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Paper

# ANALYSIS OF WATERJET TREATMENT FOR HERBICIDE-FREE VEGETATION MANAGEMENT ON RAILWAY TRACKS

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## ABSTRACT

Vegetation management is essential for the functionality and operational safety of railway tracks. Because the approval of the herbicide glyphosate on railway tracks will expire by the end of 2022 in Europe, there is an urgent need for alternative vegetation management strategies. An eco-compatible alternative could be the use of pressurized water, possibly supplemented with abrasives, to substitute current herbicides. This study examines two different approaches of waterjet methods to remove plants from railway tracks, either by cutting or defibering the aerial parts of plants. Here, a range of plant species and infrastructure components (e.g., cable insulation) were processed at varying process parameters. Furthermore, the benefit of using garnet abrasive for enhanced plant damage was examined. The experiments revealed that, with an appropriate parameterization of the waterjet process, plants could be effectively damaged without affecting the surrounding infrastructure.

## 1. INTRODUCTION

Vegetation management is essential for the functionality of railway systems and safety of rail traffic. According to Section 4 (3) of the German General Railway Act (AEG) [1], railway operators must construct and maintain railway infrastructure safely. In the last decades, most countries within the European Union (EU) primarily used chemical leaf and soil herbicides to keep the track area free of plants and ensure the functionality of the track. Glyphosate is currently the most commonly used leaf herbicide for effective vegetation control [2]. In the EU, the approval of the active ingredient glyphosate for vegetation control on railway tracks will expire by 2023 [3, 4], so operators of railway infrastructure are under political, legal, and social pressure to find glyphosate-free alternatives for vegetation control [2, 5]. Meanwhile, some focus on replacing glyphosate with a potentially more socially acceptable chemical herbicide such as pelargonic acid. Others are trying to avoid the use of herbicidal agents in general and therefore increasingly look for non-chemical methods [2, 5].

The suitability of multiple methods for future vegetation control is currently being investigated. This study is part of the project “Development of an Alternative Method for Vegetation Control on Railway Tracks” of the German Centre for Rail Traffic Research (DZSF) at the German Federal Railway Authority (EBA) and is funded by the Federal Ministry for Digital and Transport (BMDV). The aim of the project is the basic development or adaptation of non-synthetic chemical or alternative methods in vegetation management on railway tracks. A method or combination of methods shall be integrated into a prototype vehicle that can be used to test applicability. Initially, 18 alternative measures to glyphosate-based vegetation control were selected and evaluated theoretically for their suitability for vegetation control on railway tracks.

One of the promising methods for vegetation control is the treatment with pressurized water. The use of pressurized water is known for surface treatment in urban and industrial areas [6–8], is applied industry-specific for cutting materials [9–11], and is used in the track for rail head cleaning [12]. Based on the current potential analysis, the technology can be used promisingly in combination with other mechanical and electrophysical processes [13].

In general, chemical-free methods have their advantages and disadvantages. However, the success of the chosen method depends strongly on its implementation and the boundary conditions of the application. Vegetation control with waterjets allows application at a remote distance from the plant. That could be beneficial here. For example, in an area close to the rails, the plants still could be treated, while methods using a ground-level applicator, such as machine weeding or electrophysical treatment, must maintain a certain distance to the infrastructure components. In addition, pressurized water causes only minor involvements of natural and biodegradable substances, such as water or abrasive. Therefore, mechanical methods, which include the action of the water jet, are considered non-toxic and can be used in water protection areas. [5].

We carried out pilot experiments to determine appropriate parameters for reliable vegetation management with waterjets on railway tracks. In a collaboration with the Fraunhofer Institute for Production Technology IPT, the Department of Plant Physiology (iPP – RWTH Aachen University), and the Institute for Rail Vehicles and Transport Systems (ifs – RWTH Aachen University), common plants on railway tracks and railway components were treated in a high-pressure waterjet machine to determine crucial parameters such as pressure, application distance and nozzle position. The implementation of the method was done with and without abrasive in comparison. A suitable parameter range for the water jet process must be found to damage the plants without simultaneously affecting the integrity of the railroad infrastructure.

## 2. METHODOLOGY

To evaluate the effectiveness of the waterjet on the plant structure, a specified setup of typical plants in combination with infrastructure components was processed using an industrial waterjet machine. An H.G.Ridder Type Waricut HWE P2030 5-axis AWJ machine tool was used for experiments (**Figure 1**). Originally designed to cut complex structures, the machine system is capable of water pressure of up to 600 MPa. The machining range of the X-Y-Z axes is 2050 mm x 3050 mm x 400 mm, with a maximum linear feed rate of 20 m/min. This machine is equipped with two individual AWJ heads, each of them configured by different kinematics and z-axis. The machining unit used for the experiments allows the C axis to be rotated by +/- 540 degrees and the B axis to be tilted +/- 95 degrees. A UHDE Type 6045 intensifier pump was used, capable of water pressure of 600 MPa at a flow rate of 2.8 l/min, powered by a 45-kW electric motor. All components of this machine system were controlled by a SIEMENS Type Sinumerik 840D SL CNC control unit. Here, the waterjet tool was configured with a provided injection-type waterjet head, so that either a standard injection abrasive waterjet (AWJ) or an injection-type plain waterjet (iPWJ) can be used by entraining abrasive or disrupting the abrasive flow into the mixing chamber. For all configurations, a 0.25 mm water orifice and a 0.76 mm focus tube were used.


**Figure 1.** Waterjet machine and arrangement of the specimen.

The experiments were conducted based on design of experiments (DoE) methods. In the parameter studies, three water pressure levels $p$ of 75 MPa, 150 MPa, and 300 MPa were investigated. It should be mentioned that the stand-off distance (SOD) of the AWJ nozzle over the specimen was adjusted to match the dedicated application. Here, the geometrical design of the track vehicle is limited to a distance of 300 mm above the ground [14]. Hence, the waterjet was applied at SODs of 100, 200, and 300 mm, respectively. This parameter pattern was carried out in two ways, once with and once without the addition of abrasive grit into the jet tool. Here, a garnet abrasive of mesh size #120 was used, entrained with a constant flowrate $\dot{m}_A$ = 200 g/min. The feed rate $v_F = 2000\ mm/min$ was set constant for this fundamental experiment, corresponding to a 1,2 km/h equivalent. Note, the last two factors were not varied further to make a fundamental decision regarding the subsequent system variant. Finally, the AWJ part was extended to an inclination angle of β = 45 deg in addition to the perpendicular β = 90 deg impact on the specimen surface. The design of the experiments primarily served to uncover requirements for further investigations, without neglecting the framework conditions of the subsequent application. **Table 1** gives an overview of the experiments, where the first number of the individual run represents the factor category that has been varied further to the three water pressure levels by the following letter.

**Table 1**. Parameters investigated

| Run | Water pressure $p$ [MPa] | Stand-off distance (SOD) [mm] | Abrasive mass flow $\dot{m}_A$ [g/min] | Inclination angle $\beta$ [deg] |
|---|---|---|---|---|
| Run 1 a | 75 | 300 | - | 90 |
| Run 1 b | 150 | 300 | - | 90 |
| Run 1 c | 300 | 300 | - | 90 |
| Run 2 a | 75 | 200 | - | 90 |
| Run 2 b | 150 | 200 | - | 90 |
| Run 2 c | 300 | 200 | - | 90 |
| Run 3 a | 75 | 100 | - | 90 |
| Run 3 b | 150 | 100 | - | 90 |
| Run 3 c | 300 | 100 | - | 90 |
| Run 4 a | 75 | 300 | 200 g/min | 90 |
| Run 4 b | 150 | 300 | 200 g/min | 90 |
| Run 4 c | 300 | 300 | 200 g/min | 90 |
| Run 5 a | 75 | 200 | 200 g/min | 90 |
| Run 5 b | 150 | 200 | 200 g/min | 90 |
| Run 5 c | 300 | 200 | 200 g/min | 90 |
| Run 6 a | 75 | 100 | 200 g/min | 90 |
| Run 6 b | 150 | 100 | 200 g/min | 90 |
| Run 6 c | 300 | 100 | 200 g/min | 90 |
| Run 7 a | 75 | 300 | 200 g/min | 45 |
| Run 7 b | 150 | 300 | 200 g/min | 45 |
| Run 7 c | 300 | 300 | 200 g/min | 45 |
| Run 8 | 150 | 200 | 200 g/min | 45 |
| Run 9 | 75 | 200 | 200 g/min | 45 |

A batch of individual workpiece materials represents a specimen that was processed for each parameter setup. First, the effect on the plant structure was determined with the aim of cutting or shredding parts of the individual plants with the water jet. Moreover, the effect of the primary or direct damage to the plant structure could lead to secondary damage by reduced biomass or height of the plants and possibly resulting in the death of the whole plant afterward. For this purpose, herbaceous (herb-Robert and ribwort plantain – stems 2-4 mm with leaves), grassy (upright brome – stems 2-3 mm), and partially woody plants (blackberry vines with an average diameter of 5 mm) were processed correspondingly. Second, typical infrastructure components from a railway track made of plastics were processed in analogy, because such materials are considered critical for waterjet application due to their softness. These were standard signal cables used in the track with a diameter of 20 mm and 32 mm, insulation of polyethylene, and a plastic cover made of 4 mm thick polypropylene [15].

For each run, the specimens were placed side by side on the test stand and processed in a single line for each parameter combination. All objects were removed, labeled, and analyzed visually. The evaluation includes measuring the cutting depth and the cutting width. In addition, the test plants were left to grow for one month to understand the post-effects of the treatment. A cause-effect analysis of the experimental section included the fatal losses of the complete plant or whether parts of the plant died or grew back.

## 3. RESULTS AND DISCUSSION

The study revealed that different results could be achieved on both the test plants and infrastructure components. Furthermore, the parameter range was limited where, on one hand, the plants were sufficiently damaged for vegetation control, and the infrastructure components were barely damaged on the other. The evaluation was conducted to find a fundamental waterjet configuration that allows effective damage to the plant structure while avoiding significant interference with the railway infrastructure components. It will serve as a basis for innovative approaches to vegetation management with water jets.

Results of iPWJ (no abrasive, $\beta = 90\ deg$)

When assessing the results achieved with the highest pressure level $p$ = 300 MPa, it was found to have a devastating effect on plants. In several runs, blackberry vines were cut off or received up to 3-mm-deep cuts in their bark. In addition, the stems of the remaining test plants were cut off completely. However, even at the highest SOD = 300 mm and without abrasive added, significant damage to the infrastructure components was obvious (**Figure 2**). Regarding the depth of cut and fraying of surface, the damage increased with the smaller SOD = 200 and SOD = 100 mm respectively.

From these results, it was concluded that a pressure level of $p$ = 300 MPa can be considered high for a corresponding application on the railway track. Due to the major damage, this factor level has been excluded from further experiments here. As an option, the highest pressure level could only be applied in track areas where cables, plastic covers, and components with similar hardness do not exist.


**Figure 2.** Results of $p$ = 300 MPa and SOD = 300 mm (no abrasive, $\beta = 90$ deg).
Left: plastic cover, middle: signal cable, right: blackberry vine.

A medium pressure level $p$ = 150 MPa damaged both blackberry vines at reduced distances (SOD = 200 and SOD = 100 mm, respectively) and the other test plants in a wide-ranging manner. However, the damage to the infrastructure increased at SOD = 200 mm (**Figure 3**) or below. Thus, for SOD = 300 mm or beyond, water pressure of 150 MPa seems to be adequate. At the same time, this distance should not fall below a minimum value of SOD = 200 mm in areas with infrastructure components.

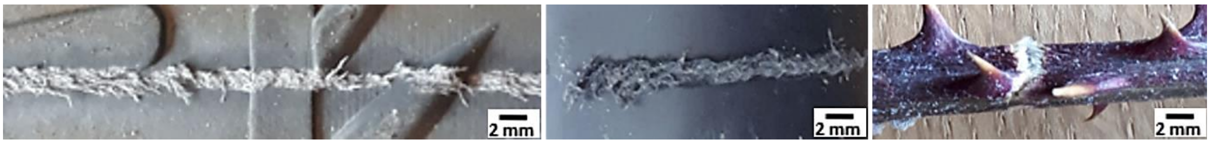


**Figure 3**. Results of $p$ = 150 MPa at a SOD = 200 mm (no abrasive, $\beta = 90$ deg). Left: cover, middle: signal cable, right: blackberry vine.

At the lowest pressure level $p$ = 75 MPa (**Figure 4**), almost no damage to the infrastructure was observed at SOD = 300 mm. With decreasing distance, the damage could be increased respectively. At SOD = 200 mm, the cable made of polyethylene was slightly damaged even at $p$ = 75 MPa, but the cover made of the harder polypropylene was virtually not damaged. At the closest SOD = 100 mm, more severe damage occurred, eroding the insulation of the cable or fraying the plastic of the cover. Here, the effect on blackberry vines was barely sufficient, so the damage was unsatisfactory at SOD = 200 and 300 mm correspondingly. As an intermediate conclusion of the lowest water pressure, cutting the blackberry vines (5 mm diameter) was limited to the closest SOD = 100 mm.

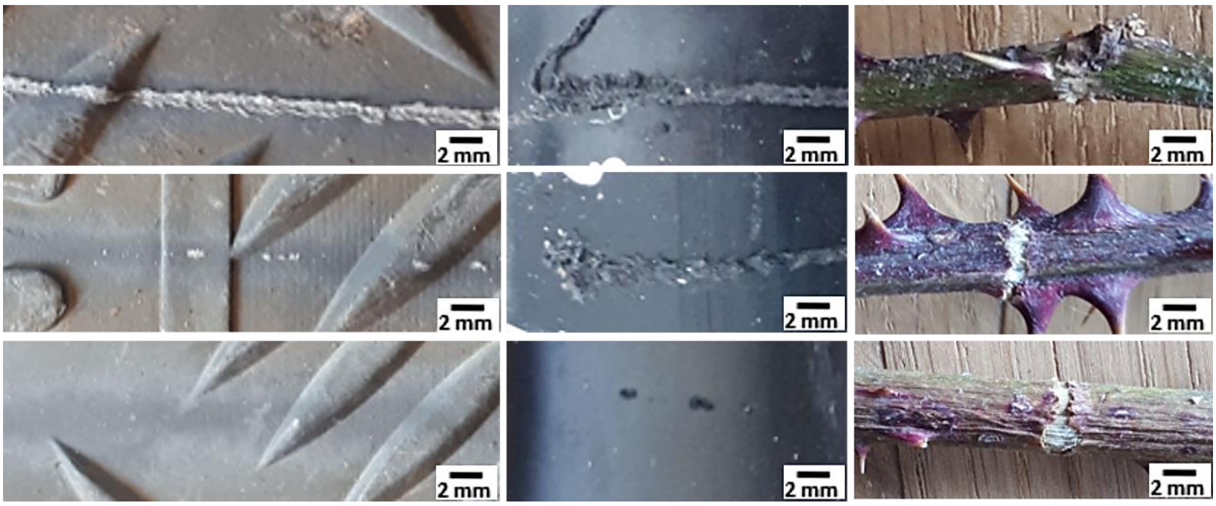


**Figure 4**. Results of $p$ = 75 MPa at a SOD = 100 mm (top), 200 mm (middle) and 300 mm (bottom) (no abrasive, $\beta = 90$ deg). Left: cover, middle: signal cable, right: blackberry vine.

Summarizing the achieved results of iPWJ without using abrasive, the damage of even herbaceous plants was apparent at pressure levels between $p$ = 75 and $p$ = 150 MPa. Noticeably, the damage to the plants occurred here by defibering or cutting off the leaves and stems. In a comparison between the medium pressure level $p$ = 150 MPa and the highest pressure level $p$ = 300 MPa, the latter does not lead to remarkable advantages. A rise in pressure is usually accompanied by increased consumption of resources, higher maintenance costs, and more expensive equipment. Comparatively, the factor SOD showed great potential for optimization. On one hand, the highest SOD = 300 mm was, in some cases, on the limit of destroying the plants completely. On the other, a SOD = 100 mm was too close not to damage the infrastructure components. Here, a pressure level of $p$ = 150 MPa can be seen as a maximum although the closest SOD = 100 mm initiated certain damage to the infrastructure components for all investigated pressure levels, e.g., by deep cuts or fraying of the insulation of the cables. Contradictory, for cutting woody plants such as blackberry vines, a small SOD = 100 mm may be necessary at the lowest pressure level. Herbaceous plants were processed sufficiently even at larger SODs. As an intermediate conclusion for iPWJ in vegetation control on railway tracks, the system should be capable of water pressure between $p$ = 75 and 150 MPa.

Results of perpendicular AWJ ($\dot{m}_A$ = 200 g/min, $\beta = 90\ deg$)

For the AWJ experiments, the same DoE as for the aforementioned tests was considered, according to **Table 1**. Here, the previously used iPWJ configuration was connected to an abrasive supply, so that a standard AWJ configuration was accomplished. In analogy to the iPWJ tests, a comparison of the effect on both the test plants and the infrastructure components was made to evaluate the use of an abrasive.

At the highest pressure level $p$ = 300 MPa, the occurred damage to the infrastructure components was different in comparison with iPWJ. Due to the interaction of the abrasive particles with the water jet, a larger area was interacted with. The effect changed from cutting or fraying to roughening or blasting of the surface, for an increased SOD. Especially at SOD = 100 mm, the damage was very severe, such that the material was heavily roughened and frayed (**Figure 5**). When processing blackberry vines, a similar roughening of the bark around the cut area was seen. The depth of cut ranged from 1 mm at SOD = 300 mm to 4 mm at SOD = 100 mm respectively. All other test plants were almost completely cut off or defibred at all SOD levels investigated. Similar to the industrial application of waterjets, the use of abrasive increased the cutting performance, in particular for the highest pressure level $p$ = 300 MPa. Here, damage was already severe after a single pass, meaning that multiple treatments could harm the infrastructure components fatally. Correspondingly, the highest pressure level $p$ = 300 MPa could only be used in areas without sensitive infrastructure components or where such components will be protected.

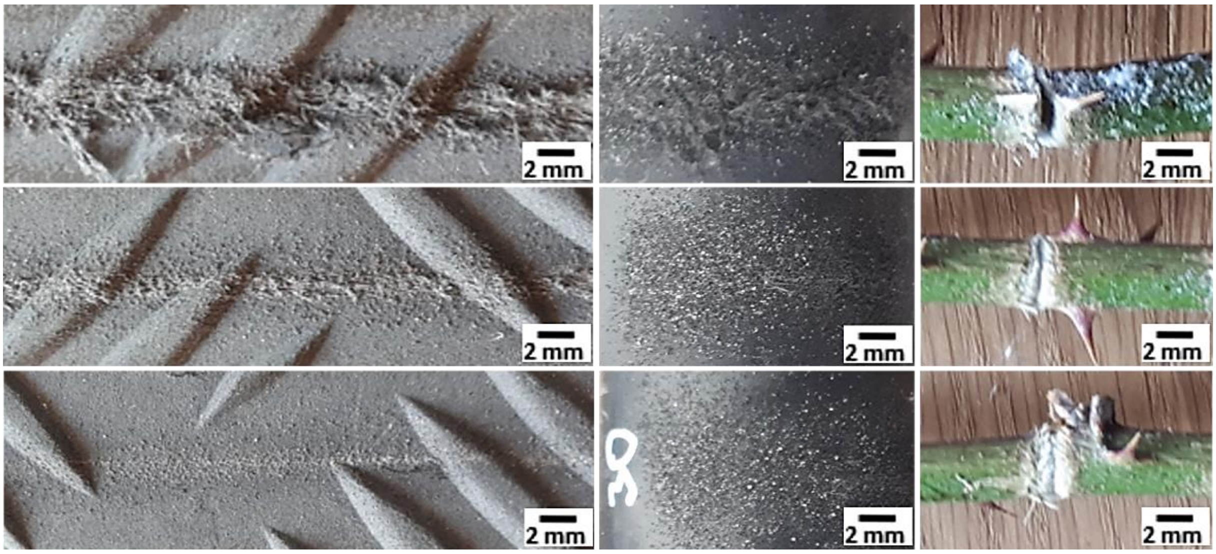


**Figure 5.** Results of AWJ (abrasive, $\beta = 90$ deg) at $p$ = 300 MPa and SOD = 100 mm (top), SOD = 200 mm (middle) and SOD = 300 mm (bottom)
Left: cover, middle: signal cable, right: blackberry vine.

At a pressure level $p$ = 150 MPa and SOD = 300 mm, it was shown that the damage to the infrastructure components decreased. Particularly with the polypropylene cover, barely any damage occurred on the surface. Only the surface of the cable showed roughening. However, the effect on blackberry vines also decreased. Thus, at $p$ = 150 MPa and SOD = 300 mm, only the bark was damaged (**Figure 6**). As the SOD level was decreased, the depth of cut increased to 4 mm, but the damage to the infrastructure components also become more evident. Most test plants were either cut or defibred at all distances.


**Figure 6.** Results of AWJ (abrasive, $\beta = 90$ deg) at $p$ = 150 MPa and SOD = 300 mm.
Left: cover, middle: signal cable, right: blackberry vine.

At a pressure level $p$ = 75 MPa, little damage to the infrastructure was observed at all three distances, and no damage was caused at this pressure even at a SOD = 100 mm (**Figure 7**). But these settings could no longer damage the blackberry vines sufficiently, so the bark was only roughened. Also, most of the test plants were defibred at all distances, but not completely cut off.

In sum, the results of the treatments with abrasive revealed that for herbaceous plants, like the experiments without abrasive, a pressure $p$ of 75 to 150 MPa effectively damaged the plants by crunching or cutting off. An increased pressure $p$ = 300 MPa did not bring an advantage concerning the damage to plants but increased the resources needed.


**Figure 7.** Results of AWJ (abrasive, β = 90 deg) at $p$ = 75 MPa and SOD = 100 mm.
Left: cover, middle: signal cable, right: blackberry vine.

The SOD level appears to be an important aspect, even when entraining abrasive. Similar to iPWJ, the highest SOD = 300 mm turned out to be not sufficient for all plants. However, the SOD = 100 mm was too close for infrastructure components with a pressure level above $p$ = 75 MPa, despite the better effect on the test plants. In comparison with the previous experiments achieved with iPWJ, the use of AWJ changed the results more to a roughening of the surface, even on the infrastructure components, but the leaves and stems of the plants also showed extensive damage coming from the abrasive interaction. Overall, it can be expected that more parts of the plants will dry out after treatment. When treating partially wooden plants such as mature blackberry vines, a narrow SOD = 100 mm would be necessary, but SOD can also be increased to cut or defibre herbaceous plants.

Results of inclined AWJ ($\dot{m}_A$ = 200 g/min, $\beta = 45\ deg.$)

In this last experiment, the nozzle was pitched at an inclination angle $\beta = 45\ deg$ at a constant SOD = 300 mm. In other words, the effective SOD was increased to achieve the influence of non-perpendicular jet impact within the geometrical limit of the envisaged test vehicle. The other parameters remain unchanged and abrasive was used. Focussing on the infrastructure components, **Figure 8** reveals that the damage could be decreased further in comparison with the foregoing results; only a slight roughening of the plastic cover and insulation was evident. Except at the highest pressure level $p$ = 300 MPa, where the damage was more severe, both the medium and lowest pressure levels lead only to a minor impairment of the insulation material.

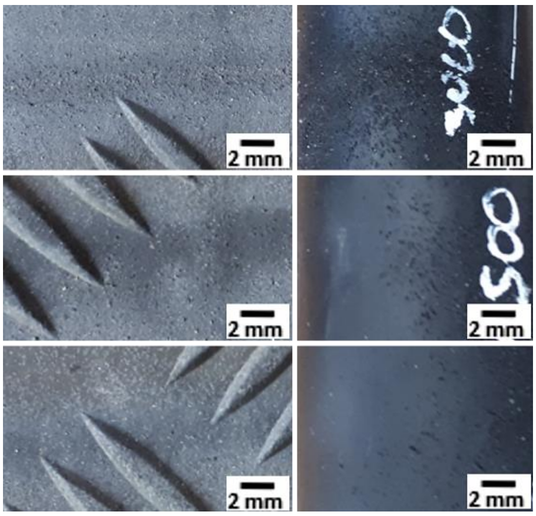


**Figure 8.** Run 7 (SOD = 300 mm, $\dot{\boldsymbol{m}}_{\boldsymbol{A}}$ = 200 g/min, $\boldsymbol{\beta} = \mathbf{45}\ deg.$):
Bottom $p$ = 75 MPa, middle $p$ = 150 MPa, top $p$ = 300 MPa. Left to right: cover and signal cable.

**Figure 9** showed the effect of AWJ at a minimum pressure level $p$ = 75 MPa, SOD = 200 mm and an inclination angle of the nozzle $\beta = 45$ deg. The effects shown here were on the test plants herb-Robert and ribwort plantain. Especially with these parameters, the effect of damage to the plants should be emphasized. The plant parts above the ballast were completely cut off, meaning the most severe damage to the plant. As can be seen in run 7 (**Figure 8**), the damage to the surface of the infrastructure components was reduced to a slight roughening of the surface. Thus, this combination of parameters showed the highest efficiency against damage to plants and at the same time only slight damage to infrastructure components. The inclination of the nozzle β = 45 deg obtained positive results because the damaging effect on plants increased due to the larger area covering the AWJ. The damage to the infrastructure components decreased because the impact is softened by the impact angle or the effective change in inclined SOD.


**Figure 9.** Run 8 and 9 (SOD = 200 mm, $\dot{\boldsymbol{m}}_{\boldsymbol{A}}$ = 200 g/min, $\boldsymbol{\beta} = \mathbf{45}\ deg$).
a+b: $p$ = 150 MPa (a: herb-Robert, b: ribwort plantain),
c+d: $p$ = 75 MPa (a: herb-Robert, b: ribwort plantain).

In analogy to the previous findings, the effective pressure range for vegetation control in railways tracks was estimated between a pressure level $p$ = 75 MPa and $p$ = 150 MPa for AWJ under $\beta = 45$ deg. Depending on the vegetation, the distance may be varied. For cutting thicker or partially woody plants a SOD of 100 mm is necessary, which could be increased in scenarios with little vegetation or smaller plants.

Revised parametrization range

The evaluation of the previous experiments was used to revise the waterjet parametrization range, as shown in **Table 2**. Combinations having unfavourable effects were crossed out. It also represents the evaluation of different combinations of parameters according to the damage to the infrastructure, meaning that the revision was focused on the factor levels of water pressure $p$.

**Table 2**. Overview of the revised parameters: Excluded pressure levels

| **Run** | **Water pressure $p$ [MPa]** | **Stand-off distance (SOD) [mm]** | **Abrasive mass flow $\dot{m}_A$ [g/min]** | **Inclination angle $\beta$[deg]** |
|---|---|---|---|---|
| Run 1 | 75 – 150 - ~~300~~ | 300 | - | 90 |
| Run 2 | 75 – ~~150~~ - ~~300~~ | 200 | - | 90 |
| Run 3 | ~~75~~ – ~~150~~ - ~~300~~ | 100 | - | 90 |
| Run 4 | 75 – 150 - ~~300~~ | 300 | 200 g/min | 90 |
| Run 5 | 75 – ~~150~~ - ~~300~~ | 200 | 200 g/min | 90 |
| Run 6 | 75 – ~~150~~ - ~~300~~ | 100 | 200 g/min | 90 |
| Run 7 | 75 – 150 - ~~300~~ | 300 | 200 g/min | 45 |
| Run 8 | 150 | 200 | 200 g/min | 45 |
| Run 9 | 75 | 200 | 200 g/min | 45 |

The highest pressure level $p$ = 300 MPa was completely excluded. The results showed that the damage to the infrastructure components was too severe and that the effectiveness on the plants did not increase much compared to 150 MPa. At a pressure level $p$ = 150 MPa and SOD = 200 mm or less, it will be necessary to check whether sensitive infrastructure components are located in the working area. In general, many of the test plants could be damaged by this pressure level. By entraining abrasive, the effect could also be intensified by roughening the plant surface. If thicker and partially woody plants are to be cut, the distance must be reduced accordingly. AWJ of a pressure level $p$ = 75 MPa may be used throughout the track, according to achieved results, as the damage to the infrastructure components was very low. The effectiveness on plants was mainly achieved with smaller and thinner plants, thus an early treatment time during the vegetation period should be chosen. For thicker plants or denser vegetation, the SOD should be reduced further.

Finally, an inclination angle $\beta =$ 45 deg of the nozzle was advantageous, because the tests showed that especially for dense vegetation the plants could be cut off quite well on the surface. Note that the effective length of the free-air jet was increased by $\sqrt{2}$ for inclined SOD, but the geometrical boundaries of the following prototype were considered. However, the cutting ability with thicker or partially woody plants decreased for $\beta =$ 45 deg.

## 4. CONCLUSION

In this study, a fundamental investigation was conducted experimentally. The aim was to design and prototype mobile equipment for waterjet treatment that can be tested on railway tracks. In the experiments, standard injection-type waterjet equipment was used to obtain crucial factors in both system and process parametrization and to maximize the potential of waterjets for vegetation management. Thus, an optimal pressure level, the use of abrasives, and the stand-off distance were of special interest for the prototype, in addition to the power supply and weight of the necessary equipment.

The experimental results identified a specific parametrization range for injection-type waterjets at a pressure level between $p$ = 75 MPa and $p$ = 1500 MPa, in which the plant specimens were damaged sufficiently, without affecting the considered railway infrastructure. The minimum pressure level $p$ = 75 MPa was promising when the SOD could be reduced. Beyond that, the pressure of 300 MPa caused severe damage to the infrastructure components, thus this high pressure level was excluded after evaluation.

In the future, this study will be extended toward an application on real-world railway lines. Here, it will be of special interest to consider annual (vegetational) seasons and the time frame when the plants could be treated best. To optimize the processing speed, an approach with multiple treatments could be promising. Further experiments will reveal how multiple treatments affect the condition of the infrastructure components and plants respectively. A longer observation of impacts and process optimization will be necessary to implement resource efficiency and sustainability.

## 5. ACKNOWLEDGMENTS

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## 7. NOMENCLATURE

| | |
|---|---|
| AWJ | Abrasive Water Jet |
| iPWJ | injection-type Plain Water Jet |
| EU | European Union |
| $\beta$ | Inclination angle |
| $\dot{m}_A$ | Abrasive mass flow |
| $p$ | Water pressure |
| SOD | Stand-off distance |
| deg | degree as unit of angle |
| kW | Kilowatt |
| MPa | Megapascal |
| mm | Millimeter |