TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 68, Issue I, March, 2025

DESIGN AND ANALYSIS OF A STEAM-BASED WEEDING MODULE FOR SUSTAINABLE AGRICULTURE

Mihai Dan ȘERDEAN, Florina Maria ȘERDEAN, Silviu-Dan MÂNDRU

Abstract: *Weed control is a critical aspect of modern agriculture, requiring sustainable and efficient solutions to minimize environmental impact while maintaining crop productivity. This paper presents the design and analysis of a steam-based weeding module with cover to be attached to an autonomous mobile platform, which delivers high-temperature steam at the soil surface to eliminate unwanted vegetation without the use of chemical herbicides. The module's 3D model and structural components are detailed, followed by a Finite Element Method (FEM) stress analysis to evaluate its mechanical reliability under operational conditions. The results confirm that the proposed system is robust and capable of withstanding maximum pressure stresses, offering an eco-friendly alternative to conventional weed control methods.*
Key words: *sustainable agriculture, steam-based weeding, eco-friendly weed management, Finite Element Method*

1. INTRODUCTION

The advancement of robotics and automation has significantly transformed agriculture, improving productivity and reducing labor costs. With growing demand for sustainable practices and stricter pesticide regulations, alternative eco-friendly weed control methods are increasingly sought after. Autonomous weeding solutions offer a promising approach by minimizing manual labor and environmental impact, contributing to more sustainable agricultural practices.

Among the available weed management approaches, sustainability is a key concern, as conventional techniques often pose challenges related to soil health, biodiversity, and resource consumption. To date, three primary methods have been employed in weed control: mechanical, chemical, and thermal approaches. Each of these techniques offers specific advantages and limitations, necessitating further refinement to maximize efficiency while minimizing ecological disruption.

Mechanical Weed Control. Mechanical weed removal involves the physical disruption of unwanted plants using rotating discs, blades, or rollers. This method is effective in reducing weed populations without relying on chemical inputs and there are a few good solutions [1], [2]. However, repeated mechanical interventions can lead to soil compaction, erosion, and loss of organic matter, ultimately affecting soil fertility and moisture retention [3], [4], [5]. Additionally, mechanical methods often struggle to eliminate deeply rooted weeds, requiring frequent applications that increase operational costs and energy consumption.

Chemical Weed Control. Chemical weed management, primarily through herbicide application, has been widely used due to its high efficiency and cost-effectiveness. However, excessive reliance on herbicides has raised serious environmental and health concerns. The widespread dispersion of these chemicals contaminates soil and water sources, reduces soil microbial activity, and contributes to the emergence of herbicide-resistant weed species [6]. Furthermore, studies have indicated that chemical weed control methods can negatively impact non-target organisms, disrupt ecological balances, and even contribute to climate change through the emission of greenhouse gases [7]. These concerns have led to stricter regulations

Received: 30.01.25; **Similarities**: 05.03.25: **Reviewed**: 24.02./25.02.25: **Accepted**:20.03.25.

on herbicide use, further driving the need for alternative solutions.

Thermal Weed Control. Thermal methods offer a promising alternative by using high temperatures to destroy weed tissues. Various thermal techniques have been explored, including steam, flame, and laser-based approaches, each with distinct operational mechanisms and environmental impacts.

- **Steam-Based Weeding:** Steam application is an emerging method that delivers high-temperature vapor directly to the weeds, causing their cells to rupture and leading to plant death. Unlike traditional flame-based techniques, steam does not produce direct CO_2 emissions, making it a more environmentally friendly option. However, most existing steam-based systems are primarily used for soil sterilization before planting rather than continuous plantation maintenance [8], [9], [10].
- **Flame-Based Weeding:** This method involves the application of direct flames to burn weeds, effectively destroying them through intense heat exposure. While efficient in eliminating unwanted plants, flame-based techniques require large amounts of fuel, increasing operational costs and contributing to CO_2 emissions [11]. Moreover, flame-based weeding poses fire hazards, particularly in dry and arid regions.
- **Laser-Based Weeding:** Laser technology has garnered research interest due to its ability to deliver concentrated energy to specific weed targets leading to the first agricultural devices equipped with such technology [12]. By precisely directing high-intensity laser beams onto weed stems, this approach can effectively eliminate unwanted plants without affecting surrounding crops [13], [14]. However, laser-based weed control presents several challenges, including the need for high-precision targeting systems, high energy consumption, and significant equipment weight, which can lead to soil compaction. Additionally, adverse environmental conditions such as high humidity can reduce laser efficiency, further complicating large-scale implementation.

Despite advancements in weed control technologies, existing solutions still present limitations in terms of sustainability, efficiency, and cost-effectiveness. Mechanical methods can degrade soil structure, chemical approaches raise environmental concerns, and thermal techniques require further refinement to optimize energy use and minimize unintended ecological impacts. In light of these difficulties, there remains a strong need for innovative, sustainable, and eco-friendly weeding solutions that balance efficiency with minimal environmental disruption.

The solution proposed in this article consists of a steam-based thermal weeding module designed for weed elimination, which can be attached to an autonomous mobile platform. This thermal weeding system operates at the soil surface by enclosing weeds with a cover, through which steam is delivered directly onto the plant, causing its elimination. The article focuses on the design and finite element analysis of a specialized steam module with a cover aimed at concentrating steam on unwanted plants.

2. STEAM-BASED WEEDING MODULE WITH COVER

2.1 Introduction

The necessity of developing a dedicated module for delivering steam on the soil surface is justified by the fact that, in certain situations, direct steam application to the weed roots is not essential. This aspect is particularly relevant for young and small weeds with shallow roots. In such cases, using a soil injection module may cause undesirable effects, such as disturbing the upper soil layer, especially when penetration does not reach the required depth for efficient steam distribution.

Moreover, since young weeds have underdeveloped and weak roots, they can be indirectly affected by the heat generated by steam applied to the soil surface. Thermal energy propagates through the weed stems, progressively destroying the structure of sensitive roots, even without direct contact. This property makes surface-applied steam highly effective for weeds in early growth stages, thereby reducing the need for invasive interventions.

Additionally, applying steam at the soil surface represents a valuable alternative for plantation maintenance, minimizing the impact on soil structure. This approach is particularly beneficial in intensively cultivated areas, as it reduces the risk of compaction and maintains optimal conditions for crop root development. Delivering steam through a cover that encloses the weed allows its elimination through exposure to high temperatures, destroying tissue structure without affecting cultivated plants.

Using this type of module significantly optimizes plantation maintenance, complementing the functionality of root injection modules. In hard or dry soil, where continuous use of injection nozzles may cause excessive wear, this module offers a practical and reliable alternative, reducing equipment strain. Furthermore, for smaller plantations or regular maintenance, applying steam at the soil surface is sufficient, as weeds do not have enough time to develop deep roots that require direct steam injection.

Thus, implementing a module for surface steam delivery provides a customized solution for plantation needs, enabling faster, more efficient, and sustainable maintenance. This method also leverages the heat propagation advantage through weed structures, affecting fragile roots even without direct intervention, making it ideal for controlling young and small weeds without compromising soil quality, crop health, or system performance. This approach aligns with the modernization and optimization requirements of precision agriculture.

2.2 3D Model of the Proposed Steam-Based Weeding Module with Cover

The 3D model of this steam weeding module was created in SolidWorks and is presented in fig. 1, while a section view can be seen in fig. 2. The proposed module utilizes a specially designed cover to concentrate and direct steam onto the weeds, ensuring a uniform and efficient distribution of heat at the soil surface. The system integrates multiple structural components, as detailed in fig. 3, each playing a specific role in optimizing the weeding process through exposure to high temperatures.

Fig. 1. 3D model of the proposed steam-based weeding module with cover.

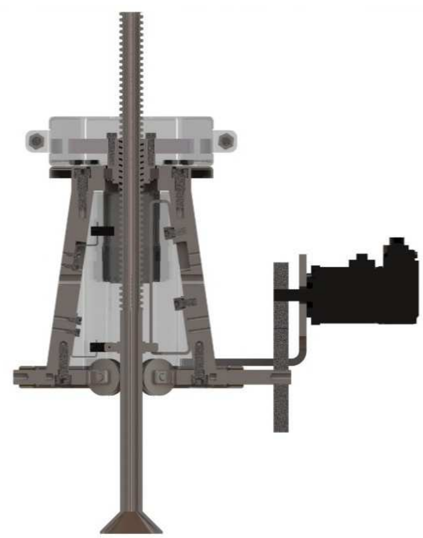

Fig. 2. 3D model of the proposed steam-based weeding module with cover – section view.

The base plate, consisting of two main components, the left support plate 12 and the right support plate 15, plays a crucial role in the structure of the proposed steam-based weeding module. It incorporates the central ring 13, on which the entire module is mounted, ensuring stability and balance.

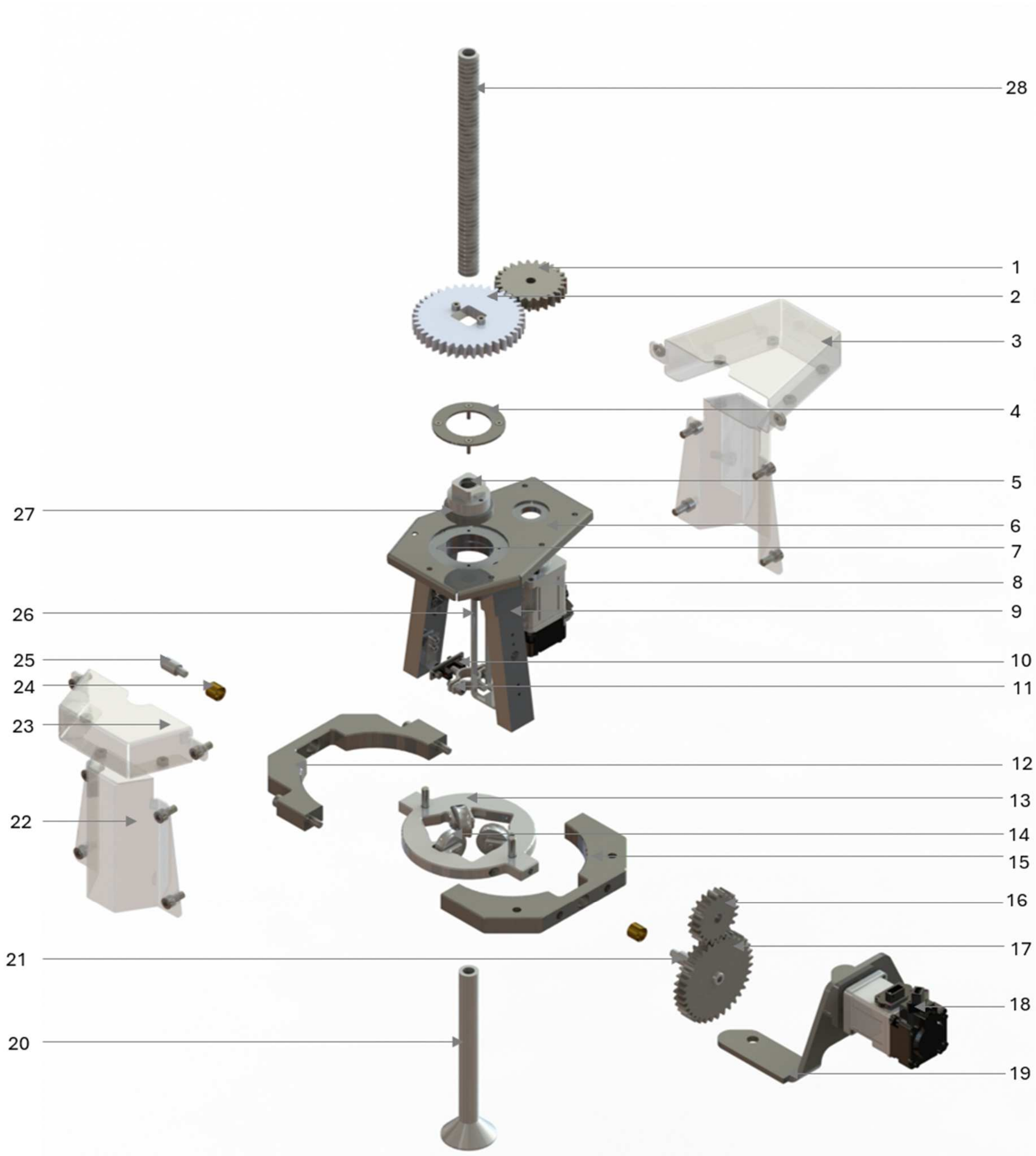

Fig. 3. 3D model of the steam delivery system at the soil surface - exploded view, where: 1 – Pinion; 2 – Driven gear wheel for vertical rod movement; 3 – Right cover; 4 – Circular cover; 5 – Special nut; 6 – Protection plate; 7 – Upper plate; 8 – Motor for controlling vertical rod movement; 9 – Support elements; 10 – Slotted optical switch; 11 – Circular element for detecting minimum and maximum positions; 12 – Left support plate; 13 – Central ring; 14 – Pipe guiding rollers; 15 – Right support plate; 16 – Pinion for module tilt angle adjustment; 17 – Driven gear wheel for tilt angle control; 18 – Motor for tilt angle adjustment; 19 – Motor support for tilt angle adjustment; 20 – Pipe with cover for steam direction; 21 – Shaft for supporting and rotating the driven gear wheel and central ring; 22 – Side cover; 23 – Left cover; 24 – Low-friction bushings; 25 – Shaft for supporting and rotating the central ring; 26 – Rotation restriction element for the pipe; 27 – Radial-axial bearing; 28 – Pipe with external trapezoidal thread.

The base plate not only indirectly supports all the module's components but also enables its attachment to the autonomous mobile platform, facilitating seamless integration and operation within the overall system. The vertical support element is composed of three main subcomponents but in a compact, adapted configuration: two inclined support legs 9 and an upper plate 7. The upper plate is essential as it secures the support legs in a correct and stable position, integrates the bearing 27, and provides support for the servo motor 8.

The upper plate 7 is fitted with the protective plate 6, which, together with the left side cover 23 and the right side cover 3, ensures complete enclosure and protection of the gear assembly. This mechanical assembly plays a crucial role in the system's operation, being responsible for the vertical movement of rod 28, which consequently enables the vertical displacement of the rod equipped with the cover 20.

The servomotor 8 is mounted directly on the upper plate 7, positioned at the rear of the module with cover. It is directly connected to pinion 1, which has 25 teeth. For the vertical movement of the rod, the driven wheel 2, which has 40 teeth, is used and is secured to the special nut 5 with two M4x16 DIN 912 screws. This nut has an internal trapezoidal thread TR 16x4 and is mounted on the upper plate 7 through bearing 27, ensuring precise rotation with minimal mechanical play. The gear assembly operates with a gear module of m=2, and the transmission ratio is 1.6, ensuring an optimal balance between speed and the force transmitted during the lifting and lowering process of the rod.

Above the upper plate 7, a circular cover 4 is mounted, serving to secure bearing 27 in a vertical position, thereby contributing to the stability of the mechanism. By rotating the special nut 5, the vertical movement of rod 28 is enabled, which features an external trapezoidal thread TR 16x4. This component is essential to the mechanism, having a cylindrical design and an internal bore that facilitates the passage of pressurized steam toward the exhaust section. The steam is then directed through the covered pipe 20, ensuring optimal thermal flow distribution over the weeds for efficient and uniform elimination.

The control of the lifting and lowering motion of the system is achieved through an encoder integrated into servomotor 8, allowing for precise monitoring and regulation of the rod's position. Additionally, to detect the extreme positions, both minimum and maximum, the module is equipped with slotted optical switches 10 of type OPB900-OPB913. These switches are activated by a circular element 11 mounted on the exterior of the covered pipe 20, which is responsible for directing the steam.

This system ensures that the rod does not exceed the maximum allowable position, preventing potential mechanical damage, while also guaranteeing that it fully retracts to its initial position before beginning a new weeding cycle for the next unwanted plant.

Additionally, the circular element 11 plays a crucial supplementary role. On the opposite side from the position detection function, it prevents the uncontrolled rotation of the covered pipe by being blocked by element 26, which restricts its rotational movement. This feature is essential as it ensures that the rod remains in a stable position throughout its vertical displacement, thereby preventing the twisting of the hose or the steam supply conduit connected directly to the upper end of rod 28, which could otherwise disrupt the system’s operation.

Component 20 is guided at the lower section, through three pipe guiding rollers 14, strategically arranged at a 120-degree angle. These rollers feature a concave profile through which the pipe passes, ensuring optimal stability and preventing potential blockages during operation.

An important advantage of the covered pipe 20 is that it can detach from component 28, allowing for quick and easy replacement. Moreover, the geometry of its final section can be customized according to the type of plantation and specific working conditions at the time of maintenance, thereby providing enhanced flexibility in usage.

To protect the internal components of the assembly, the lower section is equipped with two lateral covers 22, designed to effectively shield and safeguard the internal mechanism. These covers are secured using four M6 DIN 912 screws to the legs of the support element 9. In addition to their role in protecting against external factors, these covers also enhance operator safety during routine maintenance, reducing the risk of injury and ensuring safer handling of the system components.

The proposed covered weeding module offers the ability to tilt its upper section up to 25 degrees to the right and left (fig. 4). This feature significantly improves flexibility in operation and adaptability, allowing it to accommodate different plantation types and varying crop bed configurations.

Fig. 4. 3D model of the steam delivery system at the soil surface, in a rotated position

This angular movement is achieved through servomotor 18 (which can be similar or even identical to servomotor 8), directly connected to support 19 and pinion 16, which has 25 teeth. In turn, this drives the driven gear wheel 17, which has 35 teeth and a gear transmission ratio of 1.4. This configuration enables the precise orientation of the upper components, which are assembled onto the central ring 13.

In addition to supporting the central ring 13 and the driving gear wheel 17, the shaft 21 responsible for supporting and rotating the driven gear wheel, along with the central ring and the shaft 25, ensure the rotational movement of the central ring 13. This rotation is facilitated by low-friction bushings 24, which are mounted together with the shafts onto the base plate, thereby ensuring smooth and efficient system operation.

Through this tilting mechanism of the module’s upper section, including the pipe with cover, the module can be used together with a steam injection system at the weed roots in a much more efficient manner. This functionality allows for improved access to weeds in hard-to-reach positions or challenging soil conditions, thus providing enhanced versatility and adaptability to various types of agricultural terrain.

3. STRESS ANALYSIS WITH FINITE ELEMENT METHOD

The finite element method (FEM) was used for the key component of the steam-based plantation weeding module. The component that will be subjected to the highest stresses during operation due to steam pressure was identified as the pipe with cover and analyzed in detail.

The material used for the component analyzed with FEM is stainless steel 1.4016, chosen for its remarkable mechanical properties. It has a yield strength of 320 N/mm², ensuring structural stability under stress, and a tensile strength of 500 N/mm², providing excellent resistance to the tensions that may arise during the use of the module for weeding.

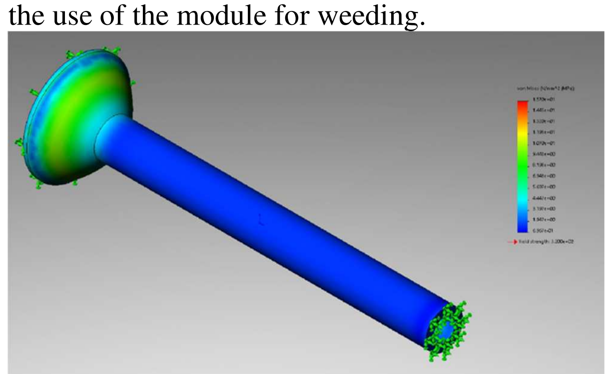

Fig. 5. Stress in the pipe with cover

In the FEM analysis, a reference parameter of 12 bar equivalent pressure was used for the analyzed element, corresponding to the maximum theoretical value to which a component can be subjected in this case. This value was chosen to assess the behavior of the pipe under the most challenging conditions, ensuring an accurate estimation of performance and structural behavior, particularly regarding stress distribution and potential deformations that may occur at this maximum pressure.

Regarding the von Mises stress analysis, the FEM results indicate values ranging from 6.967×10^{-1} N/mm² at node 8235 of the discretization to 1.570×10^{1} N/mm² at node 9745 of the discretization, with the highest values concentrated in the cover area. The maximum resulting displacement is 8.478×10^{-4} mm and, as expected, it also occurs in the cover, in the region with the highest stress concentration.

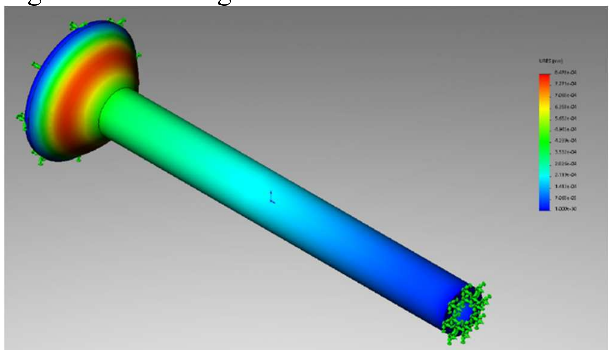

Fig. 6. Displacement in the pipe with cover

Following the FEM analyses conducted on the cover nozzle, a minimum safety factor of 20.38 was obtained at node 9745 of the discretization. This value indicates that the structure of the component is capable of withstanding the stress caused by maximum pressure, providing an adequate level of safety under the specified operating conditions. The obtained safety factor confirms the robustness and reliability of the design, demonstrating that the component will operate safely even under maximum stress conditions.

4. CONCLUSION

As agriculture moves toward more sustainable practices, there is a growing need for eco-friendly and autonomous weed management solutions, as existing methods—mechanical, chemical, and thermal—each present limitations that leave room for improvement.

The development of the steam-based weeding module with cover proposed in this paper represents a step forward in addressing these challenges. By delivering steam at the soil surface, this system effectively eliminates weeds without relying on chemical herbicides, reducing soil contamination and preserving biodiversity. The FEM stress analysis confirms that the module's structural integrity remains intact under operating pressures, ensuring long-term reliability. Future improvements could focus on optimizing energy efficiency, enhancing automation, and adapting the system for various crop types. The proposed solution contributes to the modernization of precision agriculture, aligning with global efforts to promote environmentally friendly and sustainable farming practices.

5. REFERENCES

[1] Mark Redbond, M. *Robots – The Future of Agriculture*, Special Feature – Application Technology, 2015. Available at: https://irtotrio.hu/wp-content/uploads/2020/11/IPC-Nov-Dec2015-final-lores.pdf.

[2] Andreas Schaefer, A. *Plant Robot "Bonirob"*, Available at: https://www.youtube.com/watch?v=utiNto4BeOg (last accessed 04.01.2025).

[3] Daniel C. Cloutier, D. C., Michel L. Leblanc, M. L. *Mechanical Weed Control in Agriculture*, in *Physical Control Methods in Plant Protection*, C. Vincent, B. Panneton, and F. Fleurat-Lessard (Eds.), Springer, Berlin/Heidelberg, 2001. doi: 10.1007/978-3-662-04584-8_13.

[4] Giacomo Tamburini, Silvia D. Simone, Michele Sigura, Francesco Boscutti, Lorenzo Marini, *Conservation tillage mitigates the negative effect of landscape simplification on biological control*, J. Appl. Ecol., ISSN 0021-8901, Hoboken, NJ, 2016. doi: 10.1111/1365-2664.12544.

[5] Dinesh K. Sharma, Shikha Tomar, Debashis Chakraborty, *Role of earthworm in improving soil structure and functioning*, Curr. Sci., ISSN 0011-3891, 113, 1064–1071, 2017. doi: 10.18520/cs/v113/i06/1064-1071.

[6] Tohid Rouhi-Kelarlou, Ahmad Golchin, Ali Ashraf Soltani Toularoud, *Ecotoxicological impact of butisanstar and clopyralid herbicides on soil microbial respiration and the enzymatic activities*, Chemosphere, Volume 357, 142029, ISSN 0045-6535, 2024, https://doi.org/10.1016/j.chemosphere.2024.142029.

[7] Christine M. Cornish, Olivia F. Johnson, Sheel Bansal, Jacob A. Meier, Ted D. Harris, Jon N. Sweetman, *Common use herbicides increase wetland greenhouse gas emissions*, Science of The Total Environment, Volume 933, 172881, ISSN 0048-9697, 2024,

https://doi.org/10.1016/j.scitotenv.2024.172881.

[8] Andrea Peruzzi, Michele Raffaelli, Marco Ginanni, Marco Fontanelli, Christian Frasconi, *An innovative self-propelled machine for soil disinfection using steam and chemicals in an exothermic reaction*, Biosystems Engineering, Volume 110, Issue 4, Pages 434-442, 2011, ISSN 1537-5110, https://doi.org/10.1016/j.biosystemseng.2011.09.008.

[9] Michele Raffaelli, Luisa Martelloni, Christian Frasconi, Marco Fontanelli, Stefano Carlesi, Andrea Peruzzi, *A prototype band-steaming machine: Design and field application*, Biosystems Engineering, Volume 144, Pages 61-71, 2016, ISSN 1537-5110, https://doi.org/10.1016/j.biosystemseng.2016.02.001.

[10] Zhen Yang, Xiaotao Wang, Mohammad Ameen, *Influence of the Spacing of Steam-Injecting Pipes on the Energy Consumption and Soil Temperature Field for Clay-Loam Disinfection*, Energies, Volume 12, 3209, 2019. https://doi.org/10.3390/en12173209.

[11] Erik Sivesind, Michel Leblanc, Daniel Cloutier, Philippe Siguin, Kevin Stewart, *Weed response to flame weeding at different development stages*, Weed Res., Volume 23, Pages 438–443, 2009. doi: 10.1614/WT-08-155.1.

[12] *Laserweeder from Carbon Robotics*, https://carbonrobotics.com/laserweeder, accessed on 04.01.2025.

[13] Thomas Heisel, Jens Schou, Christian Andreasen, Søren Christensen, *Using laser to cut and measure thickness of Beta vulgaris L. and Solanum nigrum L. stems*, Weed Res., Volume 42, Pages 242–248, 2002. doi: 10.1046/j.0043-1737.2002.00282.x.

[14] Thomas Heisel, Jens Schou, Søren Christensen, Christian Andreasen, *Cutting weeds with CO2 laser*, Weed Res., Volume 41, Pages 19–29, 2001. doi: 10.1046/j.1365-3180.2001.00212.x.

Proiectarea și analiza unui modul de erbicidare cu abur pentru agricultura sustenabilă

Rezumat: Controlul buruienilor este un aspect esențial al agriculturii moderne, necesitând soluții sustenabile și eficiente pentru a minimiza impactul asupra mediului, menținând în același timp productivitatea culturilor. Acest articol prezintă proiectarea și analiza unui modul de erbicidare cu abur și clopot, destinat a fi atașat unei platforme mobile autonome, care livrează abur la temperatură ridicată la suprafața solului pentru a elimina vegetația nedorită, fără utilizarea erbicidelor chimice. Sunt detaliate modelul 3D și componentele structurale ale modulului, urmate de o analiză a tensiunilor prin Metoda Elementului Finit (MEF) pentru a evalua fiabilitatea sa mecanică în condiții de funcționare. Rezultatele confirmă că sistemul propus este robust și capabil să reziste solicitărilor cauzate de presiunea maximă, oferind o alternativă ecologică la metodele convenționale de combatere a buruienilor.

Cuvinte cheie: *agricultură durabilă, plivire pe bază de abur, gestionarea ecologică a buruienilor, metoda elementelor finite*

Mihai Dan ȘERDEAN, PhD. Student, Technical University of Cluj-Napoca, Department of Mechatronics and Machine Dynamics, Mihai.Serdean@mdm.utcluj.ro.

Florina Maria ȘERDEAN, Assoc. Prof. PhD. Math., Technical University of Cluj-Napoca, Mechanical System Engineering Department, Florina.Rusu@omt.utcluj.ro.

Silviu-Dan MÂNDRU, Prof. PhD. Eng., Technical University of Cluj-Napoca, Department of Mechatronics and Machine Dynamics, Dan.Mandru@mdm.utcluj.ro.