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Development of an Integrated Solution to Prevent Spring Frost Damage Using an Aqueous-based Insulating Foam

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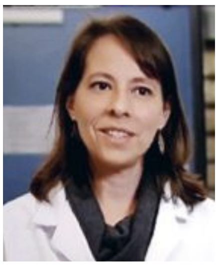
Abstract: In recent years, agricultural crops experience unusually early onset of vegetation due to global warming, which can cause major frost damage with devastating effects on crop yields. To mitigate the risk of frost damage, an integrated solution was developed, consisting of an aqueous-based biocompatible foam and a portable foam applicator enabling wine cultivators to treat up to 1000 m^2 of vineyards with one filling containing 10 L of foam. The foam is biocompatible, stable for several days and easily removed by rain. Foam application yielded an insulation efficiency of up to 1.5 °C during spring frost nights for the buds covered by the foam when combined with an electrically heated wire. Moreover, it was observed that the foam also created a 'mini greenhouse' effect at positive temperatures during the day, which might be a positive side effect helping the plants to grow at this early stage of the year.

Keywords: Aqueous gel foam · Biodegradable · Insulation · Integrated solution · Spring frost



Dr. Véronique Breguet Mercier is a professor in the ChemTech institute at the School of Engineering and Architecture of Fribourg. After completing a MSc (2003) and PhD (2008) in bio & chemical engineering at the Swiss Institute of Technology Lausanne, she worked for almost 10 years in development and production at Syngenta in Monthey. She then joined the HES-SO where she teaches industrial chemistry & bioprocesses, and is involved in research projects aiming at developing new sustainable processes and solutions for the industry.

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Laurent Rapillard is a professor within the Systems Engineering department at the School of Engineering in Sion. After completing his MSc in Mechanics in 2002 he worked in the medical industry, mainly developing biopolymers for vertebroplasty. He joined the HES-SO in 2008 where he teaches statics, dynamics, and FEM simulation. He completed several projects that required application of non-Newton fluids and complex processes such as food and drug extrusion and a battery sprayer for viticulture

1. Introduction

In recent decades, the phenology of agricultural crops is continuously changing all over the world due to global warming. An early budburst towards mid/end of May, exposes plants to a high risk of frost damage because polar air masses sweep over most European countries until the end of April. This led in recent years to substantial losses in yield of different agricultural crops, such as grapevine and fruit trees.[1] The main reason for this harmful effect is the excessive cooling of the plant surface which leads to ice formation inside the tissues due to radiative heat flux from the atmosphere.[2] It is known that the main harmful factor is not the cold temperature but ice formation. Significant yield loss follows these frost events each year, which can be mitigated with various methods that are classified as active (direct) and passive (indirect).[3,4] Current methods to mitigate frost risk include: spreading of smoke or fog, air circulation (wind turbine), water spraying, heating (hot air turbine or small heaters), and electrically heated wires. These methods require a lot of energy and work. The additional inconvenience of methods based on heating is that the energy is brought into an open space and therefore dissipated very quickly, which makes these systems very ineffective. Indeed, heaters and other means of combustion are difficult to use over a large area, such as a vineyard, and their effectiveness is limited to the vicinity of the heat source. Furthermore, this approach contributes to environment degradation by using combustion gases.[5]

Consequently, new technologies are being sought to replace current methods, most of which date back to the 1970s. These include gel-based insulating foams or kaolin-based particle films.[6–8] However, their effectiveness and development are still an open field for research. It is also believed that the complex technology and high cost of materials used in foam production is one of the reasons that these approaches still have not become a widely accepted commercial product.

Several foam formulations have already been developed previously: Krasovitski and his team[9] developed a foam composed of betaine C (coconut amido alkyl betaine) as a surfactant, Lauramide 11 (coconut diethanolamide) as a stabilizer and glycerol as an antifreeze additive. Another foam solution was prepared by Siminovitch, from suitable water dilutions of commercially available hydrolyzed-protein concentrates containing a stabilizer and supplemented with 1% gelatin.[10] Bartholic also developed a new foam generator and dispensing system capable of applying the Agrifoam with a 1.3 cm layer 70 cm wide over plants.[11] All those solutions were tested on tomato and strawberry plants, and showed satisfactory results with up to 9 °C temperature differences between the control probe and the foam.

Alongside the various foam formulations, there are also different research studies on particle films for frost protection. Wisniewski and his team studied a hydrophobic kaolin particle film that prevents plants from freezing due to extrinsic ice nucleation.[12] Fuller compared acrylic polymer (Antistress™) and a hydrophobic kaolin particle film (CM-96-018), and demonstrated that the acrylic polymer (Antistress™) did not clearly show a consistent frost protection effect, while the hydrophobic particle film demonstrated a capability of protection against freezing.[13] Biodegradable liquid films (BLF) were also used as an alternate strategy to protect against the winter chill for grapevines as an alternative to replace vine burial in China.[8]

Regardless of the technology, the most important criterion for the selection of components to comply with agricultural use is their degree of toxicity, but also important are the properties allowing to generate the foam in order to ensure successful protection of plants, as well as the foam's heat resistivity and stability.[9]

Therefore, the essential objective of this interdisciplinary project was to develop an integrated solution consisting of an insulating foam and a portable foam dispenser device, mainly for vineyard application but also other perennial fruit crops such as apricots, cherries or apples. The foam should fulfill the following requirements: non-toxic, biodegradable, stable, adhesive, low-cost, an aqueous foam offering high thermal insulation and which dissolves when exposed to rain.

1.1 *Foam Development*

There are numerous chemical compounds that can be used for foam formulation. Essential compounds that are needed for the development were classified based on former successful foam formulations which involved a gelling/stabilizing agent, cryoprotective products, wetting agents/surfactants, stabilizers and preservatives against bacterial growth preservatives for bacterial growth. The gelling agents are substances that can increase the viscosity of a liquid without substantially changing its other properties. Mostly proteins and polysaccharides are used as bio-gelling agents. Cryoprotective substances are used to protect the biological tissues from freeze damage. They provide a strong anti-freezing effect when added to the formulation. Wetting agents/surfactants are used to lower the surface tension in order to increase the spreading and penetrating properties of the liquids. Lastly, stabilizers prevent chemical degradation and make the formulation physically stable. Stabilizers and gelling agents are classified separately but might overlap in functionality. Therefore, some compounds can be used both as a gelling agent and a stabilizer.[14] A literature review was completed for each classification, and specific compounds were chosen according to their chemical and physical properties, as shown in Table 1. The following aspects were considered when evaluating and selecting the substances: stability, foaming ability, thermal stability, compatibility with the other compounds, solubility in the water and adsorption.

1.2 *Foam Dispenser Prototype*

The objective was to design an ergonomic prototype producing the expansion of foam and applying it to the crops (Fig. 1). The prototype had to meet the following criteria:

- 1.5 hour autonomy;
- Ability to maintain liquids above the melting point (30 °C);
- Capacity for 12 liters of product and 1 liter of rinsing water on board;
- Adjustable at shoulders, chest, hips and application nozzle;
- Parameter control *via* a manual control interface;
- Weight of less than 24 kg;
- Ability to treat 500m^2 during the 1.5 hours working cycle.

2. Materials and Methods

The foam basis was prepared as follows: water was heated to around 60–80 °C under stirring, and the gelling agent was added gradually over 10–15 minutes. After dissolution, the other components were added gradually until dissolved. The solution was then cooled to room temperature. For the foam generation, the gelled solution was re-heated in a hot water bath until reaching the melting point (~35 °C) and turning liquid. Next, the foam was generated by sparging compressed air through either a pipette or

Table 1. The alternative chemical compounds for foam formulation

Gelling Agents	Cryoprotective	Surfactants	Preservatives	Stabilizers
Gelatine from bovine or porcine skin	Glucose	Ammonium lauryl sulfate	Acetic acid	Calcium acetate hydrate
Agar-agar	Gycerol	Sodium dodecyl sulfate	Fumaric acid	Soluble starch
Carrageenan	Ethylene glycol	Sodium lauryl sulfate	Sodium acetate	Sucrose
Guar gum	Egg yolk	Sodium lauryl sarcosinate	Potassium acetate anhydrous	Salt stabilizer
Pectin from apple	Egg albumin	Coconut amido alkyl betaine	Potassium sorbate	Cocamide DEA
Cleaned gum arabic	Honey		Sodium sorbate	Carboxymethyl cellulose
Xanthan	Tannic acid		Calcium sorbate	Methyl cellulose
Sodium alginate	Kaolin		Dimethyl dicarbonate	Stearic acid
Carboxymethylcellulose sodium salt	Dimethyl sulfoxide			
Sodium alginate	Propylene glycol			
Gum tragacanth				
Sodium pectate				
Starch				

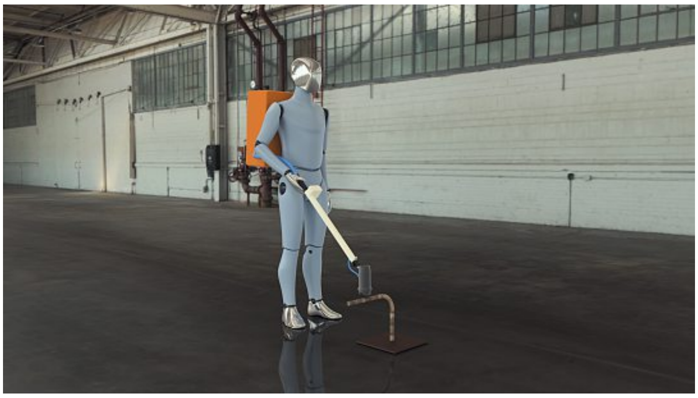

Fig. 1. Foam dispenser design intent.

a syringe needle at lab scale, or through a nozzle with the foam dispenser prototype in the field trials.

The generated foam was then poured onto an inert wood stick or onto small plants (grapevine Muscat provided by Changins College for Viticulture and Oenology) and temperature was monitored using the Tinytag Talk2 temperature logger (Gemini, UK). Several samples were stored either in a freezer (–20 °C) or in a climatic room (Binder MKF 240), simulating temperature cycles of days and nights during spring frost (–5 °C to 10 °C) over 3 to 6 days.

For field testing, foam was applied using the foam dispenser prototype on apricot trees (*Samourai*, Agroscope Chateauneuf-Conthey, Switzerland) or grapevines (Experimental vineyard, cultivar *Chasselas* L, Changins – Nyon, Switzerland / Domaine de l'Etat du Valais Grand Brûlé, *Gamay* Leytron, Switzerland), and temperature was monitored using Tinytag Talk 2 probes during 2 to 3 days in April 2022.

3. Results

3.1 *Foam Formulation*

The foam formulation was first developed by testing various gelling agents from Table 1. Then, the other ingredients were modified and tested. The foam properties from different formulations were compared by analyzing the apparent density, foam expansion ability, adhesion to plants and wood sticks, as well as foam stability over time (data not shown). According to those criteria, the optimal composition was established and is described in Table 2.

The most important criterion for the substances is being non-toxic to the plant, and not altering its metabolism. Gelatin is an animal protein prepared by the thermal denaturation of collagen involving long strings of amino acids. It can be obtained from animal skin, bones, and connective tissues of animals.[15] It is known that sugars modify the gelation properties of gelatin, increasing the gel strength and its melting point. The other important chemical property of gelatin is that it is water soluble.

Glycerol is a colorless, odorless, viscous liquid derived from both natural and petrochemical feedstocks. It contains three hydrophilic alcoholic hydroxyl groups that are responsible for its solubility in water and for its hygroscopic nature. Glycerol is compatible with many other chemical materials, it is virtually non-irritating and has no known negative environmental effects, which is an important property for the production of non-toxic and biodegradable foam.[16] Ammonium lauryl sulfate is an anionic surfactant that disrupts the surface tension of water by forming micelles around the polar water molecules. It was used in the formulation in order to ensure foam formation.

3.2 *Foam Dispenser Prototype*

The prototype was designed at the School of Engineering Valais/Wallis (Sion, Switzerland) in the shape of a backpack (Fig. 2). In short, it was built with an insulated plastic box, containing a 12 liters reservoir for the foam solution and a 1-liter reservoir for the rinsing water. The foam dispenser was equipped with a battery to power a heating element required to keep foam solution above its melting point, and to power a peristaltic pump needed to feed the nozzle at the desired flowrate. The foam expansion was then achieved using a blowing turbine. This device, with full reservoir and battery, is capable of treating between 500 to 1000 m^2 of vineyard per hour.

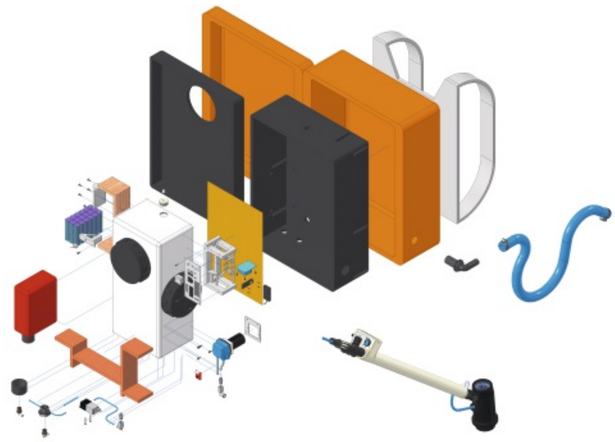

Fig. 2. Foam dispenser scheme.

3.3 *Laboratory-scale Insulation Tests*

For the first thermal insulation tests, a plant branch was put inside a glass cylinder once without foam (blank) and once with sample covered with the foam and then placed in a freezer. The results from the tests were compared and the effect of the foam was observed (Fig. 3).

Table 2. Chemical composition of the ideal foam

Classification	Products	Manufacturer	Percentage	Weight (g)
Gelling agent	Gelatin procine skin (225 Bloom)	Sigma-Aldrich Chemie	2.40	1.20
Cryoprotective	Glycerol 86%	Carl Roth GmbH	1.00	0.50
Wetting agent	Ammonium lauryl sulfate	Sigma-Aldrich Chemie	0.50	0.25
Preservative	Fumaric acid	Sigma-Aldrich Chemie	0.10	0.05
Stabilizer	Sucrose	Sigma-Aldrich Chemie	28.00	14.00
Other additive	Water	Laboratory water	68.00	34.00

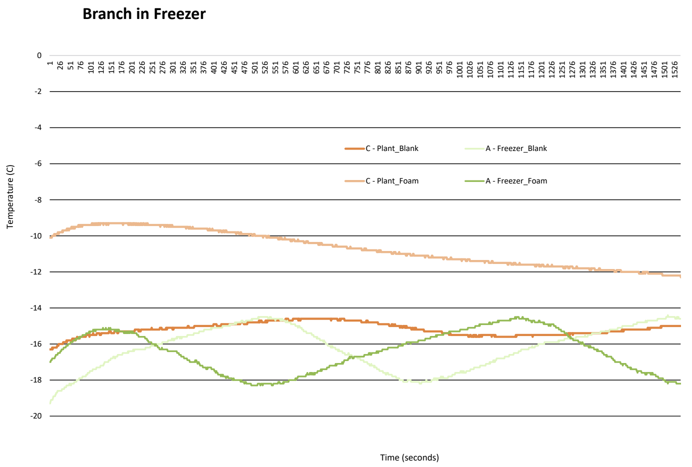

Fig. 3. Temperature as a function of time for tests with and without foam on a branch in the freezer.

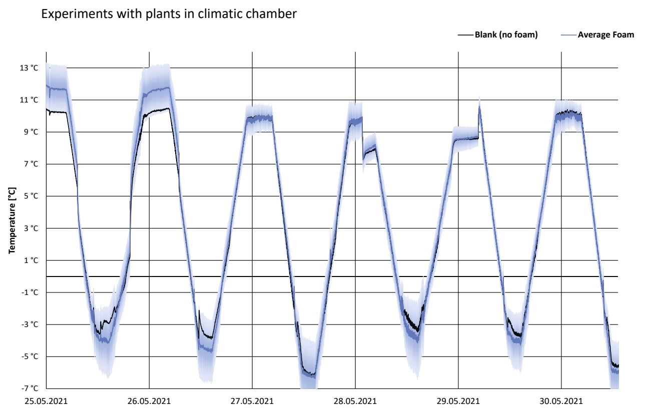

Fig. 5. Temperature over 6 days in the climatic chamber with grape plants (Blank = temperature in the climatic chamber for plant without foam, Average Foam = 3 different plants with foam, temperature measured on the plant under the foam). The average value is shown with standard deviation in light blue.

The freezer had a continuous repeating temperature pattern between –15 and 20 °C with around 75% humidity. Even though the freezer temperatures varied, the plant temperature values remained steady in both cases (blank and with foam). However, the temperature difference between the blank sample and the foam-covered sample was obvious, showing around 4 to 5 °C positive insulation efficiency.

Wood sticks placed in the climate chamber (Fig. 4) showed similar results to the branch in the freezer, but with only 1 to 2 °C of insulation efficiency. Indeed, some replicates did not show any insulation efficiency. The trials with young grapevine (Muscat) cuttings in May 2021 did not show satisfactory results (Fig. 5). Actually, for negative temperatures in the climate chamber, the Tinytag probes under the foam measured either similar temperatures or values lower by 1 to 2°C when compared to the control. For positive temperatures, the opposite behavior was observed with higher values measured under the foam than in the climatic chamber during the first two days. Those results were rather surprising and difficult to explain. Several hypotheses, linked to heat transfer phenomena, such as radiation, evaporation or transpiration of the plant, have been put forward but none have been clearly highlighted or proven thus far. However, those measurements showed that the plant does not produce thermal energy during the night that the foam could store. Following those results, it was decided to implement a heat source under the foam with the help of an electrical wire.

3.4 *Field Trials*

Based on previous results, three campaigns of measurements were planned in the field in early spring 2022. A campaign in the experimental vineyards of Changins, a campaign at the wine estate 'Grand Brûlé' with the collaboration of the agricultural service from Valais and finally, supplementary trials on apricot trees. However, an important modification was implemented and a metallic wire with an electrical power supply (battery) was installed to create a small heat production (around 2–3 W/m) around branches under the foam (Fig. 6).

Fig. 4. Picture of trials with wood sticks and grapevine plants in climatic chamber freezer.

Fig. 6. Foam on grapevine branch in Grand Brûlé, with addition of heat supply (blue electrical wire).

The results obtained are summarized below:

- It was difficult to obtain a homogeneous foam cover on the set of vine shoots, better for apricot trees;
- The night temperature gain exists but it is lower than expected, around 1 °C (Table 3) with heating wire having a power of 2.8W/m;
- The plants are not affected at all by the foam and the latter disappears after the first rain;
- There is a greenhouse effect under the foam with a temperature about 10 °C higher under the foam compared to the ambient temperature during the day.

The mixed results obtained in terms of nocturnal temperature gain showed that the initial project may not be viable for a winegrower, however the obtained results motivate us to seek new opportunities for this integrative solution, for instance protection of seedlings on the ground (replacing the current plastic-based solutions), *etc.*

Table 3. Average gain of temperature during night during field trials (apricot trees and vineyard)

	Abricot	Vineyard
Average insulation gain at negative temp.	1.8 °C	0.8 °C
Standard deviation	0.65 °C	1.1 °C

4. Conclusions

This interdisciplinary project was funded by the HES-SO Engineering and Architecture Faculty, and was the result of a successful collaboration between the ChemTech institute (HEIA-Fribourg), the Institute of System Engineering (HES-SO Valais-Wallis, Sion) and the College for Viticulture and Oenology in Changins. The formulation of an easily applicable water-based and biocompatible foam with insulating capacities could be achieved rapidly after the start of the project. Subsequently, a functional prototype of a foam applicator was developed following laboratory experiments and adapted to the properties of the foam.

Even though the first insulation tests on branches in the freezer were encouraging (insulation effect of up to 5 °C), the tests on an inert material (wooden sticks) and small vine cuttings in a climatic chamber showed only very little (0.5 to 1 °C) to no insulating properties. Nevertheless, the foam remained stable for several days and was easily removable by water. Moreover, no phytotoxicity or other negative effects on plant physiology following foam application was observed, indicating a good biocompatibility of the formulation.

Field tests in vineyards and orchards, performed with the addition of an electrical wire to provide a small heat input, resulted in a gain of maximum 1.5 °C increase under the foam compared to the control test without foam. A 'magnifying' effect during positive daytime temperatures was also clearly demonstrated, where the value under the foam was higher than the ambient temperature by 4 to 10 °C. At this stage, the results are not yet sufficiently encouraging to counter the spring frost. This low value, combined with the extra work required of the farmer to fix the heating wire and deposit the foam, does not currently constitute an economically viable solution. Increasing the power supply to the wire would certainly be a first solution to intensify the heat release under the foam, and thus the temperature increase during frost events.

However, we also believe that the prototype and the foam developed have potential for other applications, especially for soil cultivation. First of all, applying foam on a horizontal surface will be easier than on a branch. In addition, placing insulating foam on seedlings (strawberries, lettuce, *etc.*) can have a better effect against frost thanks to the heat stored by the ground. On the other hand, the foam could help the growth of the plant during the day since the temperature is higher under the foam, simulating the effect of a 'mini greenhouse'.

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