Patents on plasma treatments in agriculture

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ABSTRACT

Patents in the field of plasma agriculture are analyzed in this paper. The first patent application in this technological niche appeared in 1995 and disclosed a method for seed treatment using non-equilibrium gaseous plasma. Since then, over 60 patents were filled in different countries, representing about 7% of published scientific papers in journals indexed by the Web of Science. About half of the patent applications were submitted to the Russian office, followed by Chinese, US, and Korean offices. Five or six patent applications have been submitted annually in the past few years. No Slovenian application has been registered so far.

Keywords

Plasma, agriculture, patent, search

1. INTRODUCTION

Plasma agriculture is among the most promising fields of scientific research and industrial developments. It is an interdisciplinary niche where non-equilibrium thermodynamics meets farming and food industry. There are hundreds of research groups currently involved in developing plasma techniques to treat seeds, plants, crops, storage and packaging devices, food, and feedstock. Many are academic, and they are concentrated on chemical and biological modifications caused by plasma treatment. Some groups have studied the influence of plasma treatment on germination and growth of plants. Few groups have also performed field experiments and studied the role of plasma parameters on the amount and quality of crops. Indirect treatments are popular, too. In such cases, either water for spraying or watering plants is treated by gaseous plasma or soil is treated. The influence of plasma processing on the water-soaking capacity or microbiological picture is studied.

2. PLASMA SEED PROJECT

The project is focused on the development of methods for seed treatment and lasts about 3 years. The following partners are involved in developing a device suitable for treating seeds in the continuous mode: Interkorn Ltd. (Beltinci), Department of Surface Engineering, Jožef Stefan Institute (Ljubljana), Trac Ltd. (Šentjernej), Žipo Lenart, National Laboratory of Health, Environment and Food (Maribor), and Institute of Agriculture and Forestry (Maribor). The project coordinator, Interkorn Ltd., is the largest provider of seed coatings in Slovenia. It provides processing of seeds from separation to cleaning and deposition of various coatings. Processed seeds are further distributed among farms. Quality control and ecological production are among the company's priorities. The company produces and treats seeds of corn, wheat, barley, other cereals, and soybeans. The treatment of seeds is performed on an automated line, which allows for a high quality of processing and traceability of seed batches. It has almost 100 regular customers who provide feedback about harvesting and storage. The company has specialized in treating seeds to protect them against fungi (molds), worms, and birds to enable optimal harvesting. The unique coatings are adopted for use in the west Pannonia region, which has specific climate and soil conditions and ecosystem. The company also provides services for seeds' treatment before storage to minimize the proliferation of molds, which may produce toxins that are harmful to humans and animals. The scientific coordinator is Dr. Nina Recek, a researcher of the Department of Surface Engineering at Jozef Stefan Institute. Other project partners are involved in research

on plasma-seed interaction and development of different components for a prototype of the line, which will be used to treat various seeds in the continuous mode. The goal of plasma treatment is to disinfect seeds and improve water uptake and, thus, faster germination as compared to untreated seeds.

3. LITERATURE SURVEY

3.1 Scientific papers

Over 900 scientific papers have been published in journals ranked in the Web of Science. At the time of writing this document, 23 papers are highly cited in the field – received enough citations as of March/April 2020 to place them in the top 1% of their academic fields based on a highly cited threshold for the field and publication year. One paper is labeled as "hot paper" – such papers were published in the past two years and received enough citations in March/April 2020 to place them in the top 0.1% of papers in its academic fields. The majority of these papers deal with scientific aspects, but some also report experiments in the fields. The number of papers rewarded with "highly cited in the field" for the past decade is presented in Figure 1.

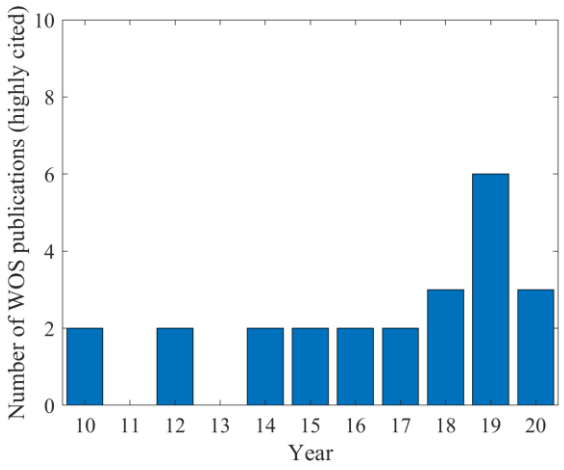

Figure 1: Number of highly cited papers in the field published in the last decade.

The number of scientific papers published in journals indexed by the Web of Science for the past decade is plotted in Figure 2. One can observe a graduate increase in the published papers. The number of papers published per year has tripled in the last decade, which indicates the scientific importance of the interdisciplinary field of plasma agriculture.

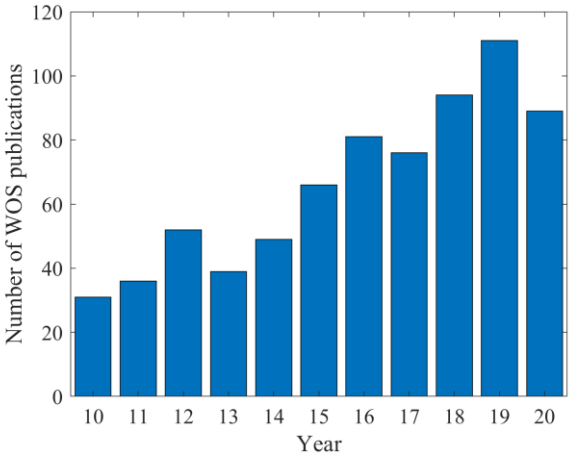

Figure 2: Number of scientific papers published in the past ten years in plasma agriculture.

3.2 Patent applications

While the number of scientific papers indicates the scientific importance of the subject, technological importance is revealed from the patents applied at various patent offices worldwide. The first patent in the field of plasma agriculture indexed in the ecpacenet database has the priority date 1995-07-05 [1]. The patent by Filippov, Bitjutskij, and Fedorov discloses a method for pre-sowing seed treatment. The method provides plasma treatment of seeds with low discharge intensity and pressure of inorganic gas, resulting in increased nutritive value of products and reduced power consumption. Since this pioneering work, numerous patents have appeared. Figure 3 represents the number of patents filed per year. The number is slowly increasing. By the time of writing this paper, as many as 67 patent applications appeared in the database. One of the last applications was also Russian [2]. Disclosed is a method for grain disinfection, which involves exposure of the treated grain to a stream of cold plasma at atmospheric pressure. Cold plasma flow is generated due to negative corona discharge between anode and cathode with pulsed voltage in air. Grains with the moisture content of 7-14% are placed on the anode surface and treated for 10 minutes. According to the authors [2], the invention provides a stable disinfecting effect when processing grain (for food and sowing) intended for storage.

Russian inventors are particularly active in filing patent applications in the field of plasma agriculture. Figure 4 reveals the number of patent applications submitted to patent offices in different countries. The Russian office received as many as 33 applications. Next on the graph is the Chinese office with 20 applications, followed by the US office (6 applications) and the Korean patent office (3 applications). Other patent offices received only one application each.

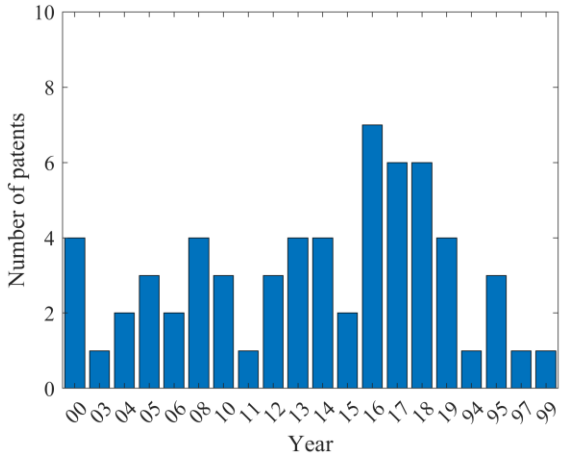

Figure 3: Number of patent applications registered in the Espacenet database.

Of particular importance are patents on the indirect treatment of seeds, usually treating a liquid by gaseous plasma and then soaking seeds in plasma-treated liquid. For example, RU2702594 (C1) [3] discloses a method of activating water or aqueous solutions. The method involves exposing a particular volume of treated water or aqueous solutions to plasma. Contactless activation is carried out. Water or aqueous solutions are exposed to a continuous electrodeless plasma flame created by a UHF-plasmatron, which generates a low-temperature plasma jet in a vapor-gas medium at atmospheric pressure. Device for contactless plasma activation of water or aqueous solutions contains a flame UHF-plasmatron with a capacitive coupling, which includes a magnetron and rectangular as well as coaxial waveguides. The coaxial waveguide is hermetically isolated from the rectangular waveguide by a radio-transparent quartz tube-insulator. The central conductor of the coaxial waveguide is a copper tube configured to supply plasma-forming gas and ends with a nozzle with a hole to form a directed jet of plasma-forming gas. The working part of flame UHF-plasmatron is placed through the seal into a sealed chamber containing a vessel with treated water or water solution fixed on a rod-elevator. The invention provides contactless plasma activation of water or aqueous solutions, enables the exclusion ingress of electrode material into the activated liquid, and provides a high degree of purity of treatment and safety.

A similar device useful not only for water treatment is disclosed by Hummel et al. in the patent application submitted to the US Patent Office [4]. Here, methods and systems for generating a plasma-activated liquid or gas and applying the plasma-activated liquid for agricultural use are disclosed. A system embodiment includes a hand-held device that can be pointed and directed at different target areas of a plant. A method embodiment includes generating a plasma discharge in a gas environment or a liquid environment and applying the gas or liquid to a plant.

Another method for plasma treatment of water is disclosed by Rothschild [5]. The invention generally concerns a machine that creates and infuses charged air products into a flowing water system. A plasma discharge is not in direct contact with the flowing water but is separated from the plasma by a void volume space. The resulting activated water may be used as an industrial wash, antibacterial wash, a medicinal drink, or can be used in agriculture, e.g., for irrigation of crops, plants, or seed treatment.

Nevertheless, another method for the treatment of liquids by gaseous plasma is disclosed by Chieh [6]. An agriculture plasma liquid apparatus includes an inlet pipe, an outlet pipe, an air inlet port, and a plasma liquid generating device. The diameter of the inlet and outlet pipes is rather large. The plasma liquid generating device is connected to the air inlet port to suck air from the air inlet port, communicates with the inlet pipe and the outlet pipe to import liquid flow from the inlet pipe and generate plasma particles into the liquid flow outputting through the output pipe. This solution is useful since many bubbles are formed within the innovative device, so the contact area between gaseous plasma and liquid is large compared to standard solutions.

A more powerful device for the treatment of water with gaseous plasma is disclosed by Lu et al. [7]. The utility model discloses a high-temperature thermal conductance water plasma generation system. Its structure includes high-temperature thermal conductance water plasma generator group, waterway system, and thermal energy system. The central part of the high-temperature thermal conductance water plasma generator is a high-temperature heat pipe, including an inner tube and urceolus. The high-temperature heat transfer medium is mounted between the inner tube and the urceolus at the bottom. The waterway system constitutes a water tank, filter, high-pressure unfamiliar water pump, solenoid valve, and hot water tank. The thermal energy system includes an oil tank, a high-pressure oil pump, an oil flow control valve, a fuel nozzle, and an electronic ignition wire that gradually connects. The high-temperature thermal conductance water plasma generation system causes water decomposition, so the water is transformed into a gaseous plasma rich in hydrogen and oxygen. The device is very efficient. According to inventors, more than 90% of water passing the device is converted. This device can extensively be used for engines, industry and civil boilers, agriculture, chemical industry, and even medicine, as claimed by the authors.

Rocke and Wandell disclose a simultaneous on-site production of hydrogen peroxide and nitrogen oxides from air and water in a low power flowing liquid film plasma discharge for use in agriculture [8]. A reactor system that includes a single reactor or a plurality of parallel reactors is disclosed. A method that includes: injecting a mixture including liquid water and gas into at least one electrically-conductive inlet capillary tube of a continuously flowing plasma reactor to generate a flowing liquid film region on one or more internal walls of the continuously flowing plasma reactor with a gas stream flowing through the flowing liquid film region, propagating a plasma discharge along the flowing liquid film region from at least one electrically conductive inlet capillary to an electrically conductive outlet capillary tube at an opposite end of the continuously flowing plasma reactor, dissociating the liquid water in the plasma discharge to form a plurality of dissociation products, producing hydrogen peroxide and nitrogen oxides from the plurality of dissociation products. Both nitrogen oxides and hydrogen peroxide are useful for the sterilization of agricultural products in an ecologically benign manner.

Go and Lim [9] presented an invention related to a plasma generator for agriculture and stockbreeding. The plasma generator comprises a pair of main bodies, disposed of in an upper portion and a lower portion with a predetermined gap between, a plurality of electrode rods, installed in a direction perpendicular to the pair of main bodies and evenly spaced, an electrode plate installed in a direction perpendicular to the pair of main bodies installed behind the plurality of electrode rods with a predetermined gap between, an electrode sheet disposed on the electrode plate spaced apart from the plurality of

electrode rods with a predetermined gap between, configured to generate plasma due to a reaction between a plurality of electrode rods and current, and an insulating plate interposed between the electrode sheet and an electrode terminal provided on the electrode plate to prevent moisture from being introduced into the electrode terminal. The plasma generator produces reactive gaseous species and radiation in the ultraviolet and vacuum ultraviolet range of wavelengths, which was found beneficial for sterilization or at least disinfection of different products.

Lee [10] invented a technique for sterilization of water using gaseous plasma technology. The invention relates to a water sterilization device for agriculture and fishery having a variable plasma device that reduces the costs of production by simplifying an existing plasma generating device. It also raises the productivity of agriculture and fishery and enables the use of seawater and freshwater for agriculture and fishery by properly sterilizing harmful bacteria existing in the seawater and freshwater by controlling the quantity of plasma through frequency variability. The water sterilization device for agriculture and fishery having a variable plasma device according to the present invention comprises a power supply device for supplying power necessary for the device, a water pump for receiving power from the power supply device and introducing water, a variable plasma generating device for sterilizing water being introduced from the water pump by generating plasma and controlling the strength of generated plasma by controlling the frequency of power supplied, a first connection pipe having one side intercommunicating with the water pump and the other side intercommunicating with the variable plasma generating device, a sterilized water storage tank for storing water sterilized and discharged by the variable plasma generating device, a second connection pipe having one side intercommunicating with the variable plasma generating device and the other side intercommunicating with the sterilized water storage tank, a pollutant and foam discharge device installed on the top of the sterilized water storage tank to discharge foam and ozone, and a sterilized water discharge hole installed on the bottom of the sterilized water storage tank to discharge sterilized water in the sterilized water storage tank.

Liu et al. disclosed a method for improving the germination of Stevia rebaudiana seeds. The method relates to a crop seed treatment technique in the technical field of agriculture. The method comprises the following steps: selecting and sterilizing seeds, preparing 6 to 8% aqueous solution of polyethylene glycol, soaking seeds into the prepared solution at the temperature between 20 and 30 °C for 24 to 48 hours, then filtering seeds, cleaning seeds by using clear water, and airing seeds for later sowing. It is generally recognized that molecules of the polyethylene glycol can change biological membrane structures of various cells in cell engineering, in a way that lipid molecules on a plasma membrane at a contact point of two cells are dispersed and recombined. These molecules can also change the osmotic regulation capability of plants, influence on plant physiology and are favorable for absorbing nutrition and inducing the activity of stimulation cells. The method can remarkably improve the capability of resisting adverse situations when the Stevia rebaudiana seeds are germinated so that these seeds still maintain a higher germination rate and germination energy in adverse situations.

As early as in 2007, Russian inventors disclosed a technique for treating fruit [12]. The processing and storage of fresh-cut vegetables, berries, fruits in agriculture, food-processing, and related branches of industry is disclosed. The method involves washing fruit and vegetable products with water preliminarily activated in one or two electrode chambers of one or more diaphragm-type electrolysis units. Further removing water remained on the surface of products after the washing process by blowing with the use of gaseous plasma flow until complete removal of water is achieved. Plasma is produced in a medium of inorganic gas or a mixture of inorganic gases at a frequency of electromagnetic field of 4-40 MHz and at specific electromagnetic power of plasma discharge. Apparatus has at least one washing chamber, one drying chamber, one or more transportation mechanisms, one or more diaphragm-type electrolysis units with power sources, a plasma source with two electrodes, a plasma guide, a high-frequency generator, one or more reservoirs for inorganic gas, and vacuum oil-free pump. The effect of this method is prolonged shelf life of fruit and vegetable products.

The search for patents, as presented in this document, indicates that both direct and indirect plasma treatment result in a good finish of agricultural products. The indirect plasma treatment has a definitive advantage that treated material is preserved since the products are exposed to radicals only (not to powerful gaseous discharges). On the other hand, direct plasma treatment is faster since the concentration of reactive species within the plasma is, by definition, more substantial than in any medium treated by plasma. The users can choose between these two extremes or use a combination of direct and indirect treatment. In such a case, the liquid can be treated with a powerful discharge, while products are exposed to mild plasma conditions.

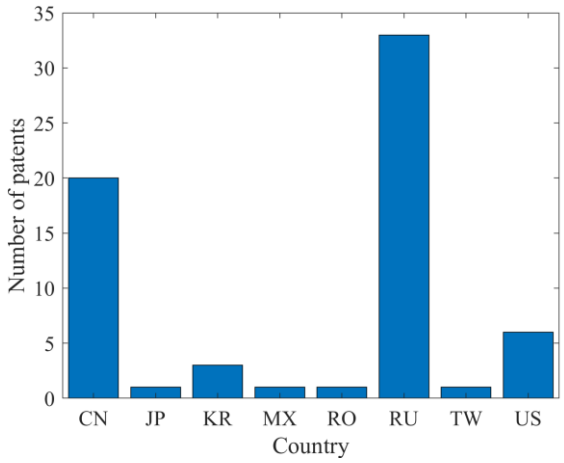

Figure 4: Number of patent applications registered in different countries.

4. CONCLUSIONS

Several innovative techniques have been protected with patent applications in the interdisciplinary field of plasma agriculture. The most innovative countries are China and Russia. The patent applications span from direct treatment of seeds, plants, or crops to indirect treatments using gaseous plasma to modify the chemical properties of liquids. Several techniques are applicable on a large scale, but the beneficial results in terms of improved germination, growth, or better quality or quantity of crops are rarely reported. Plasma agriculture, therefore, remains a technological challenge. Although the scientific literature reports better germination of seeds treated by gaseous plasma either directly or indirectly, the descriptions of patented solutions lack of quantitative reports. In most cases, patent literature does not mention any field experiments, so it is not easy to judge direct applicability. Another deficiency of patent literature is the lack of details about the exact treatment parameters. The patents disclose types of discharges used for

plasma generation but hardly mention the useful range of discharge parameters.

5. ACKNOWLEDGMENTS

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