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# Development of an application system for selective, thermal weed control in row crops with vegetable oil

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The use of thermal weed control methods in row crops is currently not suitable for selective weed control because of insufficient precision. Flaming-, hot water-, superheated steam- or hot foaming units have the disadvantage to require a relatively large safety distance to the crop plant in order to avoid damages. The spray application of hot, vegetable oils from renewable raw materials should, in addition to high precision in the application, also enable an effective and environmentally friendly control of weeds even in the intra-row area. At the Institute of Agricultural Engineering at the University of Bonn, an application system was developed to investigate the harmful effectiveness of hot vegetable oils.

**Key words**
Plant protection technology, precision farming, organic farming, vegetable oils

In commercial farming the regulation of weeds in the field to protect crop species is very important (Koch 1967). In contrast to the predominantly used chemical and mechanical weed control systems, thermal weed control systems currently occupy a niche, but have important advantages in the area of socio-political acceptance and environmental compatibility (Huber and Kleisinger 2006).

Conventional flame weeders are used especially in organic agriculture for weed control in the pre-emergence, but have the disadvantage of beeing only conditionally selective between the row (inter-row) and working at a great distance to the crop plant (Diver 2002). Despite various optimization efforts this process is not yet satisfactory due to its inefficiency (Bertram 1996), since most of the energy used is lost on the way from the flame weeder (burner) to the plant (Dierauer 2000).

Hot water and hot water foam systems are currently used exclusively in the municipal or private areas of weed removal on parking areas or sidewalks (Huber and Kleisinger 2006). For this purpose, water is heated as a carrier in a continuous-flow heater to a temperature of 95 °C and applied to the target plants over a large area (Kristoffersen 2008). To improve efficacy, a biodegradable insulating foam can be added (Rask, 2007). By transferring heat, the plant cells are heated to a lethal temperature level (temperature of 45 °C) causing the cell wall to deteriorate by protein denaturation (Sutcliffe 1977; Levitt 1980). Depending on the weed species and density, the amount of water required for a successful control is high and may lead to soil sludge and incrustation (Hansson and Ascard 2002). In perennial weeds, multiple treatments are required (Daar 1994). The use of these systems in row crops for selective weed control without damaging the crop plant is currently not possible because of a lack of precision, efficiency and high energy losses. In order to reduce the process costs significantly, the energy must be emitted in a more targeted manner and thus taken more efficiently to certain plant organs.

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At the Institute of Agricultural Engineering of the University of Bonn, a new and alternative, thermal weed control method for selective use in series cultures is currently under investigation. Vegetable oils are used as carrier substance. Compared to water, oil is significantly more advantageous for thermal weed control because it can be heated to temperatures up to 300 °C (Bhatia 1990). With the help of a spraying application, hot vegetable oil has to be applied precisely to individual weed plants. The oils favorable thermophysical and fluidmechanical properties anable a faster absorbtion of heat energy and a more efficiant transfer to the plant organs. Due to a low surface tension, oils can also accumulate particularly well on plant surfaces (Heini 2012).

The environmental compatibility of the oils from renewable raw materials and as a possible substitute for synthetic herbicides offers a good alternative for both conventional and organic farming and thus contributes to a more sustainable agricultural production.

The aim of this research project is to determine suitable vegetable oils and to develop a laboratory test device, which enables efficient heating and precise application in order to apply significant damage to arable weed plants in subsequent experiments. In addition, technical influencing parameters such as drop height, oil temperature, droplet size and adsorption behavior have to be investigated in a hot oil application, as well as an economic evaluation with regard to energy input, application volume and weed control success.

## Material and methods

### Selection of suitable vegetable oils

In the course of this research, approximately 100 vegetable oils were investigated for their physical properties with experimental evaluations and literature data for a possible use as heat transfer media. The suitability of vegetable oils for the thermal weed control depends on different influencing factors. An essential criteria is the way of production, wheather the vegetable oils are cold-pressed or refined. Refined oils have the advantage, that undesired accompanying substances such as pigments, odor, taste or mucous substances are removed by the refining process. This manufacturing process has a positive effect on the smoke point (Widmann 1994). Compared to most cold-pressed oils, the smoke point of refined vegetable oils often exceed 150 °C. This allows heating up vegetable oils to high temperatures without the formation of smoke above the liquid phase. Two other important of suitable vegetable oils for weed control are the viscosity and the density. For a successful spray application, the oils must provide favourable flow characteristics even at lower temperatures and should not solidify at room temperature. Otherwise nozzles and valves of the application device can be plugged.

To determine the viscosity of vegetable oils at different temperatures, viscosity-temperature profiles at the range of 0–250 °C were investigated for selected oils by using a cone-disk rheometer. At the same time, a density-temperature profile was created with a density meter for each vegetable oil in order to examine the change of consistency with increasing liquid temperature.

The specific heat capacities of potential vegetable oils were also determined from the literature. A high heat capacity allows the fluid to store a lot of heat energy that can be transferred to the plant surface during application (Kuchling, 2010). Therefore, a rapid heating of these oils is time and energy-intensive.

Hence, substrates with a high heat capacity and a simultaneous rapid heating behavior at temperatures above 150 °C are particularly advantageous for thermal weed control.

In addition to the thermophysical and fluid-mechanical properties, economical and ecological factors, such as purchase price, availability, origin and biodegradability are also importaint in the selection of suitable vegetable oils. For reasons of sustainability, vegetable oils should origin from domestic cultivation and should not exceed a price of 5 € per liter in order to keep the costs low.

## Experimental determination of the warming behavior of vegetable oils compared to water

In addition to literature research, an experimental study was conducted on the heating behavior of rapeseed and sunflower oil compared to water. For this purpose, 100 ml of liquid were heated in a beaker on the highest heating stage on a magnetic stirrer (IKAMAG REC-G, IKA GmbH & Co. KG). Temperatures were recorded with a temperature sensor (Pt100, Ahlborn Mess- und Regelungstechnik GmbH). While water was heated to the boiling point, both oils reached their smoke point at about 220 °C. In order to be able to evaluate the heating process economically, the energy required to heat the liquids must also be considered. It is also possible to draw conclusions about the energy efficiency of the entire process. The determination of the economical impact was evaluated by the absorbed heat quantity $\Delta Q$ (in J) during the heating process of liquids by using the equation:

$$\Delta Q = m \cdot c \cdot \Delta T \qquad \text{(Eq. 1)}$$

with the mass m (in kg), the specific heat capacity c (in $J \cdot kg^{-1} \cdot K^{-1}$) and the temperature change $\Delta T$ (in K). When calculating the heat absorption, it must be noted that the values of the specific heat capacity c of water and vegetable oil are temperature-dependent. These are valid only for the temperature of 25 °C, but can be neglected for the further investigations.

## Development of a laboratory test stand

In addition to the selection of suitable vegetable oils, the development and technical testing of a laboratory test stand for thermal weed control is another focus of this research.

The test stand shown in Figure 1 is essentially composed of an electrically heated nozzle heater (Figure 2, Türk & Hillinger GmbH) consisting of a brass tube (L = 100 mm, D = 14 mm) with an integrated low-mass tubular heater (U = 230 V) combined with a build-in thermocouple. This heating technology is used in the adhesive industry for heating nozzles and hot runner tools. Therefore it has to be modified by an internal brass cylinder for the intended experimental purposes (heating of vegetable oil).

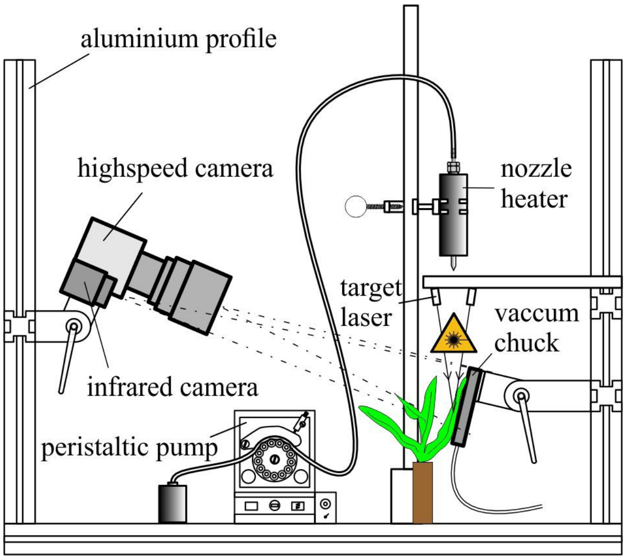



Figure 1: Laboratory test stand with nozzle heater (schematic drawing)

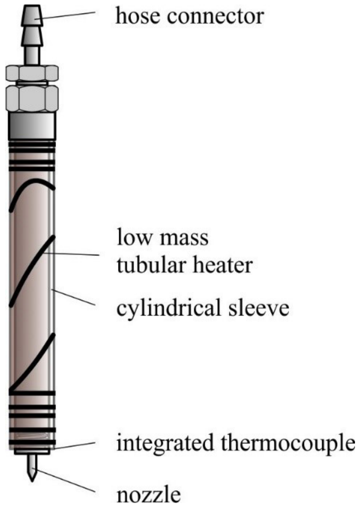



Figure 2: Structure of a nozzle heater (schematic drawing)

With the help of a self-developed, separate control unit, liquids can be heated to temperatures up to 400 °C in steps of 1-degree Celsius. The actual temperature is displayed permanently on the thermocouple, installed at the lower end of the nozzle heater. For laboratory tests with vegetable oils the heating temperature was limited to 250 °C for safety reasons. A thread in the inner brass cylinder makes it possible to screw in different application nozzles, which can also be tested for their suitability as a single drop nozzle. The drop size can be influenced by selecting the nozzle shape and the opening diameter.

The dosage of the plant oil is metered by a preconnected, electrically driven, pulsation-free peristaltic pump (Perimax 12, Spetec GmbH). It transports the vegetable oil from above into the brass cylinder of the nozzle heater by using a heat-resistant silicone hose from a storage container with a pressure < 1500 hPa. The volume of the brass tube is 6 $cm^3$ and enables heating up to 230 K in the flow at an output < 10 ml $min^{-1}$. In order to garantee the previously defined volume of liquid at every application nozzle opening, the inner diameter of the hose, the number of the hose pump rollers, their rotational speed and the control system of the pump had to be optimized.

Using the infinitely variable speed range of the pump (from 1 - 80 rpm) and different tube diameters (from 0.1 to 3.1 mm) it is possible to generate delivery rates of 0.004 to 40 ml $min^{-1}$ as well as the individual drops, without the use of a nozzle switching valve. The problem is, however, the conveying of very cold or highly viscous vegetable oil. Only with a viscosity < 80 mPa · s (Figure 4) it is possible to convey small volume units with a peristaltic pump and small hose diameters (< 0.5 mm) without problems. In this case, the vegetable oil must be pre-heated at temperatures < 10 °C in the storage tank.

In order to apply the oil exactly to certain areas of the plant surface, two line lasers are installed at an angle of 90° and a distance of 120 mm from each other for better sighting (Figure 1).

Using a 100 x 50 mm vacuum plate (Figure 1) plant leaves can be gently fixed with the help of a vacuum. Furthermore, the accumulation behavior of plant oils can be simulated at different blade positions. In order to avoid damages of the leaf surface, the vacuum can be controlled via a mechanical throttle valve in the range of 10 hPa to 200 hPa.

In addition, an infrared camera (PI 160, Optris GmbH) is mounted on a joint holder to measure the temperature and the cooling behavior of oil droplets in flight as well as on the plant surface with a maximum deviation of 2 °C. This provides insights into the cooling behavior of plant oils as a function of the starting temperature, the flow rate, the drop height, the plant surface and the leaf position. In experimental tests (Figures 8 and 9) rapeseed oil was heated to 100 °C and 250 °C with the laboratory test stand. Both single drops and droplets were applied selectively to a plant surface using the peristaltic pump combined with a manual control unit. The results of the measurements were represented by the respective mean value of the tenfold repetition in a line diagram.

A high-speed camera (HotShot 1280, NAC Image Technology) enables more accurate investigations of the flight behavior of oil droplets as well as their impact and attachment behavior on plant surfaces. All components are connected to each other by a 40 x 40 mm aluminum profile rail system, which allows a simple and variable adjustment of the position.

## Results

### Rapeseed and sunflower oil most suited for thermal weed control

The investigation of 100 oils has shown that both, rapeseed and sunflower oil, are particularly suitable for a hot oil application. Due to the manufacturing process by refining, both oils can be heated > 220 °C without smoke formation, which is essential for the thermal weed control. Table 1 summarizes the essential properties of refined rapeseed and sunflower oil compared to an unrefined and unsuitable walnut oil (exemplary). These values were used for a selection decision. Both refined oils are sustainably produced Europe-wide, which has a positive effect on the carbon footprint and the price of currently < 1,50 € per liter for purchase quantities > 1000 l. On the other hand, walnut oil, like most other cold-pressed vegetable oils, has a significantly lower smoke or flame point, which is unsuitable for hot oil application. Because of the few inner European cultivation areas, large amounts of walnut oil would have to be imported for the thermal weed control, unfitting from an ecological as well as from an economic point of view (price per liter > 40 €).

Table 1: Properties of refined rapeseed and sunflower oil as well as unrefined walnut oil

| | Unit | Rapeseed oil refined | Sunflower oil refined | Walnut oil unrefined |
|---|---|---|---|---|
| Smoke point | °C | 220 | 225 | 160 |
| Flash point | °C | 317 | 316 | > 200 |
| Viscosity (20/250 °C) | mPas · s | 67/1 | 59/1 | 72/5 |
| Density (20/250 °C) | $kg \cdot m^{-3}$ | 919/765 | 917/756 | 915/773 |
| Spec. heat capacity | $J \cdot kg^{-1} \cdot K^{-1}$ | 1970 | 1970 | 1970 |
| Growing area | | Europa | Europa | Asia/Europe/America |
| Price | $€ \cdot l^{-1}$ | < 1,20 | < 1,50 | > 40 |

### Vegetable oils can be heated significantly faster compared to water

The experimental warming tests with water (specific heat capacity c = 4190 J $kg^{-1}$ $K^{-1}$), rapeseed and sunflower oil (specific heat capacity c = 1970 J $kg^{-1}$ $K^{-1}$) have shown that both vegetable oils, based on their 53 % lower heat capacity, can be brought approximately 30 % faster to a temperature > 100 °C with the same energy input.

Water (m = 0.1 kg) was heated from 25 °C to a temperature of 99 °C over a period of 6 minutes (Figure 3) ($\Delta T$ = 74 K). This corresponds to a heat absorption ($\Delta Q$) according to equation 1 of 31 kJ. In contrast, rapeseed and sunflower oil reached a temperature of about 148 °C at the same time with a heat absorption of 24.2 kJ.

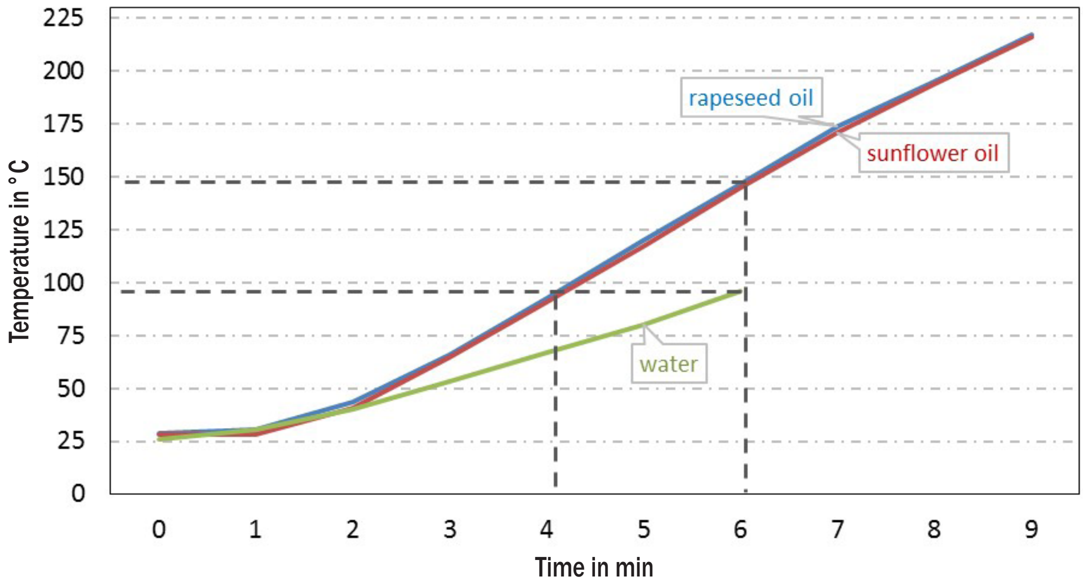



Figure 3: Heating rate of respectively 100 ml water, sunflower and rapeseed oil

The rapid and 53 % more energy-efficient heating process (in each case $\Delta T$ = 74 K) compared to water and the property to reach temperatures > 200 °C illustrates the potential of vegetable oil as a heat transfer medium for a thermal weed control by means of spray application.

During the heating phase of rapeseed and sunflower oil the density decreased linearly from about 918 kg · $m^{-3}$ (at 20 °C) to about 760 kg · $m^{-3}$ (at 250 °C) with an expansion coefficient of 0.840 · $10^{-3}$ $K^{-1}$. The resulting volume increase of up to 20 % has to be observed in the case of a closed heating tank system in order to avoid overflowing.

## Changes in viscosity due to temperature increase

During the heating phase, significant changes in the viscosity of rapeseed and sunflower oil can be observed compared to water. For both vegetable oils, the viscosity decreases significantly with increasing temperature by about 98 % from about 63 mPa · s (at 20 °C) to 1 mPa · s (at 250 °C) (Figure 4).

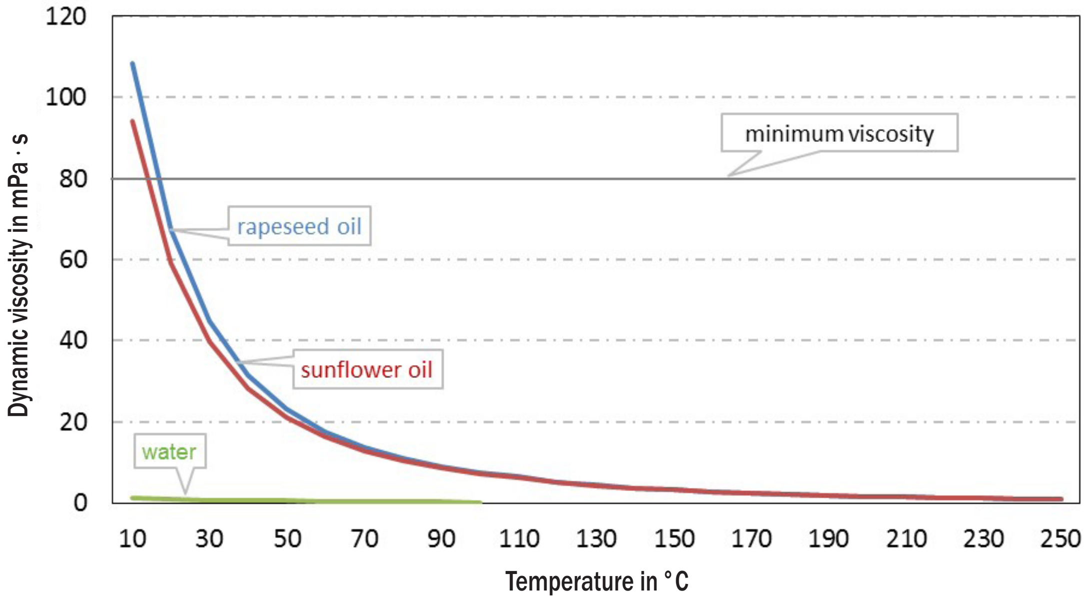



Figure 4: Viscosity-temperature diagram of water, rapeseed and sunflower oil

### Variable volumetric flow metering and determination of droplet energy

Experimental tests have shown that the selected vegetable oils can be heated to temperatures of up to 250 °C using the laboratory application device. The equipment of the peristaltic pump with a self-developed motor control unit allows to apply individual oil droplets in a reproducible manner in addition to a full jet without the use of a nozzle switching valve. During the generation of individual drops it was found that the oil droplets separated earlier from the nozzle tip with decreasing viscosity (temperature increase). By weighing single drops with a laboratory balance (Sartorius) at temperatures of 20, 100, 150, 200 and 250 °C and taking into account the respective density, average drop volume of 0.017 ml (at 20 °C) to 0.011 ml (at 250 °C) significantly decrease. As a result, 58 (at 20 °C) up to 90 drops (at 250 °C) can be generated from 1 ml of vegetable oil.

In addition to the drop volume, the amount of energy in a single drop has a significant influence on the success of the weed control. Considering the decreasing density, the delivered amount of thermal energy of a single droplet according to equation 1 is between 2.82 J ($\Delta T$ = 130 K) and 4.08 J ($\Delta T$ = 230 K). This amount of energy, which is applied to weed plants at room temperature (20 °C) can be transferred theoretically without taking into account the losses due to external influences.

### Development of application nozzles

In addition to the viscosity, the form of the application nozzle also has a significant influence on the dripping behavior of vegetable oils. In the development and experimental testing of different nozzle designs, an elongated nozzle (L > 10 mm) and a pointed nozzle shape with hole diameters between 0.2 and 0.3 mm proved to be particularly suitable for single drop formation with heated vegetable oil (No. 6, Figure 5). The heat loss is about 4 % (T = 250 °C) compared to a flat nozzle because of the elongated nozzle shape. With the help of detailed pictures of the high-speed camera, it can be shown that oil droplets drip off much worse by a short, flattened (No. 1, No. 2, No. 4, Figure 5) or concave application nozzle (No. 3, Figure 5) up to a second drop formation (Figure 6). In addition, these nozzle shapes favor an unintended „hike up“ of individual drops along the nozzle shaft towards the nozzle heater bottom and the formation of a local cumulative oil droplet, which drips off uncontrolled (Figure 7).

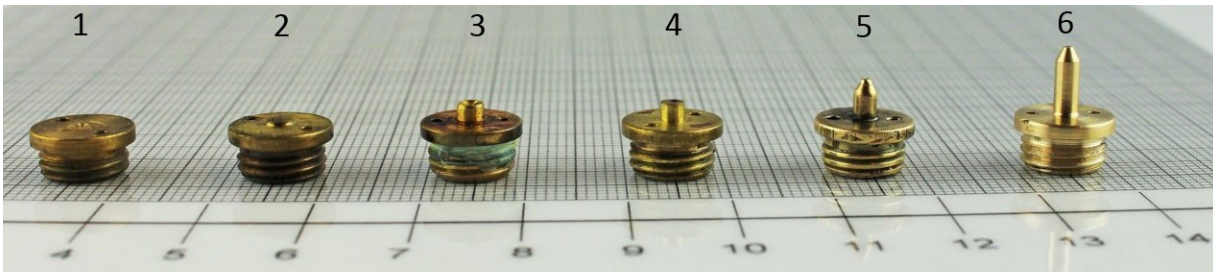



Figure 5: Development steps of a suitable application nozzle

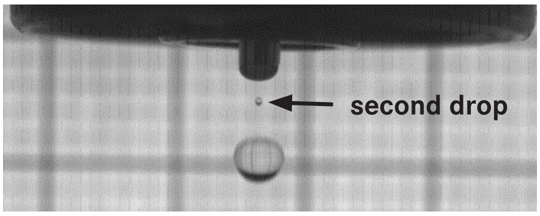
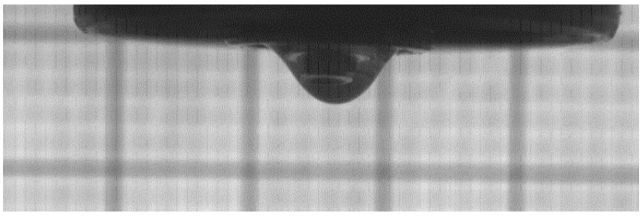



Figure 6: Short, concave nozzle with a second drop



7: Accumulation of an oil drop at the base of the nozzle heater

## Determination of the cooling behavior

Measurements with the infrared camera have shown that individual plant oil drops lose up to 70 % of their temperature after leaving the application nozzle as well as subsequently in free fall compared to their original temperature inside the nozzle heater. This is due to the low mass of a single oil droplet of about 0.009 g (T = 250 °C) with a comparatively large surface area of about 0.24 mm² in contact with ambient air. The drops cool down much faster on their surface than at the inner core.

For a successful, thermal weed control by protein denaturation, a heat transfer (T > 45 °C) must be carry out to the weed plant over a period of at least 2 seconds. The duration of the heat effect for lethal damage dependents on the liquid temperature and the plant size (Virbickaite 2006).

Figure 8 shows that a rapeseed oil droplet (blue graph) heated to 250 °C cools down to 80 °C on its way to the plant surface (drop height 15 cm, 20 °C ambient temperature), which coincides to a loss of approximately 68 % of its initial temperature. However, this temperature level is sufficient to damage the plant tissue over a period of about 12 seconds before the oil cools below 45 °C. This prevents further protein denaturation.

The red graph shows the cooling behavior of a rapeseed oil drop heated to only 100 °C. In free fall the drop loses about 40 % of its initial temperature which corresponds to 60 °C liquid temperature on the plant surface. At this temperature variant, the rapeseed oil can transfer plant-damaging heat energy for less than 6 seconds before the liquid temperature drops below 45 °C.

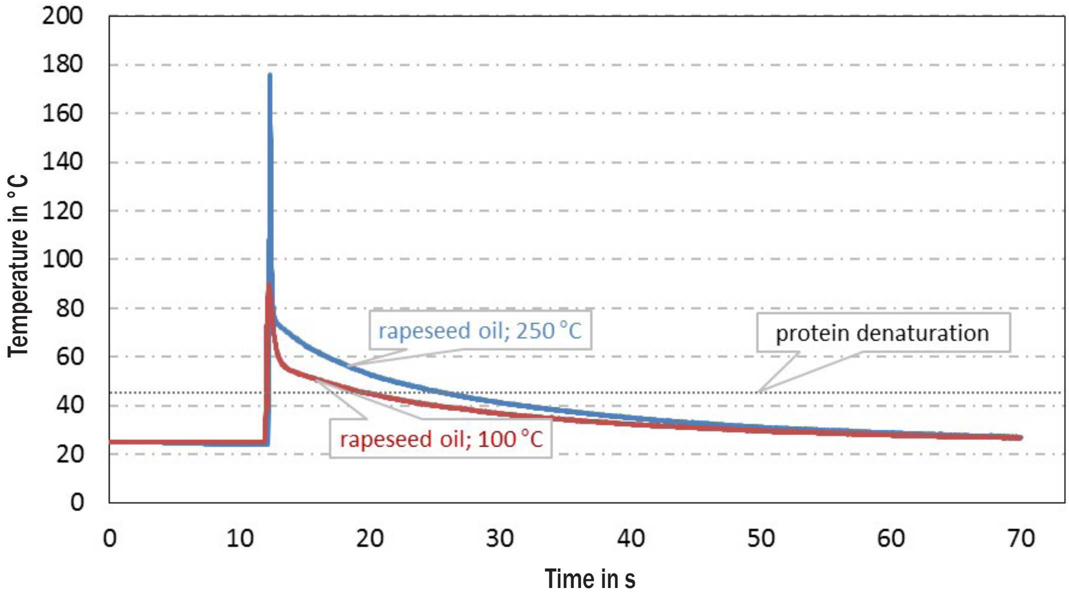



Figure 8: Cooling behavior of rapeseed oil (1 drop, 15 cm drop height)

Figure 9 shows the same test facility as in Figure 8, but with a 5-fold increased flow rate in the form of fast successive single drops. This leads to a significantly increasing temperature on the plant surface by a dropwise, increased input of heat energy. As a result of the summation of the single droplet energy, particular of the droplet core temperature, a delayed cooling process also occurs, which leads to a longer persistent and considerably more intensive plant damage.

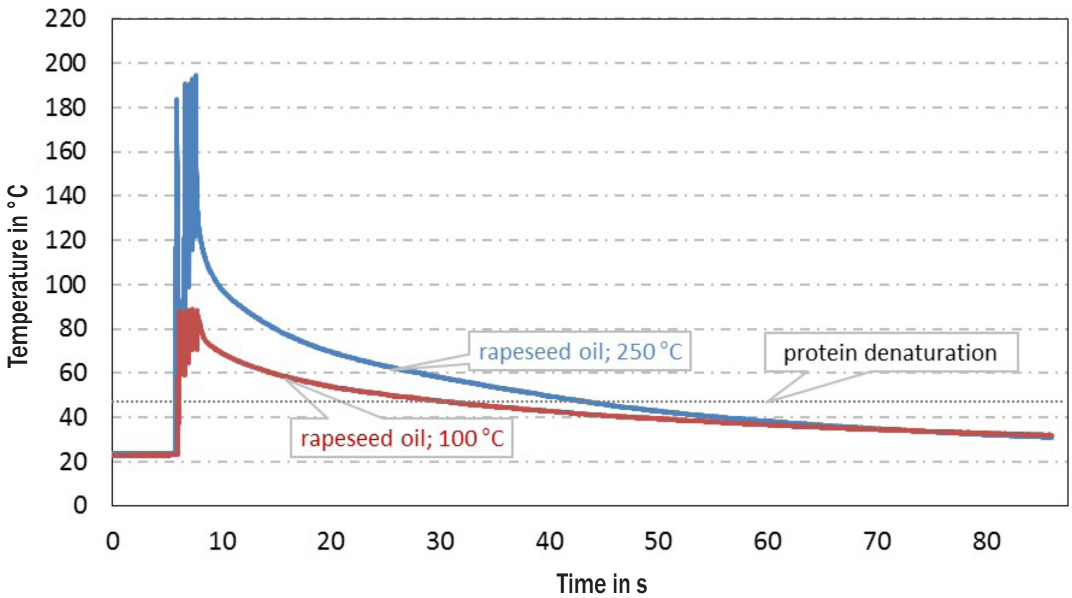



Figure 9: Cooling behavior of rapeseed oil (5 drops, 15 cm drop height)

At an initial temperature of 250 °C (Figure 9, blue graph), the temperature loss of the fifth drop is only 52 % until it hits the plant surface. It takes about 35 seconds before the oil temperature on the target surface falls below 45 °C. In contrast, the weed harmful residence time of vegetable oil at an initial temperature of 100 °C (Figure 9, red graph) with a loss of temperature in free fall of approximately 30 % is about 18 seconds.

## Conclusions

The laboratory application device developed at the Institute of Agricultural Engineering allows the heating of plant oils to temperatures up to 250 °C.
Experiments have shown that rapeseed and sunflower oil are particularly suitable for hot oil application because of their thermophysical, fluid-mechanical and economic properties. In order to compensate high temperature losses during the application of small amounts of liquid to weed plants, the oils must be heated to more than 150 °C. For this purpose decentralized heating by means of a nozzle heater directly before the nozzle is suitable. This nozzle should be as long and pointed as possible for dosing single drops without problems. With the help of an optimized control technique, liquid doses of 0.004 to 40 ml $min^{-1}$ can be accurately dosed with a peristaltic pump and applied to herbicides in a targeted manner. The use of an infrared camera also makes it possible to measure the temperature of the vegetable oil precisely in the free fall as well as on the plant surface.

In experimental laboratory tests, a clear link between oil volume and oil temperature could be established in relation to the duration of the heat effect. The assessment of the individual process costs can only take place after the acquisition of further findings. This is to show whether it is more advantageous to control weeds with low application rates and high temperatures or with high application rates and lower temperatures.

First experiments with characteristic, dicotyledonous weeds have shown that application to the growth center causes lethal plant damages and is therefore particularly suitable for a thermal weed control with hot oils. In the further course of this research project, agronomic examinations with various monocotyledonous and dicotyledonous arable weeds (green amaranth, rye-grass, dandelion, shepherd's-purse, cornflower, etc.) will clarify the influence of the oil quantity depending on the oil temperature and the drop height on the weed control success by a hot oil application. The focus of the study will be on the plant age (cotyledon, two-leaf, four-leaf stage) and the area of application (leaf area, stems, growth center). With the help of these findings, the entire process has to be evaluated with regard to its effectiveness and the fields of application in agriculture. In addition to the continuous optimization oft he laboratory test stand, this will be a major focus of further research work.

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