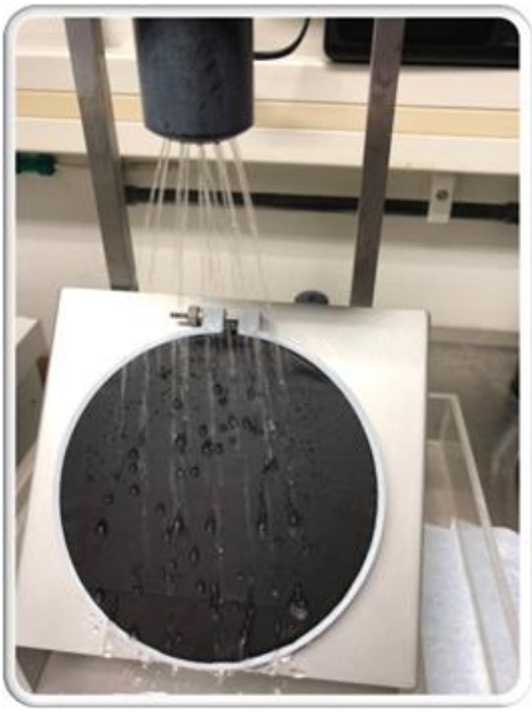
A few industry partners in the textile case have made significant investigations and development efforts regarding PFAS-free alternatives during the project. Two examples below are Helly Hansen and Mammut.

Helly Hansen

During autumn 2020, Helly Hansen will launch a novel fabric in the skiing and mountain categories, substituting PFAS and fluoropolymers in both water repellence treatment and membrane. The *Lifa Infinity® PRO™* is a 3-layer construction made possible by pairing a solvent free polypropylene membrane with *Lifa® dry* 100% polypropylene fibres in the outer fabric, offering inherent water repellence properties by material choice and construction. No added DWR chemicals and dope dye fibres minimizes overall chemical use.

The product has the expected attributes in its category; water resistance, breathability, and wash durability. To achieve water repellence without DWR finishing, Helly Hansen looked at two main factors: surface tension and surface structure. The Lifa ® dry 100% polypropylene fibre offers low inherent surface tension (28 – 31, similar to hydrocarbon DWR finishes) and very low water absorption (0.005%). In traditional DWR-treated fabrics, the surface structure effect is often compensated by adding effective DWR chemistry, but nevertheless often overlooked as a massive contributor to the overall performance. To further enhance water repellence in a DWR-free fabric, Helly Hansen tested several yarn counts and yarn densities in order to find a structural combination that maximize the effect.

The fabric was developed as an internal development project, while sharing some findings with the POPFREE research partners. As part of the POPFREE project, RISE performed detailed testing of one prototype fabric. In water repellence lab tests (Spray test ISO 4920:2012, Bundesman test SS EN 29865: 1993), the samples achieved very satisfactory results, on a similar level as good quality PFAS C6 or hydrocarbon based DWRs.



Mammut

Mammut has during the project undertaken a big testing effort, including over 100 of DWR-treated fabrics available on the market, to define relevant testing methods/criteria and review actual performance of their materials and treatments. Their goal was to find the best PFAS-free solutions available. The process has been internal and information on methods and findings has been shared and discussed with the POPFREE research partners.

Fabrics in the test were softshells, hardshells, woven fabrics, downproof and pack/bag fabrics. For the tested fabrics, both PFAS C6 and several types of PFAS-free treatments were tested. Main testing method was the Bundesmann test, offering more data on absorption and penetration of water than the mostly-used Spray test. The test method also creates a more refined scale for water repellence, as the testing conditions (time, droplet impact, mechanical wear) are harder than in the Spray test.

The test project revealed several interesting findings:

- Mammut has found that water absorption levels in the Bundesmann test offers a good indication of how the functional properties of a water repellent fabrics changes with wear, since water trapped in the fabric severely affects water vapour permeability and conductive properties (breathability and thermoregulation). Target values for absorption after 5 washes have been set as indicative performance crieteria.
- The difference between a PFAS C6 formulation and a well-adapted PFAS-free treatment was very small in terms of water absorption for new fabrics. After 5 washes many of the PFAS-free treatments had higher water absorption than 40%.
- The difference between high-performing and low-performing finishes within a specific type (PFAS C6 or PFAS-free) was bigger than between the best performing of two types – meaning that adaptation to fabric and precision in application process are crucial to achieve optimal results. This seems to be even more important to PFAS-free treatments.
- Construction/composition: There was not one “best” specific textile construction from all water management perspectives. Woven materials are easier to make dense than knitted, offering a structure less prone to trap water inside. On the other hand, with a densely woven fabric it is generally harder to achieve full chemical penetration with the DWR treatment and they are also less water vapour permeable, affecting the final fabric performance of a laminated fabric.
- Generally, natural fibres are harder to treat for long-lasting water repellence, likely because of their inherent highly hydrophilic properties.
- Chemistry: There is not one specific chemical that fits all uses – it is an interaction of functional chemicals, processing agents, the chemistry that comes with the fabrics and impurities from production processes. The DWR chemistry also affects other properties such as bonding, colour fastness, handfeel and tensile strength which are important for the overall processability and usability of the fabric.
- Application process: As most laminated fabrics are DWR finished before lamination, the DWR effect on bonding strength is an important factor. This is especially evident with PFAS-free DWR treatments, as they tend to interact more with bonding glues.
- Contamination and oil repellence: Questions were raised regarding PFAS-free fabrics which were well-performing in tests, and later had customer claims for bad performance.

One question was if oil repellence had a major impact because of production and use contamination of membranes. This is still an unresolved question.

5.3 Case cosmetics

In the first part of the project, a scanning of cosmetics from H&M product portfolio as well as from other suppliers was performed looking for PFAS listed in the cosmetic ingredients database CosIng which contains 102 PFAS molecules. Overall, PFAS were found in foundations and face creams, mascara, powders and lip pencils.
Focus was then placed on finding alternatives to PFAS in pressed powders and lip pencils as these were the products of highest interest to our partners.
The most common PFAS used in pressed powders is PTFE; as all powders do not contain PTFE in the same product palette, the use of PTFE could be related to specific coloured pigments.
In lip pencils, perfluorononyldimethicone is used instead. The hypothesis here is that this PFAS contributes to low friction. Here frictions measurements were attempted with a product containing PFAS and an alternative free from PFAS, but no significant difference could be measured.

To identify potential alternatives, the ingredient list of pressed powders as well as lip pencils that do not contain PFAS was studied. In many cases the products had been completely reformulated and it was not possible to identify a clear substitute to the original PFAS.
Concerning pressed powders, other alternatives seem to be synthetic waxes such as sodium myristate or magnesium stearate. The alternatives usually need to be used in higher amount as compared to PFAS (a few percent *vs* less than 1 percent of the total formulation). As several products free from PFAS are already on the market, it was decided not to spend more effort in trying to understand the function of PFAS and identify new alternatives to PTFE in powders.
In lip pencils, fats and silicones are the most common alternatives. The claims associated with perfluorononyldimethicone by the suppliers of base formulations are easy to level off, soft, not gunky. Products free from PFAS also had the claim: long lasting in humid conditions. Here again, as PFAS-free products were already on the market with equal or better claims, it was decided not to put more efforts on the development of alternatives.

5.4 Case film-forming products

Replacing fluorinated compounds in film-forming products is a great challenge in itself, due to the very special chemistry of fluorine; the fluorine group of the surfactants used in this type of products provide the low surface tension necessary to film-forming and imparts oleophobicity to the final product.
Some requirements of the film-forming formulations identified with our partners are:

- The levelling agent need to be soluble in the three formulations.
- The formulations should be stable when stored.
- A smooth coating without holes should be formed.

- The usages of the F-free formulations should be the same as usages of the PFAS-containing formulations, i.e. the consumer should not see any differences.
- Coatings should be resistant to short time water exposure.

5.4.1 Development of screening methods

In order to quickly evaluate different surfactants, a screening method was developed at the start of the project. In this method the formulation is evenly spread inside a plastic petri dish and allowed to dry. The amount of formulation is adapted to the area of the petri dish surface. Very clear effects with and without levelling agent (surfactant) can be seen with this method. The advantage of this method is that the plastic surface is well defined and a new fresh surface can be used for each tests. However, this method was later revealed not to give a good correlation with the tests performed in larger scale at Chemex. A bad result from the screening test always gave bad result on the larger surfaces used by Chemex. However, a good result from the screening test did not necessarily give a good result on the larger surface.
A second screening method was later developed for the reformulation of products 2 and 3. This method resembles the method used by the industrial partner and involves larger testing areas and another way of application of the coating, similar to the one used by Chemex.

5.4.2 Alternative surfactants

A wide range of different types of surfactants were identified and ordered to replace PFAS in formulation 1. Both silicone based and non-silicone based candidates were considered. Non-silicone-based surfactants were preferred since the use of silicone could be regulated in the future by the EU. The surface activity of the surfactants was measured using the Wilhelmy plate technique. The most surface-active compounds when it comes to surface tension lowering effect at as low concentrations as possible were judged to be most suitable. Additional surfactants were considered for formulations 2 and 3. In some cases these were mixed in the formulations without first measuring surface tension.

The most promising surfactants were mixed into formulation 1 and evaluated using the petri dish screening method. Some tests were also performed on tile surfaces and plastic surfaces. Different concentrations of surfactant in the formulation were evaluated and the most suitable concentrations determined. The stability of the formulations as a function of time was also evaluated. A selection of surfactants and recipes were sent to Chemex for further evaluation.
Reformulation of Formulation 1 with non-fluorinated levelling agents has been successful and initial trials together with selected customers have been started. Moreover, one environmentally friendly surfactant gave a very smooth coating but the appearance of the film was not as shiny as desired. However, this surfactant could be used to create surface coatings where surface shine is not as important.

The work then continued with the reformulation of two additional products. The second screening method was used in these cases. Stability of the coating towards exposure to water and oil was also evaluated. 3 suitable surfactants were identified, and these were evaluated by the industrial partner on larger sample areas. Formulations 2 and 3 still need further reformulation and testing.

5.4.3 Surfactant-free formulation

A second strategy was to have a surfactant free formulation and capitalize on solvents to obtain a low surface tension. The concept is to select a solvent that is very close to saturation concentration in the formulation. As water evaporates the concentration of solvent will exceed the saturation concentration and the solvent will move to the surface, which will give a surface tension of the formulation close to the value of the solvent itself, which is often very low. Two suitable solvents were mixed into formulation 1 at different concentrations. However, the solvents had a very negative impact on the appearance of the dried surface coating, and it was concluded when evaluating formulation 1 that the surfactant free strategy did not work. This strategy was not evaluated for formulations 2 and 3.

5.5 Case ski wax

5.5.1 Test method development

One aim of the project was to find proper screening methods for new developed ski waxes and new chemistries. Since PFAS in ski wax is associated with high hydrophobicity and low friction, focus in the project was to evaluate the feasibility of contact angle measurements and friction tests as a way of screening and benchmarking new prototypes.

<u>Contact angle measurements</u>
As in the textile case, contact angle measurements were checked for feasibility of relevant test method to screen ski waxes and new prototypes in terms of their water repellence and hydrophobic properties. Static, advancing and receding contact angles were measured as well as the associated contact angles when the base of the instrument is tilting to get the roll-off or tilting angle (when the drop starts to move and when it disappears from the image).
Contact angle measurements were first done directly on the block of ski wax, but the unevenness made it impossible to image in the instrument. Thus, ski wax was instead melted on model substrates consisting of a metal plate. One fluorine-free (FF), one low fluorine (LF) and one high-fluorine (HF) ski wax from both Swix and RedCreek were analysed. The results showed higher contact angle on the fluorinated ski waxes and greater differences between the ski waxes in the advancing contact angle. The results were promising, and the work continued with measurements on prepared ski base surfaces with less ski wax on the surface (thinner layer of ski wax).

Ski base laboratory pieces made from ultra-high molecular weight polyethylene (UHMWPE) were provided by RedCreek. The pieces were prepared by a professional wax technician in the same way as skis were prepared for glide performance testing on snow. A standard waxing protocol was decided in the project consisting of the steps; cleaning, melt CH7 wax with waxing iron (this is to zero the skis), scrape the zero wax and brush with correct brush until no longer visible (5-10 times with steel brush, then nylon brush), melt wax for testing with waxing iron

(140 - 160°C depending on wax type), put aside for 15-20 minutes to cool down, scrape the glide wax and brush until no longer visible (5-10 times with steel brush, then nylon brush), scrape off any wax on the sides of the skis and wipe off wax dust from the skis with Fiberlene cloth.

The temperature range of focus in the project has been from minus four to plus four degrees Celsius, and therefore the benchmark products suited for that temperature range have been selected, which is indicated by the number 8 in the ski wax names below (standard names used by the wax industry). The ski waxes tested was CH8 (fluor free paraffin), CH8 liquid (hydrocarbon-based fluor free spray), LF8 (low fluor content), HF8 (high fluor), FC8x (fluoropowder). Also, a reference without any ski wax was included. The various contact angle measurements seem to especially separate the reference without any ski wax from the ones with ski wax (Figure 6). Highest contact angles were obtained for the HF8 which had been melted onto the ski base but was not scraped, thus having more ski wax left. The HF8 and FC8x show slightly higher contact angle than CH8 and LF8 in both the static, advancing and receding contact angle. In the tilting experiments the reference without ski wax showed highest tilting angle (both when drop starts to move and when drop disappears) meaning that the water drop sticks more easily to that surface. The lowest measured tilting angle was obtained for FC8x (fluorine powder) indicating that the water rolls off more easily from that surface.

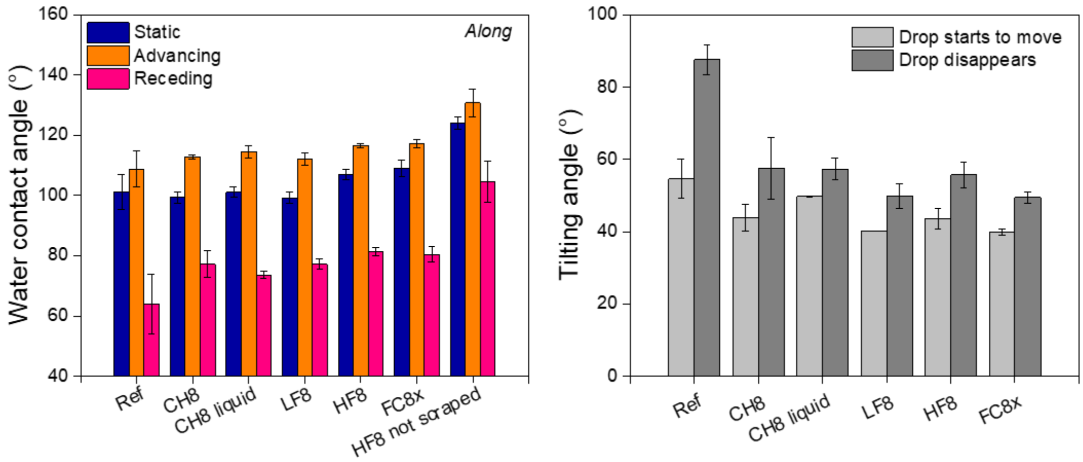


Figure 6. Static, advancing and receding water contact angle obtained with 5 µl drops (left) and roll-off or tilting angles of the base obtained with 25 µl drops when the drop starts to move and when the drop disappears.

<u>Laboratory friction tests</u>

An IMASS SP-2000 friction meter was evaluated in terms of feasibility to screen ski waxes with this laboratory friction device. Tests were done on the ski base pieces prepared with benchmark ski waxes described above. The hypothesis was that higher amount of fluorine should provide lower friction. The samples were measured against dry glass substrate, wetted glass substrate and frozen glass substrate. The measurements did not give consistent results and we decided not to continue with that technique but rather to focus more on contact angle measurements for screening of new prototypes together with the measuring snow friction with the developed friction sledge.

Development of friction sledge

A friction measuring sledge was developed as part of a MSc project, based on demands formulated at the beginning of the POPFREE project. Load cell and amplifiers were designed, developed and tested on the sledge. Load cell calibration was carried out using the Instron machine in the laboratory of the SportsTech Research Center (STRC). Special data acquisition software program was developed based on the DAQ module and LabVIEW software by National Instruments. Overall system was tested on snow and calibrated using the roller skis in the wind tunnel of STRC. Corresponding data are recorded as a friction force dependence over time.

The "Sledge" comprises a metal frame with cross-country ski fixtures underneath and a weight stack and computer holder on top (Figure 7). Construction is designed for easy ski fixation and a large number of adjustments including changing separation of the skis (fine adjustment for the ski track); of the loading weight (tests accommodating for different weight of the skiers); of the centre of gravity offset (adjustment for different postures of the skier). The Sledge is designed for three measurement modes:
(a) *Free glide time measurements*, when the sledge is released from the top of the ramp, passes a number of time gates, and is caught at the bottom of the slope (mimicking a free gliding of the skier)
(b) *Pulling by a snowmobile* (braking force comprising ploughing resistance and dynamic friction force is measured by a load cell between the sledge and pulling rope or the snowmobile and pulling rope). This method was tested but the snowmobile used had difficulties of not providing a robust movement of the sledge.
(c) *Pulling by a winch/ dragging a rope* (braking force comprising ploughing resistance and dynamic friction force is measured by a load cell between the sledge and pulling rope)

The advantages of the measurement method are realistic test conditions (real skis, realistic weight), absence of the air drag (minimizing air drag differences as influential factor on glide times), possibility of studying influence of weight distribution; measurement of static and dynamic friction; possible measurements at different environmental conditions (including indoor and outdoor tests).

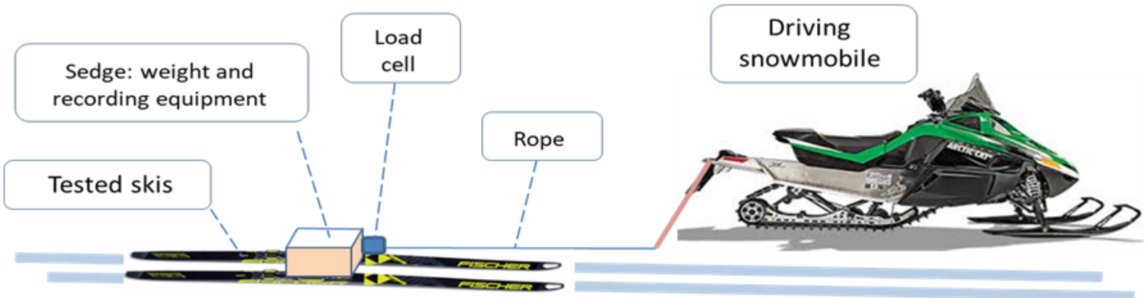


Figure 7. Developed sledge to measure friction between prepared skis and snow. Pulling was tested using a snowmobile and a winch. A load cell between the sledge and the pulling rope allowed forces to be measured.

Wide search on the state of the art on measuring ski and snowboard gliding, on snow properties and ambient conditions impact on the gliding, and on the measurement methods used by others for measuring ski and snowboard gliding and numerous snow properties was carried out during the initial stages of the ski wax case. Majority of the findings are available for free dissemination within two completed thesis works by MSc students at Mid Sweden University entitled "Measuring snow properties relevant to Snowsports & outdoor. Development of measuring method to analyse snow properties" and "Measuring ski gliding properties. Development of a measurement system for ski gliding friction".

5.5.2 Glide performance testing

Tests were performed in the Mid Sweden 365 ski tunnel in Gällö, Sweden, in two test series, see Figure 8. Special test skis were obtained from a major ski supplier through a POPFREE partner and prepared by a professional ski technician prior to tests, according to decided standard preparation and test protocol. Test conditions were monitored throughout the test with environmental measurements of temperature and humidity in both air and snow as main parameters.

Focus was on reference preparations with known waxes with and without perfluorinated substances, for verification of test methods and the possibility for comparisons to contact angle (CA) lab trials. Two different glide test methods were conducted during this test series:

1. *Defacto-standard glide testing with timing gates* and a seasoned elite skier. This is the currently preferred test method for wax manufacturers and ski teams alike. With a systematic test protocol and repeated test runs, it is a relatively reliable test methods even if it has big elements of human influence by the skier's abilities to make consistent ski runs with weight distribution and air drag as major factors for difference.
2. *Sledge pulling on even ground* with force measurements. This was the first live testing of the sledge system on snow in true ski track conditions. The intended pulling device, an electric quad bike, proved unreliable in the prevailing conditions and pulling had to be made by hand force. Nevertheless, results correlated well with both contact angle and glide testing.

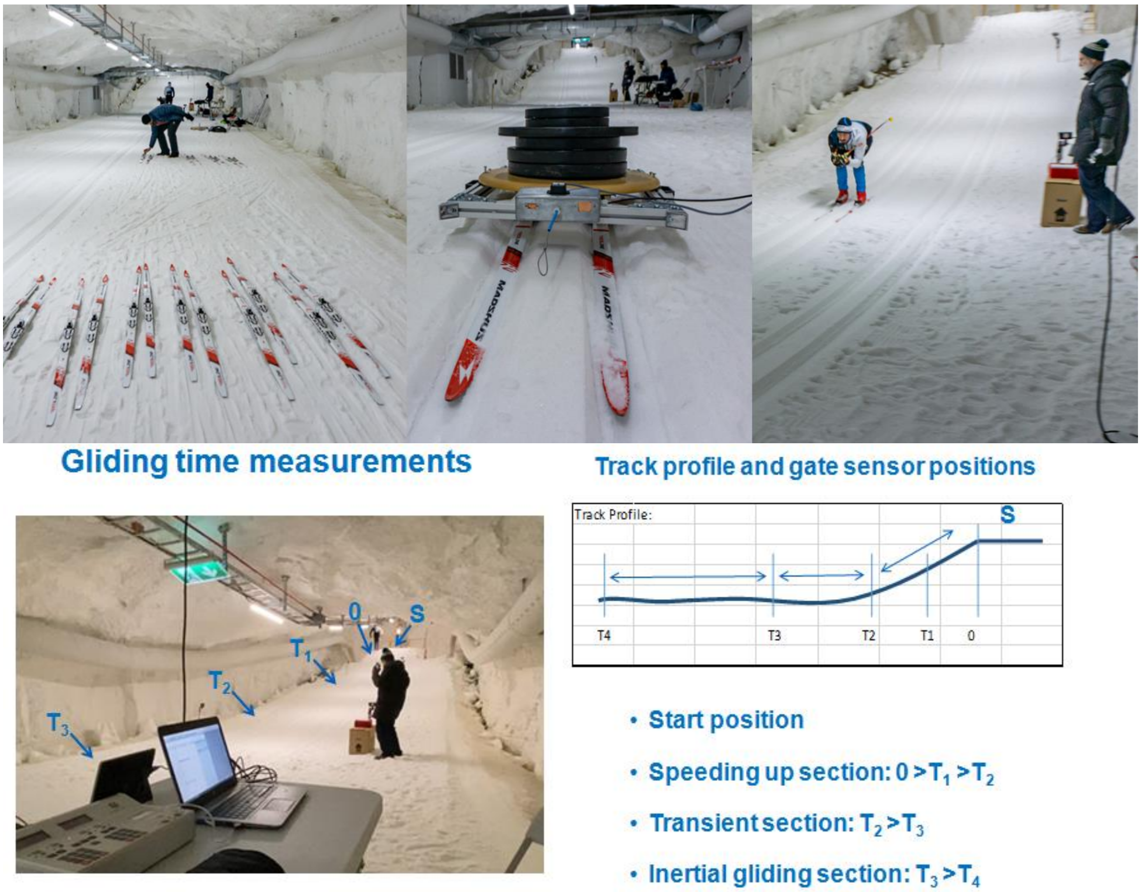


Figure 8. Photos from first test series in Gällö Ski Tunnel and the track profile for the glide performance tests.

The results showed greater difference between no ski wax and ski wax compared to differences between fluor-free and ski wax containing fluor, see Figure 9.

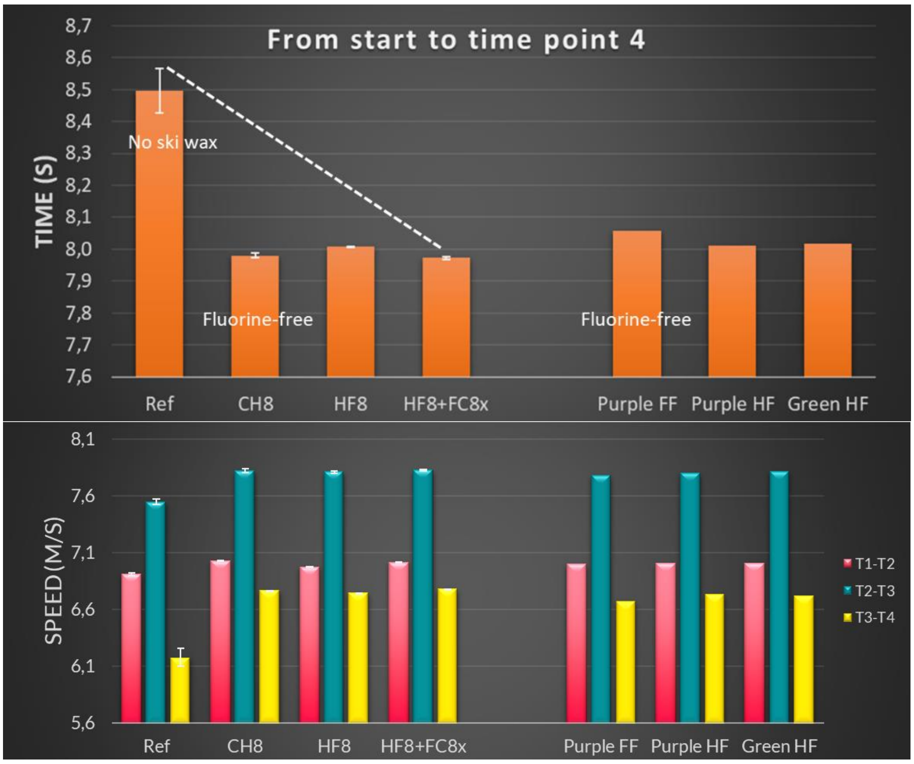


Figure 9. Total glide time and calculated speeds between the different gates in the glide performance testing in the Mid Sweden 365 ski tunnel in Gällö.

<u>Correlations between screening lab tests, dynamic friction and glide performance</u>

Since one aim in the ski wax case was to find screening methods for new chemistries and ski wax prototypes, it is interesting to see what the correlations are between the different measurements. The first test series contain four samples with test results from all three methods. The results from the four measured ski preparations show several significant correlations between contact angle measurements, dynamic friction measured with a sledge and glide time and speed (Figure 10). In all measurements the reference without any ski wax stick out with lower contact angles, more angle needed upon tilting for the water drop to roll off, higher dynamic friction and longer gliding time with lower gliding speed. Less difference is obtained between ski wax with and without fluorine. A second series of prepared skis and laboratory ski pieces will further investigate the correlation between dynamic friction and contact angles to evaluate the possibility of using those measurements as a screening of new ski wax prototypes.

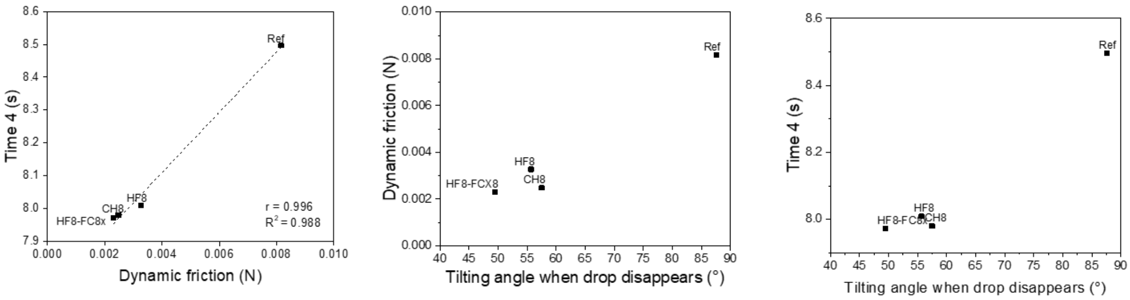


Figure 10. Selection of correlation plots between glide time, dynamic friction and contact angle measurements (here shown as the tilting angle of the base when the water drop disappears).There is a greater difference between no ski wax and ski wax than between ski wax with and without fluorine in all tests.

5.5.3 New potential chemistries

Screening of new ski wax formulations

A diploma work together with Paragon Nordic was done targeting new possible additives and alternative waxes in ski wax formulations. In total, 25 different ski wax formulations were prepared with alternative additive materials between 0.5 – 10 w/w% in the formulation as well as different waxes. At this stage, Paragon cannot reveal what the tested additives are. One reference with 5% of C6 fluorocarbon content (Ref2) and one without perfluorinated compounds (Ref4) were included for comparison. The first screening was done by visually checking if a water droplet stayed on the surfaces of spread formulation on a metal piece. The ones that passed that test were evaluated with the contact angle instrument. Nine formulations provided higher advancing contact angle than 110 ° and were selected for further tilting tests. Two samples were selected because of their low contact angle hysteresis; two samples containing the hydrophobic Betulin from Birch bark were selected because of the interesting biobased origin. The measured tilting angles of the base served as ground for deciding which formulations to test on snow (lower tilting angles were considered better). A new developed formulation with no measured contact angle was also selected for tests on snow because of expressed interest from Paragon Nordic. Tests on snow have been delayed due to the Corona virus but will be done in Spring 2020.

Contact angle measurements were tested both at a room temperature of 23 °C and at a reduced temperature of 3 °C. The measured contact angles were similar in both temperatures and measurements in room temperature is therefore suggested for future screening of ski wax formulations because they are more rapid.

5.5.4 Development of new products by industry partners

<u>RedCreek</u>

During the duration of the project, RedCreek has developed 4 new fluorine-free ski waxes, 2 paraffins and 2 liquid products, three of them are shown in Figure 11 .

<u>Brav/Swix</u>

Due to the FIS fluoro ban in season 20/21, Brav has decided to be totally fluoro free already from 2020 (the previous aim before the FIS ban was 2022). Swix has developed a range of fluoro-free products during the duration of the POPFREE project. The Marathon line is committed to wide conditions high performance waxes consisting of 100% biodegradable raw materials.

For both ski wax producers, the ingredients are considered a trade secret, but work targeting risk analysis and LCA have been done to verify that the ingredients and new products are safer than the products they are replacing.

Figure 11. New ski waxes developed by the project partners during the duration of the POPFREE project.

5.6 Case firefighting foam

The project has focused on two different firefighting foam formulations: one foam is more stable and particularly suited for sprinkler systems while the other foam is a multi-purpose foam that can be used to extinguish fires on hydrocarbon liquids and polar solvents.

The criteria for the foams were determined by Dafo Fomtec in the beginning of the project:

- The formulation should work well on hydrocarbon fuels (heptane) and polar fuels (IPA and acetone), i.e. good fuel compatibility.
- Foam should have as high expansion and as long drainage times as possible.
- The foam bubbles should be as stable as possible.
- As little fuel as possible should be emulsified into the foam.
- The foam should spread efficiently over the surface of the burning fuel.
- Foam concentrate should have a low viscosity to enable easy handling.
- Foam stability in saltwater should be high.
- High class rating according to EN 1568-3.

- High fire performance for all applications (fire brigades, chemical industry, aviation, marine, defence, etc)
- Improved environmental friendliness.

The EN 1568-3 is a well-defined European standard that is used to classify the fire extinguishing efficiency of the firefighting foams. The test methodology is in many ways adapted for characterising the properties of fluorine containing foams. For example, heptane is used as a model for all hydrocarbon fuels but creates a limitation in the evaluation of fluorine free foams (FFF), as these seem to be more sensitive to the type of fuel. Therefore, modification of the test method is under discussion to better characterise the capabilities and usefulness of fluorine free foams. This is one of the questions that will be addressed in the recently initiated Test bed PFAS led by RISE and the Swedish Defence sector.

Four different strategies were suggested at the start of the project to develop FFF foams:

1. Addition of **silica particles** to the formulation. The particles should decrease drainage rate and increase foam and bubble stability. The particles could also increase the foam rigidity which would lead to lower fuel pick-up.
2. Use **adaptable polymer systems** that have as high viscosity as possible as a premix but as low viscosity as possible as a concentrate. This alternative uses the fact that the concentrate has a higher concentration of co-solvents, salts, and other ingredients. The aim is to maximise the viscosity of the premix but at the same time keep the viscosity of the concentrate as low as possible. A high viscosity of the premix is usually connected to lower drainage rate and higher foam stability. The concentrate needs to have low viscosity for easy handling/pumping.
3. Use a **fuel-thickening polymer** that increases its viscosity when coming into contact with the fuel. This effect is most important for the extinguishing of polar fuels such as acetone.
4. Use **non-ionic surfactants** or modified ionic surfactants to increase the salt-water stability. Several environmentally friendly non-ionic sugar-based surfactants exists that could be used in fire-fighting foams. Synergistic effects between different surfactants were also evaluated.

5.6.1 Particles

Initial surface tension measurements of fire-fighting foam formulations with and without particles showed that the addition of particles changes the surface tension of the fire foam formulation. This means that the ingredients of the formulations adsorb to the particles leading to for example higher surface tension than without particles. This information was useful to know and showed that the particles are not present in the formulation as inert entities.

The influence of several particles on the foam characteristics of fire-fighting foams were evaluated using the instrument DFA-100, which is specially designed to study foams (Figure 12). The foam generation procedure was first optimised using filters with different pore sizes and different air flow rates. The goal was to generate a foam as similar as possible to the foam generated in field tests. The particles studied had different sizes and different surface chemistry.

A relation between size and hydrophilicity and foam characteristic was found. Particularly, a specific type of particle increased foamability as well as bubble stability.

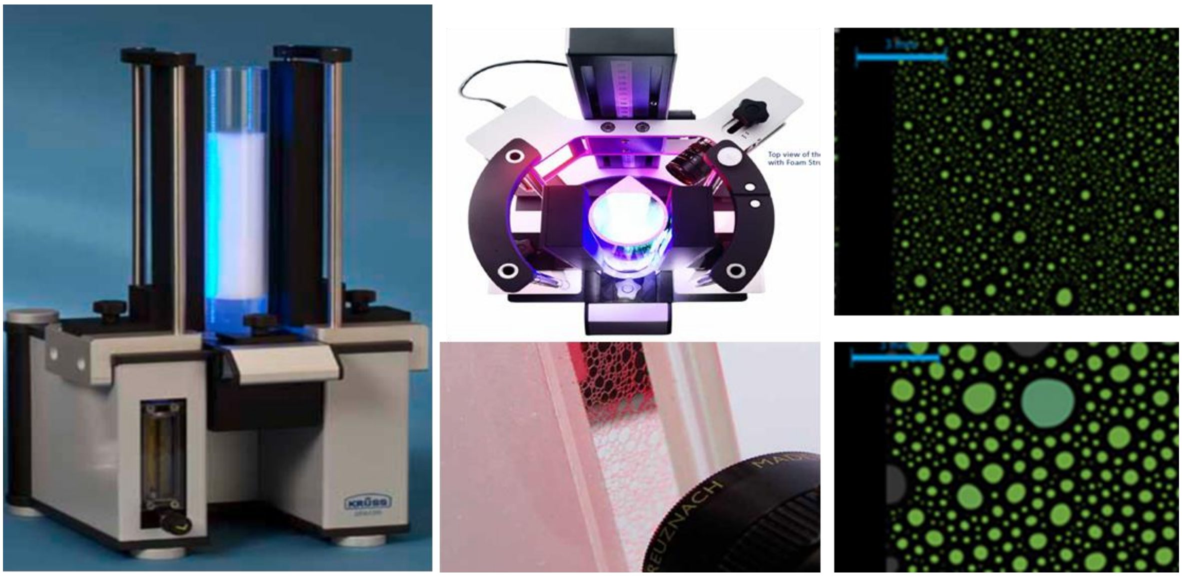


Figure 12. The DFA-100 (left and middle). Foams were generated in the instrument using sparging. Foams were also created with the nozzle as in EN 1568-3, and quickly poured into the measuring cylinder. The two pictures to the right show an increase in bubble size from the start of the measurement (top) to the end (bottom).

Based on these results, different types of silica particles were selected to be further evaluated. The functional evaluation of the alternative solutions including particles started with lab evaluations, using non-fire-based in-house small-scale standardized test methods developed at RISE. Foams were generated with lab methods (shaking, sparging) as well as with a nozzle as in the standard EN 1568-3 provided by Dafo Fomtec AB. The tests investigated drainage rate, expansion, bubble stability, resistance to "fuel pickup", resistance to fuel induced breakdown, and foam viscosity.

The most promising formulations from the lab scale trials were evaluated with the SP Method 2580 in June 11, 2019, which is a down-scale of the larger test according to the European standard EN 1568-3 (Figure 13). Additions of two different types of particles were evaluated in two different fire-fighting foam formulations. 10 different trials were made in total. It was found that additions of one type of particles improved the extinguishing properties of the foam.

The most promising particle type identified with the SP Method 2580 was evaluated in the two different fire-fighting foams using the large-scale EN 1568-3 method. An improvement was made with the addition of particles. However, the effect was not very significant. More experiments are needed to confirm the beneficial use of addition of these particles to the formulation. It can be concluded that the amount of particles that can be added in foam concentrates may be too low to have a major impact on fire performance of a foam generated from the diluted concentrate. On the other hand, in ready-to-use solutions the volume can be high and here it seems to have effect on performance. Formulations based on such concept are under evaluation in larger scale.

Figure 13. SP Method 2580 (left) is a down-scale of the larger test according to the European standard EN 1568-3 (right).

5.6.2 Adaptable polymer systems

An anionic polymer was evaluated and shown to give a much lower viscosity at high salt concentration than at very low salt concentration. The reason for this is that when the polymer is in the concentrate its charges are screened and the polymer has a less elongated conformation. When diluted in water the screening of its charges will be reduced and the polymer will expand, which increases the viscosity. Viscosities at salt concentrations more relevant for the application, e.g. closer to the concentration in tap water and sea water were also promising. The polymer was sent to Dafo for further investigation. Unfortunately, it was difficult to prepare a stable formulation with this polymer in the reference system used.

5.6.3 Fuel-thickening polymer

Water solutions of oil-thickening polymer and water solutions of a reference polymer with good solubility in acetone were prepared. Acetone dyed with methylene blue was added on the surface of the solutions and the miscibility of the acetone layer and the water solution was studied. Unfortunately, no significant differences could be seen between the test polymers and the reference containing acetone-soluble polymer as the thickener.

5.6.4 Non-ionic surfactants to increase salt-water stability

Dafo Fomtec supplied RISE with fire-fighting foam formulation, formulation without surfactant package, surfactant package, and foam booster. RISE evaluated the foam properties of 34 different combinations of formulation and surfactants using a common screening method, i.e. studying the foam generated by turning 40 ml of foam solution 20 times during 30s inside a 100 ml measuring cylinder. Four different surfactant combinations were shown to have beneficial effect in the fire-fighting foam formulation.

5.6.5 Work done by partners

Dafo Fomtec has during the POPFREE project done a lot of R&D-work in order to develop commercial FFF-products with high fire performance. They performed extensive lab work as well as several large-scale fire testing. 60-70% of the in-kind contribution from Dafo Fomtec has been spent on producing and testing new fluorine-free formulations (FFF) and approximately 4 weeks have been dedicated to sprinkler testing. At the end of the POPFREE project new FFF products have been launched and more are in the pipeline. Still, the new developments do not reach the highest fire performance comparable to AFFF-type. More R&D-work is ongoing to close the gap.

6. Environmental and health performance

6.1 Evaluation model

Within POPFREE, novel PFAS-free treatments and formulations and related benchmark formulations are evaluated to assess and compare performance, related to properties such as e.g. water and oil/dirt repellence, fire suppressant or wetting/spreading capabilities, depending on specific applications. To avoid a regrettable substitution, where a new alternative introduces new risks to human health or the environment, a three-stage environmental/health evaluation is carried out. The starting point for all evaluations is a bill of materials including information on the concentration of components.

The three stages are – in order:

I. **A Chemical Risk Assessment**, carried out for all viable alternatives which pass relevant functional performance criteria for the category.

II. **A Screening Life Cycle Assessment** to identify biggest environmental impacts for selected alternatives of high interest – with high performance or otherwise likely to be quickly adapted.

III. **A full Life Cycle Assessment** for a few alternatives of special interest.

I. Chemical Risk Assessment

All viable alternatives and related benchmark formulations were analysed in a chemical risk assessment based on CAS numbers (where available) and publicly available information such as safety data sheets, CLP data and registration dossiers (ECHA) as well as safety data sheets that were made available by consortium members or retrieved from suppliers such as MERCK/Sigma Aldrich. The evaluation includes life cycle phases from formulation of a ready-to use blend, use phase and expected end of use. From a product life cycle perspective, the focus is on "gate to grave". Different scenarios were considered for end of life treatment to include user behaviour. The data were evaluated semi-quantitatively using a "traffic-light" visualisation where red stands for high risk that cannot be handled even with precautionary measures, yellow for low to medium risk that can and needs to be managed and green for no identified risk based on publicly available data. To perform this first stage, a list of substances that are used in the blending process was used as input.

II. **Screening LCA**
In the Screening LCA, data on production of substances was considered in more detail, including resource demand (materials and energy) for production, and emissions for upstream processes. The result is a cradle-to-gate LCA that highlights environmental impacts as hot spots, connected to substances and life cycle phases. The results can be used for developing new formulations with a low environmental impact. Results from the first stage are included. The Screening LCA was carried out for relevant formulations, and the selection was coordinated with the case partners and based on the results of the Chemical Risk Assessment. Additional data needed was supplier locations and available information on process technology used by suppliers.

III. **Full LCA**
The Full LCA was applied for a small subset of formulations of special interest in the project. The aim is to enable comparison of different formulations from a life cycle perspective. Therefore, data that were not included in the Screening LCA needed to be added to make sure that system boundaries and function are equal for the systems that are compared. The data needed for this stage was complementary to what is already included in stage 2.

6.2 General observations

6.2.1 General observations regarding method and approach

Some of the results and observations are not necessarily linked to a specific case but can be applied more in general. These will be described here first and referred to in the case descriptions where relevant.

The three stages approach to start with chemical risk assessment is in general a promising strategy to gather relevant data. Information for the first step is in many cases public, mostly due to obligations for suppliers to provide data that is included in the REACH legislation (Art. 5: No data, no market). While not all specialty chemicals are fully assessed at this time, data on risks related to bulk chemicals can be found via the information portals of the European chemicals agency (ECHA). Further information can be retrieved from suppliers of chemicals who need to provide safety data sheet according to a required format with the intent to share information along the supply chain.

For the LCA part, the situation is different. For ingredients, obligations to share information are defined in legislation. Suppliers are however not obliged to provide data on how a chemical or compound is produced, what raw materials and syntheses are applied. Furthermore, where syntheses are described in a more general way in literature or patents, information on by-products, emissions and wastes is usually omitted. Data on the life cycle of chemicals can therefore be used as complementary to chemical risk assessment and reveal hazards and impacts in upstream processes, such as emissions of auxiliaries and process chemicals or resource demand. The most complete application of an LCA is performed when different options to provide exactly the same function are compared. This is not always possible in the context of perfluorinated chemicals that provide unique performance and are therefore well established for a wide range of applications. In those cases, a screening LCA of the products is still possible to identify and map environmental impacts, it is however not meaningful to directly compare two options from an environmental point of view as this would imply to "compare apples and oranges".

6.2.2 General observation regarding results

Several of the application cases used waxes (paraffin waxes/hydrocarbon waxes) that are based on petroleum as a resource and produced via refinery step to separate and purify desired fractions of alkanes. The composition of inputs from different proveniences is varying, as is the refinery process that provides several fractions according to market demand. Based on this prerequisite, that type of component is considered a UVCB (petroleum based), which stands for Unknown or Variable composition, Complex reaction products or Biological materials. Since this implies a mixture of substances instead of a fully specified substance, characterisation of properties including hazards for health and environment is limited. The contribution of mixtures to the overall market is high, in particular regarding the tonnages. Data uncertainty is high; a recent publication by Wang et al. In Environmental Science & Technology 2020 54 (5), 2575-2584 DOI: 10.1021/acs.est.9b06379 indicates that roughly 20% of the chemicals on the market are considered as UVCB. Due to uncertainty and limitations for testing, a precautionary approach to assign medium risk was chosen in the project.

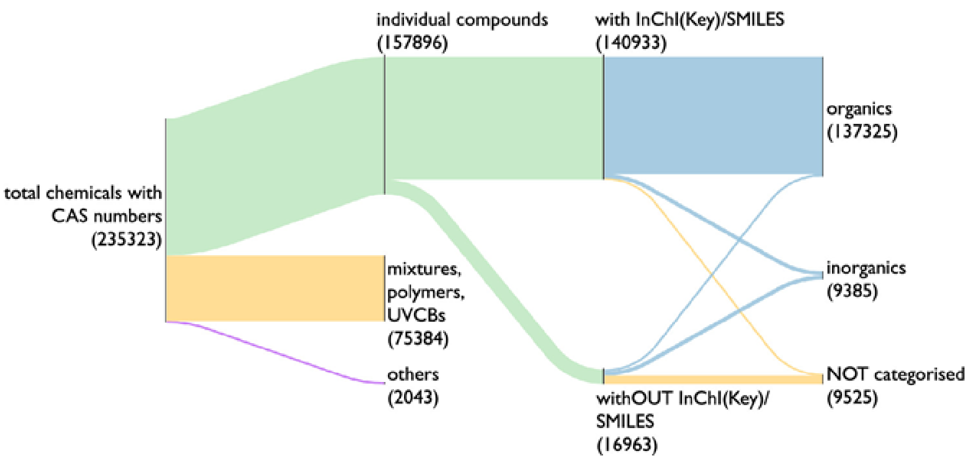


Figure 14. Illustration of the complexity of chemical databases with respect to CAS-numbers

Detailed assessment and inclusion of chemicals in databases is an ongoing process. After the legislation was implemented in 2006, chemicals were added gradually to the inventory of chemicals for which risk assessments have been performed, based on the availability of resources to perform the required procedure. When data are absent, this does not necessarily mean that a chemical is not related to risks. On the other hand, some application areas have been added to inventories early on, for example biocides, which are addressed in a separate directive implemented in 2012, and are comparably well documented regarding risks. Due to their intended use, toxic impacts on humans and freshwater organisms can be expected. Thus, biocides potentially are shown as medium to high risk chemicals, whereas specialty chemicals are not yet included in inventories.

This observation is also applicable for data in life cycle impact assessment methods, such as the recommended consensus method USETOX (2.1), which was selected within POPFREE. The number of chemicals included in the databases is in the range of 2,500, substantially less that the number of chemicals on the market. This lack of data can lead to gaps in the assessment.

The LCA method used in POPFREE is based on the recommendations of the EU joint research centre and includes a broad set of impact categories as suggested in the ILCD handbook[1]. Additionally, to a characterisation stage, a normalisation was calculated to identify which impacts show relatively high or low contribution based on the emissions in the region EU-25. The factors were chosen according to the recommendations published by JRC . Sala S., Crenna E., Secchi M., Pant, R., Global normalisation factors for the Environmental Footprint and Life Cycle Assessment, EUR (28984), Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-77213-9, doi:10.2760/88930, JRC109878 LCA calculations were performed using the LCA software SimaPro 9.0 with the database ecoinvent 3.5.

6.3 Results

Based on the method and consideration described here, some selected results from LCA are presented here. Risk assessments of all new formulations/products developed during the project have been conducted but are not presented here due to confidentiality issues. Some selected results from the LCA studies are presented here to illustrate the method.

6.3.1 Case paper

A formulation with biobased ingredients (dark red) and biocide (dark blue) was compared to a formulation based on synthetic raw materials (Figure 15). The biocide dominates all three categories related to toxicity impacts, which stand out in the normalisation stage. As a comparison, a formulation based on fossil/synthetic raw materials was modelled with the characterisation and normalisation results as illustrated below.

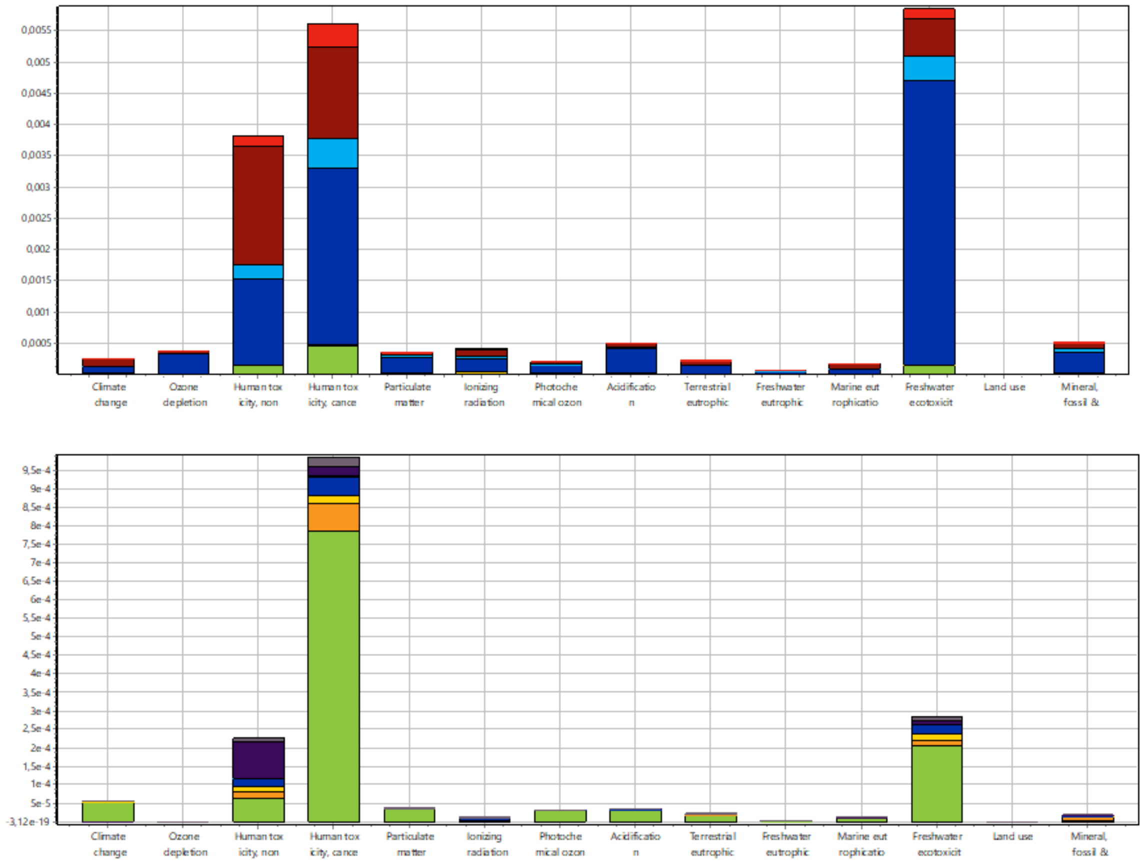


Figure 15. Results for a formulation with biobased ingredients and biocide (top) and a reference formulation based on fossil/synthetic raw materials after normalization (bottom).

The light green contributions are assigned to a synthetic co-polymer. The dark purple part of the bars is related to a vegetable oil, which contributes most to land use. The orange part of the bars is related to a mineral component in the formulation, which contributes to mineral resource depletion. None of those two impact categories show a high relative contribution, whereas the toxicity related impact categories are again relatively high.

6.3.2 Case textile and leather

Six formulations for DWR treatment of textiles were analysed, two of them including siloxanes and four containing alternative formulations, based on biobased alternatives. The results from one siloxane containing and one siloxane free formulation are presented in Figure 16.

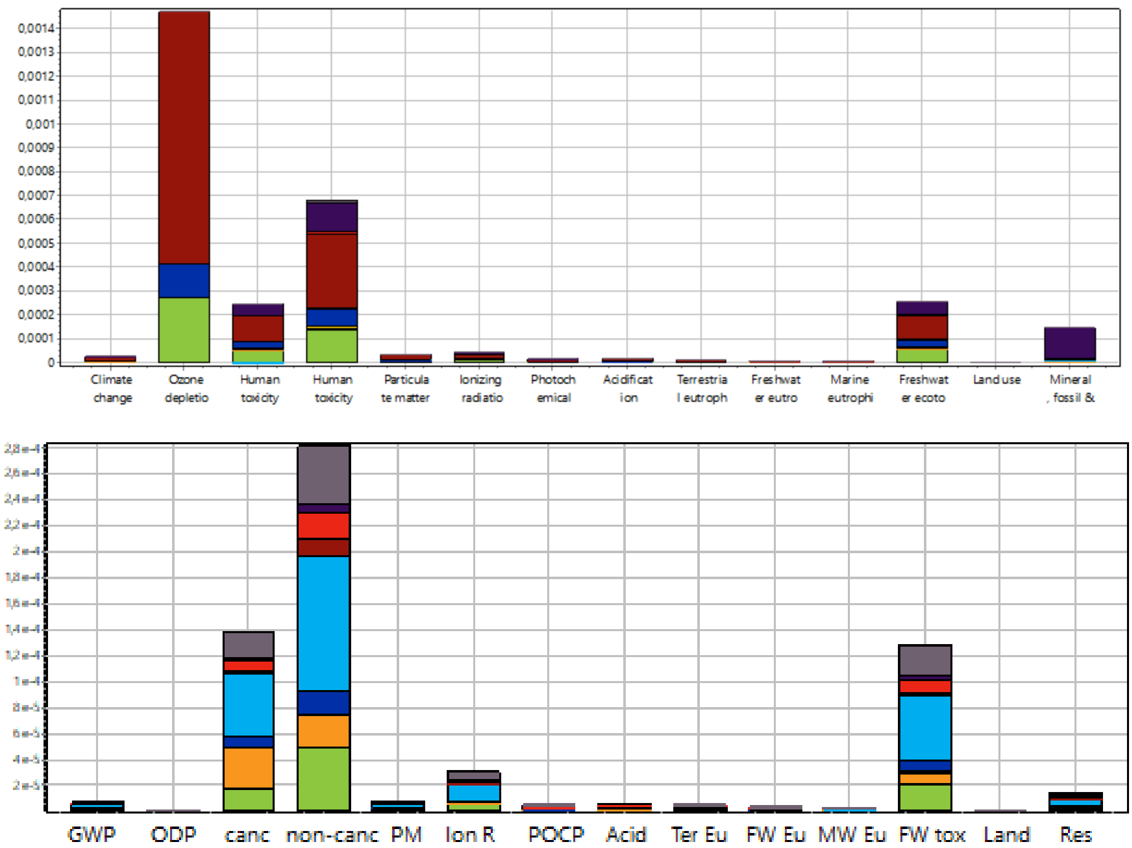


Figure 16. Results for a formulation with siloxanes and silanes (top) and a formulation without siloxanes and silanes after normalization.

The siloxane containing formulation showed a relatively high contribution to ozone depletion potential due to emission of chloroethane. The siloxane and silane free formulations show a substantially lower environmental impact and no contribution to ozone depletion potential.

As a summary, the formulations based on siloxanes show overall higher environmental impacts, mostly due to silicone components that are seen increasingly critical. Note that this assessment does not consider technical performance of the formulation. For a further investigation, it is recommended to follow-up on impurities in silicones (D4, D5, D6), which have a major impact on the overall risk assessment and also to follow up on production to verify the contribution to ozone depletion potential. Contacts with suppliers and further literature studies are recommended. Four formulations avoid siloxanes, but in one case include silanes, for which at least the upstream contribution is similar to siloxanes.
Further investigation is recommended here, otherwise this alternative has a slightly higher contribution to environmental impacts compared to others. The alternatives containing a heavy metal salt do all show a higher impact in several categories, including resource use but also toxicity impacts. As a general conclusion, the alternative which avoids both silanes and a heavy metal salt present in other options is the most preferable from an environmental/chemical risk

point of view based on a comparison by weight only. The difference between silane free alternatives is rather small; a full LCA based on an application that also considers amounts of product needed is required to verify whether this difference can also be maintained in a wider context.

7. External communication

7.1 General communication

During the project, an information letter was prepared and distributed to all partners to be use in their communication with consumers.

The project had a booth at Vasalopet's winter week in Mora in 2019 and 2020 to increase awareness about alternatives to fluorinated ski wax but also for other product segments such as textiles and food contact materials (Figure 17). In 2020, 58 000 persons had registered for a race during the Vasaloppet's winter week and thus a large audience consisting of skiers, waxers and representants from the skiing community as well as their friends and relative with no particular interest in skiing could be reached. The booth was prepared in collaboration with our partners and products such as impregnation sprays, clothing, muffin forms could be presented along with rilling tools and fluorine free ski waxes.

Figure 17. Photos showing parts of the POPFREE team in action and our key message 2020 "Valla fluorfritt".

In March 2020, the movie "Dark waters" was released in Sweden. This movie relates the story of a lawyer who revealed the environmental scandal caused in West Virginia by the uncontrolled release of PFOA in the environment during the manufacture of Teflon. POPFREE capitalized on this event to organize several communication activities:

- A preview of the movie followed by a panel discussion was organized in Stockholm on March 4th. The panel consisted of Maria Gardfjell (member of parliament from the environmental party), Birger Wallsten (expert on drinking water questions from Svenskt Vatten), Jenny Ivarsson (Expert on PFAS from the Swedish EPA, Kemi) and Tove Mallin (expert on PFAS from the Swedish center for substitution). The focus of the panel discussion was on environmental aspects and legislation.

- POPFREE was represented by Marie Syrén in a panel discussion organized after the preview of the movie on March 5th. The preview was organized by the Swedish Society for Nature Conservation with a focus on substitution challenges for an audience consisting of industrial representatives. The Swedish Center for Substitution and the Swedish environmental institute were also part of the panel.
- A viewing of the movie was organized in Östersund for the project consortium and other organizations with environmental interest on March 9th before the final project meeting. At this occasion, the POPFREE project was briefly presented to the audience.

7.2 Case specific communication

7.2.1 Case paper

The POPFREE partner Fidra conducted a survey on PFAS-use in UK food packaging, considering whether PFAS is currently used in the UK food sector, and to what extent. Using an innovative 'bead test' method to carry out preliminary screening of a large range (n = 92) of food packaging, they identified that 30% of the tested packaging was 'likely to contain PFAS'. A total of 20 samples selected from this preliminary screening were sent for further testing. Samples were collected from 9 major UK supermarkets, 6 popular takeaway chains and 4 independent takeaways (these included a café, a cafeteria, chip shop and pizza takeaway). From the independent takeaways, Fidra chose samples that were from suppliers and brands known to serve a wide range of outlets and commercial caterers. Samples included supermarket cookie bags, bakery bags and greaseproof paper, and takeaway bags, pizza boxes and moulded fibre clamshell boxes. Samples were tested for Total Organic Fluorine (TOrF), a widely accepted proxy for total PFAS. 8 of the 9 major UK supermarkets as well as all takeways tested had packaging containing significant amount of PFAS. PFAS was identified in 95% of the samples sent for TOrF testing, of which 90% are considered to be above the level expected from background contamination. The use of PFAS in UK food packaging is widespread, both across retailers and product types.
Moulded fibre boxes, which had not been the focus of the substitution work within the project, had the highest levels of PFAS. These levels are as of today not compatible with the acceptable limit for compostability set in Europe at 100 ppm by the European OK Compost certification centre.
In their report, *Forever chemicals in the food aisle: PFAS content of UK supermarket and takeaway food packaging*, Fidra suggested some recommendations such as minimizing the use of disposable packagings, lowering the compostability standards to match the accepted background level, establishing new group-based chemical legislation and recommending supermarkets and take-aways to act towards a phase out of PFAS in their products.

7.2.2 Case textile & leather

Fidra's work in the textile sector focused primarily on the use of PFAS in children's school uniforms in the UK, where they are used to produce 'stain resistant' finishes. A key argument for the use of stain resistant finishes is that by reducing the need for frequent washing and lengthening a garments lifespan, the environmental benefits outweigh the negatives associated with chemical pollution.

Fidra carried out a nationwide survey including over 600 parents or guardians of primary school age children to establish whether consumers adjusted their behaviour in response to stain resistant finishes, i.e. are the potential benefits from these finishes realised in a real-world context? Respondents were also asked to rate the importance of the environment, amongst other priorities, when making purchasing decisions and considered whether the marketing terms they sought out (e.g. stain resistant, Teflon) correlated with conscious priorities.

Fidra found that the respondents who valued stain resistant finishes washed school uniform items more frequently, and replaced them more often, than those who considered the finishes unimportant. Respondents who valued stain resistant finishes replaced trousers and skirts (the most likely garments to be labelled stain resistant) on average 7 weeks earlier than those who considered them unimportant.

Responses indicated that the environment was generally of low priority when making purchasing decisions. There was no correlation between whether consumers valued stain resistant finishes and to how they viewed the environment, i.e. placing the environment as a high priority in making purchasing decisions did not lead them to avoid stain resistance or opt for stain resistance. This suggests that consumers are not currently linking chemical coatings with environmental concern.

Fidra's **four key recommendations following the report are:**

1. Include behaviour in full life-cycle analyses to fully assess the environmental impact of stain resistant finishes.
2. Give consumers the opportunity to find out about stain resistant finishes and their environmental impacts to enable people to make purchasing decisions that match their priorities.
3. Develop ways for consumers to explore and engage with the issue, e.g. highlight links between environmentally friendly options and other benefits, such as reduced cost and convenience.
4. Encourage consumers to assess the need for washing and replacement on an individual item by item basis rather than falling into habitual behaviour patterns. Where finishes are applied this will encourage the potential environmental trade-offs to be realised.

Retailer engagement

Fidra engaged with UK retailers both directly and through communications sent to members through the British Retail Consortium. In doing so, they highlighted the issue of PFAS, its presence in stain resistant treatments and the behavioural results from our survey, encouraging a move towards either zero-finish of PFAS-free options. Almost all major UK retailers have, or are in the process of, phasing out PFAS-based stain resistant treatments on school uniforms.

Public engagement

Fidra engaged with local primary schools, presenting information in a user friendly 'PFAS uniform factsheet', and providing a small sample of parents with a randomised selection of shirts, to gain feedback after a terms wear. Parents consistently found no difference between shirts treated with fluorinated finishes and those without.

To increase public awareness, Fidra also developed a dedicated website www.pfasfree.org.uk, offering public information on 'who sells what' and background information on the health and environmental implications of PFAS, to date reaching over 7000 users.
Both Chemical Watch and Ethical Consumer ran press articles on the report and survey results, and Fidra's public engagement was covered in the local area press (East Lothian Courier).

Communication in Swedish stakeholder forums
The POPFREE project was presented at two multi-stakeholder seminars; the Textile Dialogues hosted by Swedish EPA and Chemicals Acency where several textile industry stakeholders participated, and at the National Outdoor Workshops hosted by Swedish EPA where municipal outdoor strategists and outdoor organisations participated.

Supply chain dialogue guide
As part of the textile case work, a first test version of a textile supply chain dialogue guide for PFAS substitution was compiled, building on learnings among partners, current research, textile sustainability expert review and legal frameworks. The idea was to support textile professionals with limited chemical knowledge to investigate the use of PFAS and alternatives in textile processing and inspire good practices in chemicals management and substitution work. It has been shared with the textile partners, who will trial this version after project end.

7.2.3 Case cosmetics

At the start of the project, the awareness about the use of PFAS in cosmetics was quite low at industry level. Some distributors claimed that PFAS were not used at all in cosmetic products, the organization for cosmetic and hygiene products (KoHF) in Sweden the use of PFASs in Sweden and some industries did not know whether they had PFAS in their products or not. The definition of PFAS was also misleading as some actors only considered the regulated PFOS and soon to be regulated PFOA as PFAS. The challenges associated to the use of polymeric PFAS was not well understood.
The project has spent lots of efforts to communicate with the industry about the environmental impact of PFASs. A dialog was initiated early on in the project with the organization for cosmetic and hygiene products to discuss the PFAS challenge and explain the overall issue with these compounds.

To increase awareness in the cosmetic sector, a breakfast seminar on PFAS and cosmetics was organized. Representants from the cosmetic industry and authorities as well as private persons attended the seminar. The amount of PFAS used in decorative cosmetics was discussed: scientific studies had shown that the amount of PFAS present in the products could be higher than specified in the ingredient list, probably because of impurities. However, the industry claimed that only a few products were concerned and that the amounts of PFAS used were low. It was also noticed that the understanding on the reason to phase out PFAS was low. Several representants considered their products safe to use according to the testing required by the Swedish Medical Products Agency; they did not account for environmental issues caused by end-of-life or production. In fact, the surveillance of environmental aspects and Reach regulation is the responsibility of the Swedish Chemical Agency. Unfortunately, as of today, the collaboration between the two agencies is limited when it comes to cosmetic products.

To get a better picture of the amount of PFAS used in cosmetic products, the possibility to submit a survey to the member of KoHF was discussed. The survey would also be used to gather information on the current use of PFAS by the industry, potential identified alternatives as well as remaining challenges for full substitution. Unfortunately, this survey could not be submitted by KoHF as this work was not prioritized within the organization. To gather this information, a meeting was instead organized with the support of KemI towards the end of the project to discuss these questions directly with some representants from the cosmetic industry. During the meeting, it was noticed that the awareness for PFAS had significantly increased at KoHF. However, the industries represented at the meeting were mostly manufacturers of wash off products and not of decorative cosmetics, why they could not provide us with the information we were looking for.

To reach the cosmetic industry, the POPFREE project was also presented at the Scancos conference in Oslo in October 2019 (Scandinavian Society of Cosmetic Chemists, theme: Know your ingredients).

7.2.4 Case ski wax

A survey to recreational skiers was done during winter 2018/2019 to assess the awareness of PFAS chemicals and to evaluate the will to ski fluorine-free. The survey was done in SurveyMonkey and was spread through Vasaloppet to their customers. In total 270 responses with a completion rate of 85% was achieved. We had hoped for more responses but the way it was spread was not optimal for reaching out widely. In summary, fluorinated ski waxes are mostly used in competitions, people seem willing to use fluorine-free alternatives if all do, including also the elite skiers and many see fluorinated bans as the right and only way forward (Figure 18). The results from this survey lay the ground for POPFREE Ski Goes Global, targeting a phase-out in international competitive skiing.

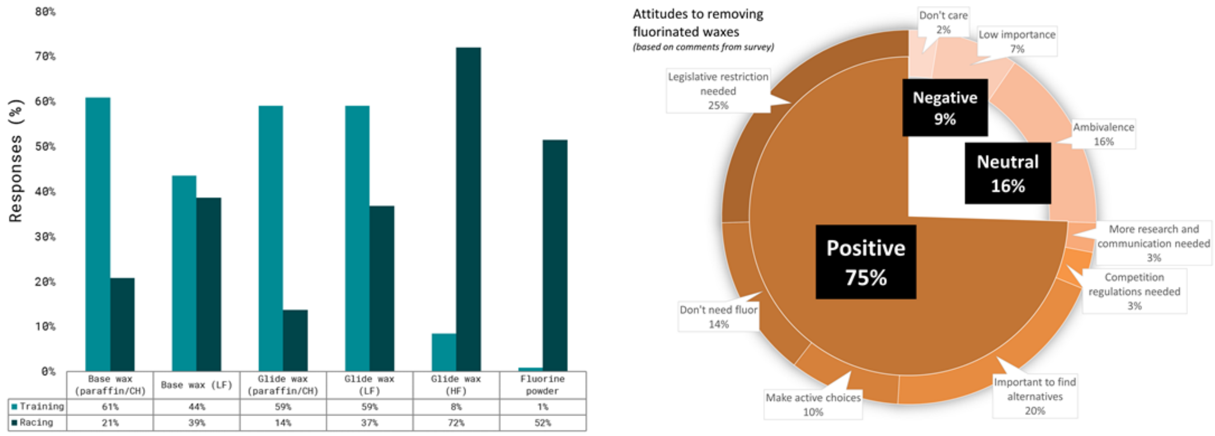


Figure 18. Results from the 2018 POPFREE survey showing: left) the % use of fluorine wax in training (light blue) and racing (dark blue) and right) a summary of attitudes to remove PFAS waxes based on comments from the survey.

Besides participation at Vasaloppet's winter week, communication activities to spread awareness and promote PFAS-free alternatives have been done through participation at ISPO Munich, the leading trade fair for sports business professionals. Here we got the chance to talk to all ski wax brands about why PFAS should be phased out. Three talks from the POPFREE ski wax case activities were given entitled: *Optimal fluorine-free glide – what's on the market today and tomorrow?*; *The FIS fluorine ban - What's next and how do we comply?* and *Gliding on skis – influencing factors.*

We were also invited to give a talk at the Snow on Tour seminar, arranged by the SNÖRIK project in connection to SkiTour 2020, the international World Cup skiing competition held over a number of stages between Östersund and Trondheim.

Within the POPFREE Ski Goes Global project, a spin off from the ski wax case, a roadmap towards PFAS-free competitive skiing was drafted together with stakeholders from the ski sport. Generated material from POPFREE and POPFREE Ski Goes Global, including "fact sheet", results from surveys and presentations have been presented and shared with many different stakeholders including ski wax companies, FIS, IBU and national ski associations.

8. Regulations and monitoring

POPFREE has participated in several high level meetings and initiatives. One example is our input to the Safe chemicals agenda summarized in report 'Safe-by-design for chemicals and materials: Towards an innovation programme in Horizon Europe'[1]. In addition, a "non paper" regarding phase out actions of PFAS mentioned POPFREE's work as a result our engagement. The European platform SusChem held in 2019 a meeting that discussed future European funding programs that support substitution activities in specifically circular material flows. A High Level Conference was organized in June 2019 by the European Commission

[1] https://zenodo.org/record/3254382#.XRMrIXlf3jh,

together with the Ministry for Food and Environment of Denmark on *"EU Chemicals Policy 2030: building on the past, moving to the future"* were POPFREE-experts participated. In 2018 experts participated and shared results at the Horizon 2020 funded Midwore final meeting hosted by the EU-commission.

Road map for future regulatory measures were discussed in several high level meetings in particular for textile, leather and firefighting foam. One example was a meeting arranged by the commission on the 15th of January 2020 in Brussels were POPFREE was one of three external presenters. The meeting was part of an assignment coordinated by Wood Environment & Infrastructure Solutions UK Limited.

The project also contributed to several reports from OECD by submitting information on current uses of PFAS and existing alternatives in, for example, textiles or food contact materials. All in all, POPFREE is mentioned in many of the later public reports related to substitution of PFAS.

External environment monitoring:

- From 4th of July 2020, PFOA will be regulated. PFOA are listed under ANNEX XVII to REACH, under Annex A (elimination) of the Stockholm convention with specific exemptions (decision SC-9/12) and included in Annex I of the POP regulation. About 800 substances are covered by this upcoming legislation.

-The *Swedish PFAS network* is following emerging technologies and current challenges for water purification and soil cleaning. Representants from POPFREE are part of the network.

-The Swedish Institute together with the Swedish EPA have started a network for collaboration of PFAS issues around the Baltic sea. POPFREE is represented in the network.

- The International Ski Federation has announced a ban for all fluorinated ski waxes at competition level starting the winter season 2020-2021. POPFREE has a continuous dialog with FIS to follow the progress of the ban and to assist in method development for PFAS-screening on skis at competitions.

- The C6 chemistry, PFHxS, is now discussed for regulation at the EU level.

- Several countries amongst which Sweden have sent to the European commission a suggestion for an EU strategy for PFAS, which is suggested to be adopted by 2025 and implemented by 2030.

- Sweden and Germany submitted a dossier to initiate restriction under REACH of long chains Perfluorocarboxylic acids (PFCAs) and short chains PFAS.

- Denmark has banned the use of PFAS in packaging and the OECD is preparing a report on the use of PFAS in packaging and existing alternatives.

- Discussions are on-going at EU level to define essential *vs* non-essential uses of PFAS to facilitate regulation for non-essential uses.

- In parallel to POPFREE, the stage 2 UDI project SilCoTex was focusing on anti-soiling treatments for textiles using silica particles.

9. Impact

By reducing the use and emission of PFAS in the environment during product manufacturing and use, POPFREE contributes to Responsible consumption and production (Goal 12 of the Sustainable Development Goals listed by the United Nation). It is well known that PFAS represent a class of hazardous chemicals both for the environment and human health. PFAS can be transported by air and water and, because of their mobile and persistent nature, PFAS are today found in many contaminated sites in Sweden but also in remote areas such as the Arctic where they have been detected in the blood of polar bears. PFAS are regularly detected in drinking water and humans are exposed daily to these chemicals through the ingestion of contaminated food (e.g. fish). By developing viable alternatives with a reduced environmental impact and promoting the use of PFAS-free products, POPFREE helps to lower the environmental and social costs issuing from remediation activities needed to purify contaminated soils and water around the world. By limiting the use of PFAS and PFAS-containing products, POPFREE indirectly "improves water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally" (target 6.3). The lobbying activities conducted within the project to drive the implementation of new regulations on PFAS lead to "the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment" (target 12.4). The strong communication campaign led by POPFREE to increase awareness throughout the value chain and help consumers to make educated choices is one contribution to "ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature" (target 12.8).

The organisation of the collaboration project with case studies running across work packages has favoured the transfer of information and sharing of knowledge on innovations and challenges amongst partners. The partners have had the possibility to learn from each other and to get insights into the challenges faced by other sectors as well as successful initiatives carried on in other product categories. In this regard, POPFREE has stimulated necessary partnership to reach complex targets such as phasing out PFAS. This work has been in line with UN goal 17 relating to the importance of partnership – a systemic change cannot be achieved by a sole actor but rather in collaboration and co-creation with many different actors and stakeholders.

Several new technologies have been developed in the project and assessed with respect to environmental and health effects. All these technologies have a positive impact on the society by minimizing the use of PFAS. However, the project has not had the possibility to perform full LCA's for all technologies, partly because some of them were not mature enough. Therefore, we can no exclude that some of the alternatives developed within POPFREE may negatively affect the environment in terms of energy, water consumption or material consumption for example.

10. Identified opportunities and obstacles to substitute PFAS

Possibilities

- *Fast development of alternative solutions in several product categories.* During the project, several partners have been able to test and patent new technologies and solutions to substitute PFAS in their products.
- *Large interest from consumers.* The interest from consumers for environmental issues and sustainability is growing, which facilitates the transition to a PFAS-free society. The willingness to compromise on performances in favor of sustainability has been clearly shown by a survey conducted among skiers where consumers were ready to stop using best performing fluorinated waxes if the elite would do the same. Several PFAS-free products from the consortium were presented to consumers, for example during the Vasaloppet's winter week.
- *Strong international drive for a phase out.* The PFAS questions is discussed in many countries around the world. POPFREE has for example joined an international network to work on a common strategy for the Baltic region. We have worked with our international partners to support them in their substitution work and phase-out initiatives.
- *Enforcement of new regulations and potential global regulations.* PFOA will as of July 2020 be regulated and several other groups of PFAS are under investigation at the European level. POPFREE has been contributing to several reports from OECD to provide information on alternative technologies and products. We have had a continuous dialog with several authorities in Sweden and invited them to our project meetings to share information.

Obstacles

- *Non-suitable standards and test methods.* Several standards exist today that are adapted to PFAS chemistry (for example Personal Protective Equipment directive, testing method and requirements for firefighting foams or food contact paper). It is sometimes impossible to reach the performance level required by these standards using other chemistries. POPFREE has worked on establishing new test methods that better correlates with the required level of performance. The challenge with existing standards has been lifted in several communication activities.
- *Lower level of performance of the alternatives.* During the evaluation of the function of the PFAS, it was noticed that some products were over-performing comparing to the real need from the consumer. Moreover, PFAS-free alternatives might have a slightly lower performance or application areas (lower versatility for application on different fabrics for instance).POPFREE has communicated with end-users to increase the acceptance for slightly lower performance products.
- *Complexity of the value chains.* Several of the value chains studied in the project have an international perspective and consist of a broad range of actors. It is therefore difficult to trace the products all the way back to the manufacturing of the raw chemicals and

thus it might be impossible to know whether PFAS have been used in one step of the manufacturing process of the final product. POPFREE has prepared guidelines and information documents to facilitate dialog along the value chain.

- *Complex definition of PFAS.* According to OECD, PFAS are defined as per- or polyfluorinated alkyl substances that contain at least one functional group. Other authorities like the Swedish EPA (Kemi) have chosen to even include per- and polyfluorinated alkanes without any functional group in their definition of PFAS. Moreover, several industries limit their definition of PFAS to regulated molecules. This render the dialog around a phase-out of PFAS rather complicated as one should make sure all partners are using the same definition.
- *Poor industrial awareness of the health and environmental effects of PFAS in some sectors.* Several communication activities have been conducted with sector organization or at specific events.
- *Slow evolution of regulation.*
- *Complexity of product categories.* Textile, for example, covers a broad range of materials and different materials will require different solutions to achieve a good level of performance. In the project, we have tested a variety of textiles with different properties (nature of the yarn, denier…) to respond to the demands from our partners.
- *Challenging collaboration between sectors because of confidentiality*.
- *Difficulty to accurately measure actual level of PFAS in products.* Several different methods are available to quantify PFAS in products (measurement of total organic fluorine, of total oxidizable precursors, screening for known PFAS…). These methods provide different information on the content of the products and it can be difficult to know which method to rely on for a specific application.

11. Conclusion

POPFREE aimed to stimulate production and use of safer alternatives for several applications. Thus, our vision was to contribute to a systemic change of phasing out PFAS. Within the project it was recognised that the push/pull instruments are important aspects of the success of such systemic change. When the project started there were some activities within front runner companies and PFAS were on the political agenda for phase out roadmaps. Since the start of the project, POPFREE as well as other initiatives have contributed to an increase in maturity for the systemic change.

More specifically:

- On the Push side:
  - Increased supply of alternatives and PFAS free products on the market
  - Increased engagement of industry to phase out PFAS
- On the Pull side
  - Increased awareness among producers, B2B customers and consumers of the legal status of PFAS and the reasons behind phase-out activities (environmental and health hazards)

- The legal discussions have intensified and have during the project period included more and more compounds in the PFAS family

Different sectors have reached different levels of systemic change but have also different challenges and opportunities related to practical substitution of PFAS. Therefore, there is still a need for further activities and research initiatives it the field to complete the phase out of PFAS in society.

12. Acknowledgements

POPFREE has been a collaboration project and as such several persons outside the project team have also contributed to the success of this project. We would like therefore to thank all our contributors and particularly Stefan Posner for his support and work with regulatory aspects as well as Anders Finnsson, Ian Cousins, Jessica Norrgran Engdahl, Jenny Ivarsson, Kettil Svensson and Stellan Fischer who were part of the reference group for the project.

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