Sensors & Transducers, Vol. 246, Issue 7, November 2020, pp. 32-37

Sensors & Transducers
Published by IFSA Publishing, S. L., 2020
http://www.sensorsportal.com

Simulation of a Cantilever Beam Based Soil Nutrient Sensor

[1,*] Akhil Nair and [2] Alok Verma
[1] University of Mumbai, Kalina Campus, Mumbai - 400098, India
[2] SAMEER, IIT Bombay Campus, Mumbai - 400076, India
E-mail: nairakhilwork@gmail.com, alok@sameer.gov.in

Received: 22 October 2020 /Accepted: 23 November 2020 /Published: 30 November 2020

Abstract: Agriculture as an occupation holds a very important role. The plant growth is affected by the climate and fertility of the soil. We can test the fertility of the soil and improve it based upon the needs of the crop to be grown. Nitrogen, Phosphorus, and Potassium are the major macronutrients found in soil. The use of a MEMS-based sensor provides high sensitivity along with compact implementation in optoelectronic devices. A cantilever beam sensor has been modeled in this paper for the detection of NPK nutrients in the soil. The cantilever beam sensor is based on the concept of local heating due to the absorption of light by the targeted nutrient. The cantilever beam is designed using a bi-material setup. The stresses felt in the beam due to thermal expansion of the materials of the cantilever beam cause the beam to bend. This bending of the beam is used to co-relate the concentration of the targeted nutrient in the soil with the bending caused due to thermal expansion.

Keywords: NPK, Soil nutrient, Sensor, MEMS, Cantilever, Simulation, Macronutrient.

1. Introduction

Farming and Agriculture are widely carried out in many countries and treated as the primary occupation of many individuals. Understanding the farming mechanism becomes very important in order to select areas of soil fertilization which is carried out on a large scale. Fertilizers help in improving the fertility of the soil by providing the required nutrients to the plants according to the necessary proportion.

The nutrients in soil represent around 0.1-5 % of the total plant biomass. Minerals like Oxygen, Hydrogen and Carbon make up for the rest of the majority of the plant biomass. We can classify the nutrients into macronutrients and micronutrients depending on the amount of the respective nutrient needed for growth of plants. Micronutrients consists of Iron, Manganese, Boron, Copper, Zinc, Nickel and many more [6]. Micronutrients are elements that are required in minute quantities compared to macronutrients.

As seen in Fig. 1, we can classify the macronutrients further into Primary and Secondary macronutrients. Nitrogen, Phosphorus and Potassium are called as primary macronutrients because their deficiencies are more common in soil as compared to the secondary macronutrients [6]. These three nutrients are commonly known as NPK nutrients collectively.

Few of the most common forms in which NPK nutrients are found in fertilizers are shown in Table 1 [7].

The sensing of these macronutrients becomes very important in determining the nutrient concentration to be used in fertilizers. The sensors designed are based on waveguides, MEMS and many on chemical analysis of the soil sample.

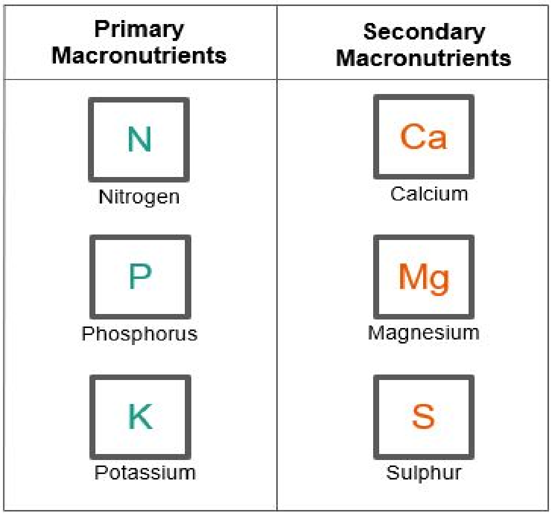

Fig. 1. Soil Macronutrients classified into Primary and Secondary Macronutrients.

Table 1. NPK Macronutrients form in soil.

Nutrient	Form
Nitrogen	Ammonium nitrate
Phosphorus	Superphosphate
Potassium	Potassium Sulfate

2. Methods of Soil Nutrient Sensing

There are various types of sensors designed for detection of nutrients in soil. We focus on detection of NPK macronutrients in soil. The conventional methods of detecting these NPK nutrients include soil sampling treatment of the soil and its chemical analysis. Other methods include:

Conductivity Method: In this method, electrodes of the same material are immersed in the sample. A particular AC voltage is passed through the electrodes and the conductivity is measured. The conductivity varies depending on the concentration of the nutrient in the soil.

Electro-Chemical Method: Electro-chemical sensors can be based on either Ion-selective electrode or Ion-selective field effect transistor. These methods use a thin film for a particular nutrient such as when the nutrient comes in contact with the film, ion-exchange occurs and an electrical signal is passed. This signal corresponds to the concentration of the targeted nutrient in the sample. This method has been studied for use in MEMS (Micro-Electro Mechanical Sensors) based sensors, hence increasing the sensitivity even higher.

Optical Method: The principle of the Optical sensors is based on the study of interaction of light with the soil nutrient. In Laser induced spectroscopy, the soil nutrient absorbs laser light of certain wavelength. This absorption is monitored to study concentration of the nutrient in the soil.

The methods mentioned above are the commonly used methods to study the concentration of nutrients in the soil sample [9].

3. Micro-Electro Mechanical Systems

Micro-Electro Mechanical Systems, better known as MEMS are systems built in the micrometer scale. They play an important role in the current age of technology in many devices. They are an important alternative to the traditional sensors due to its small size and low power consumption. Due to its small size, it can be packaged in various modules and allow quick interaction between different nodes of information. In agriculture, MEMS is being studied to be used for sensing properties of plant biomass and soil nutrient. This helps agriculture merge with the model of IoT, where quick wireless transmission of data is possible.

The main parameters for MEMS sensor in agriculture involves humidity sensors, temperature sensors, moisture sensors and photosynthetic radiation sensors [3]. Photosynthetic sensors are used for measuring the amount of light required for plant growth. Photosynthesis requires light in the 400 nm-700 nm wavelength. Photodiodes which are sensitive in this region are used. Moisture sensors consist of water sensitive nano-polymer on a cantilever beam and an on-chip temperature sensor.

The cantilever beam design for a MEMS sensor is widely used for sensing purpose. The cantilever beam consists of a beam fixed on one end and free on the other end. The cantilever is allowed to bend through different techniques as required in relation to a parameter being measured. The MEMS sensors which use ISFET (Ion selective field effect transistor) for detection of macronutrients in soil, have an ion-selective film on top of it [2]. A potential is developed in the interface between the ion-selective film and the FET (Field Effective Transistor) when the target ion comes in contact with the film. This potential is a function of the concentration of the targeted nutrient.

The issue with such sensors is that a need for a separate ion-selective film is required for each nutrient. This means that a separate structure is required for each nutrient. In this paper, we simulate a model for a MEMS based soil nutrient sensor which can be used for detecting all three NPK nutrients. This model is based on the Optical absorption of light by the targeted nutrient.

4. Modelling the Soil Nutrient Sensor

We define a model for the sensor mechanism as seen in Fig. 2. The model is based on the optical absorption of light by the targeted nutrient in the soil sample. A cantilever beam has been used for the sensing mechanism of the sensor. The components of the setup are discussed below.

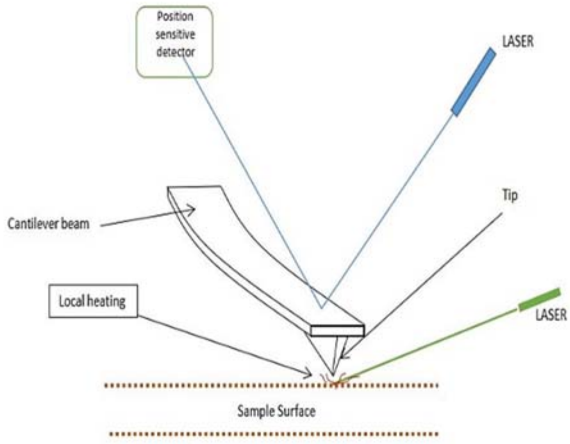

Fig. 2. Model of the MEMS soil nutrient sensor.

The model shown in Fig. 2 is used for detection of NPK nutrients in the soil sample. The NPK nutrients have been studied to have absorption wavelengths in the visible region as given in Table 2 [1].

Table 2. Absorption wavelength of NPK nutrients.

Nutrient	Absorption wavelength (nm)
Nitrogen	470
Phosphorus	540
Potassium	640

4.1. Absorption of Light by Nutrient

Atoms and molecules contain electrons attached to itself. These electrons vibrate at specific frequencies. When a light wave with a similar frequency impinges upon the atom, the electrons of that atom are set into vibrational motion. If a light wave has the same frequency as the one with which the electrons vibrate, then those electrons will absorb the energy of the light wave and convert it into vibrational energy. It is analogous to the concept of resonance in tuning forks. During its vibrational motion, the electrons interact with the neighboring atoms in such a way as to convert its vibrational energy into thermal energy.

4.2. Cantilever Beam

A Cantilever beam setup in a MEMS design is a beam in micrometer dimensions, attached to a fixed constraint on one end and left free on the other. Depending on the stresses affecting the beam due to different physical processes, we derive results from the above. We use COMSOL Multiphysics software to simulate the cantilever beam design for our sensor.

In Fig. 2, the laser light falling on the soil sample is a tunable laser with wavelength equal to the absorption wavelength of the targeted nutrient. The second laser is used to reflect off the top of the cantilever beam onto a position sensitive detector so as to note the deflection of the cantilever beam [10]. When light of wavelength equal to the absorption wavelength of the targeted nutrient is allowed to fall on the soil sample right under the tip of the cantilever, due to thermal energy released by the nutrient due to vibration of electrons, the cantilever experiences thermal expansion.

In the cantilever beam that we model, we use a bi-material cantilever beam [5]. This consists of two materials on fixed to each other as seen in Fig. 3. The circles in the image can be considered to depict the atoms of the material.

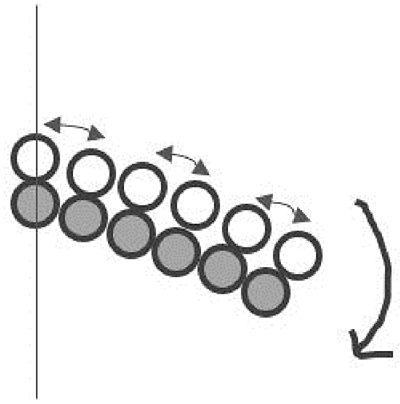

Fig. 3. Bending of beam due to stress.

The material on the top is selected such that it has a higher thermal expansion coefficient compared to the material on the bottom layer. When the beam expands due to thermal expansion, the layer on top expands faster compared to the layer on bottom. This causes stress on the upper layer to compress and bottom layer to expand. In order to reduce the stresses in the beam, the beam bends downwards [8]. The bending depends on the thermal expansion coefficient of both the materials.

5. Simulations and Observations

5.1. Simulating the Cantilever Beam

The simulations have been performed on the COMSOL Multiphysics software. The cantilever beam model is as shown in Fig. 4. The geometry of the cantilever beam is designed from the 2D Structural Mechanics model of COMSOL. We further use the ‘Heat Transfer Model’ for applying physics simulation to the model and then apply the ‘Stationary’ study for computing the final results.

The cantilever beam has two layers 1000 µm long. The top layer is of Aluminum and the bottom layer is of Silicon Oxide as seen in Fig. 5.

These materials are placed in this order because Aluminum has a higher thermal expansion coefficient than Silicon Oxide. Both the layers have been taken to be 50 µm thick. The triangular tip at the free end of the cantilever beam is taken to be of Aluminum and is 50 µm thick.

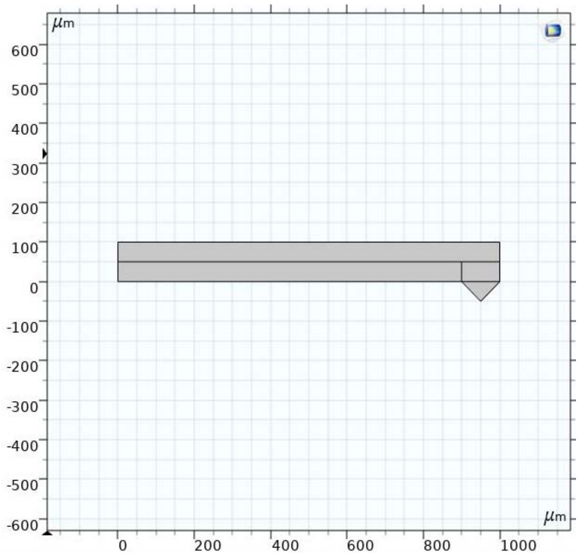

Fig. 4. Geometry of Cantilever Beam.

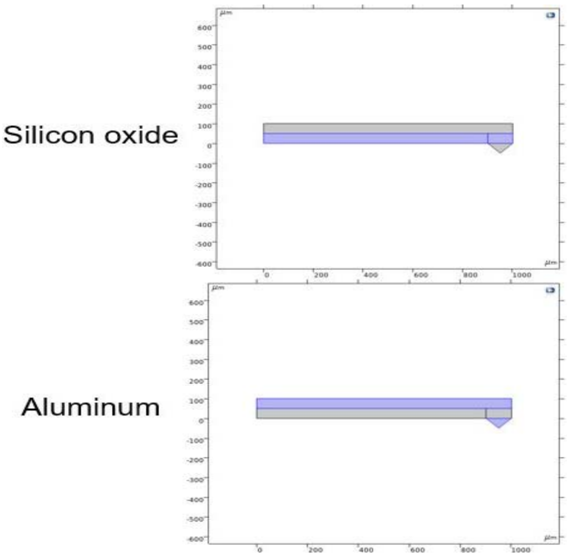

Fig. 5. Material domain selection in COMSOL.

5.2. Applying Thermal Expansion to the Beam

We keep the temperature of the fixed end of the cantilever beam to be at 293.15 K and the free end at 294 K. The temperature gradient and contour temperature that we see across the beam is shown in Fig. 6.

As we can see in Fig. 6, the higher temperature at the free end is applied on the triangular part of the beam. We now apply the thermal expansion study to our model and measure the stresses in the beam. We can see the total displacement of the beam due to the stresses felt in Fig. 7.

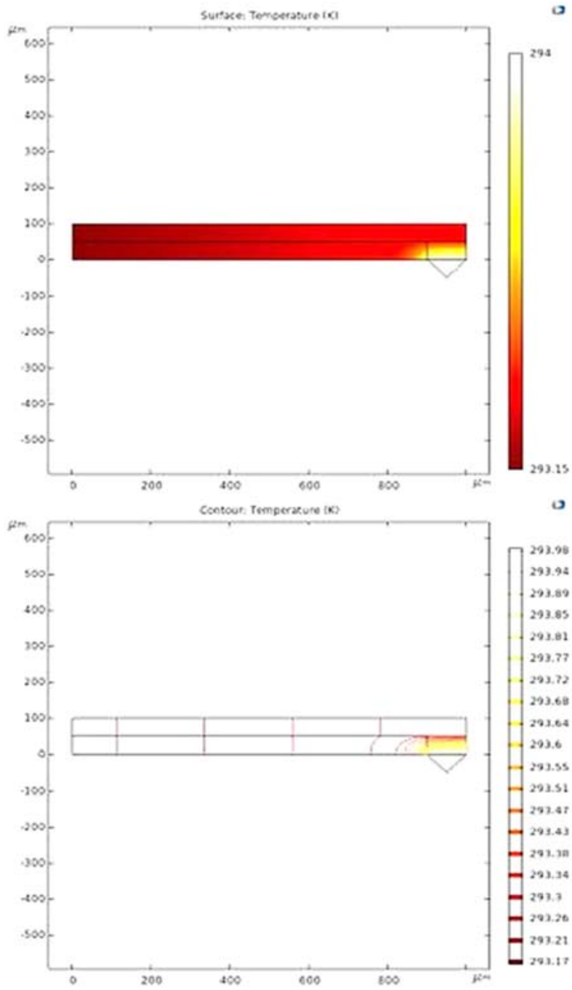

Fig. 6. Temperature gradient across the cantilever beam.

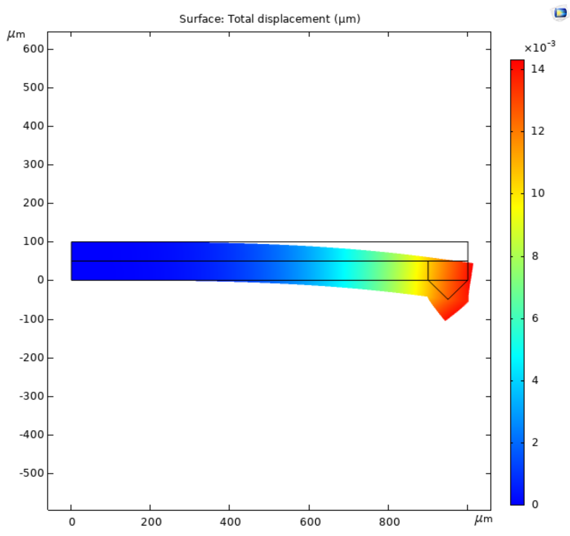

Fig. 7. Total displacement of the Beam for Aluminum as top layer.

We can see in Fig. 7 that the beam bends due to thermal expansion. The maximum displacement can be observed at the tip of the free end of the beam [4].

To observe it we plot a graph of total displacement vs length coordinate of the beam (Fig. 8).

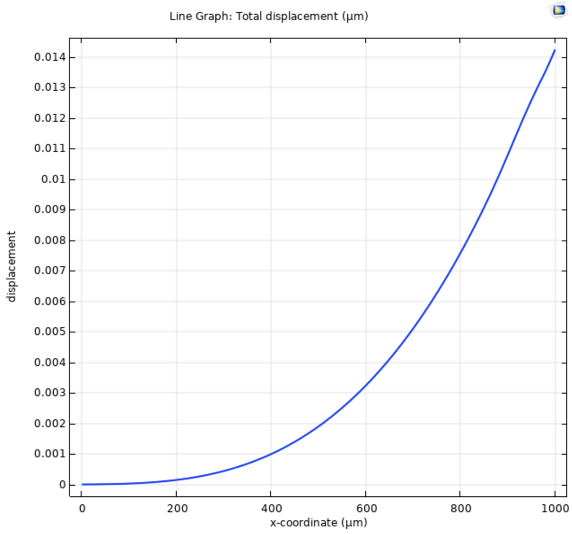

Fig. 8. Total Displacement vs x-coordinate of beam.

It can be seen that the maximum displacement of the cantilever beam can be measured at the tip of the beam. This means that the extreme end is the most sensitive part of the cantilever beam. Hence when we reflect off the laser from top of the beam onto the position sensitive detector, we reflect it at the tip of the beam in order to measure with maximum sensitivity.

We now note the deflection of the beam at different temperature differences between the fixed and free end of the beam. Table 3 shows the deflection of the beam at different temperature differences between the two ends of the beam [11].

Table 3. Displacement of beam at different temperature differences.

Temperature at fixed end (K)	Temperature at free end (K)	Displacement of cantilever beam (µm)
293.15	298	0.0804
293.15	294	0.0141
293.15	293.5	0.0058

It can be seen that even for a difference of 0.35 K we get a deflection of approximately 5 nm by the beam.

5.3. Testing Different Materials for Top Layer

We now change the material of the top layer and measure the total displacement of the beam. We first take nickel as the material for the top layer. After simulating the results for the model, we obtain the total displacement plot as seen in Fig. 9.

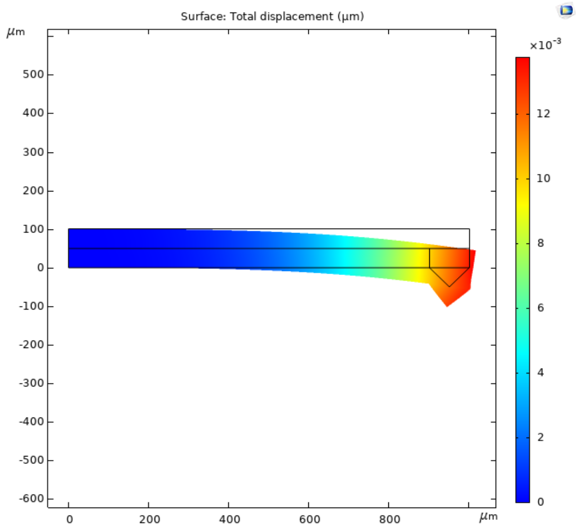

Fig. 9. Displacement of Beam for Nickel as top layer.

It can be seen from the plot that the displacement is slightly less as compared to the earlier model with Aluminum as the top layer. For the next material we use Copper as the top layer. We can see in Fig. 10 that the displacement in the model with Copper as top layer is far less than both that of Nickel and Aluminum.

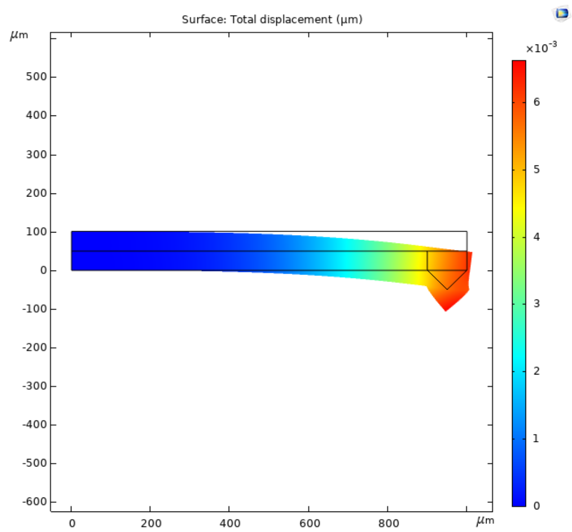

Fig. 10. Displacement of beam for Copper as top layer.

6. Results and Conclusion

We have designed a MEMS sensor for soil nutrient detection. We target the detection of Nitrogen, Phosphorus and Potassium, which are the macronutrients in soil. The light absorption method has been used to design the cantilever beam sensor setup. We have made use of a bi-material cantilever beam for our simulated model. The sensor model has been designed on the COMSOL Multiphysics software. The 'Heat Transfer Model' has been used to analyze the physics of thermal expansion in the cantilever beam. Thermal expansion occurs due to the local heating of air caused by the absorption of light by the targeted nutrient.

The materials tested for the cantilever beam have a Silicon Oxide as the bottom layer with lower thermal expansion coefficient as compared to the top layer. We test the deflection of beam to thermal expansion for three different materials on the top layer. We observe through our simulations that the beam bends highest for aluminum, then nickel and least for copper. The bottom layer is of Silicon Oxide for all three simulations.

Considering the current study of MEMS sensors which make use of ion selective electrode for the measurement of concentration of the targeted nutrient, it requires a separate film to be designed and hence a separate structure for each nutrient to be detected. In our sensor, we can use a tunable laser which works in the visible region to detect all three NPK nutrients. This allows us to design a single structure for the detection of all three nutrients in the soil sample.

Another important point in the design of a MEMS sensor for detection of nutrient in soil sample is the small size of the sensor. It can be packaged in bulk inside other optoelectronic devices hence increasing the sensitivity. Also considering the importance of technology in the current era, it paves way to implementation of agriculture related sensors in IOT devices.

References

[1]. M. Masrie, M. S. A. Rosman, R. Sam, Z. Janin, Detection of nitrogen, phosphorus, and potassium (NPK) nutrients of soil using optical transducer, in *Proceedings of the IEEE 4th International Conference on Smart Instrumentation, Measurement and Application (ICSIMA)*, Putrajaya, 2017, pp. 1-4.

[2]. Vinay S. Palaparthy, Maryam S. Baghini, Devendra N. Singh, Review of polymer-based sensors for agriculture-related applications, *Emerging Material Research*, Vol. 2, Issue 4, 2013, pp. 166-180.

[3]. Neeti Sharma, Pant BD, Jyoti Mathur, MEMS Devices Used in Agriculture - A Review, *Journal of Biosensors and Bioelectronics*, Vol. 10, Issue 1, 2019, pp. 1-4.

[4]. N. Kalaiyazhagan, T. Shanmuganantham, Performance analysis of MEMS cantilever sensor for agriculture applications, in *Proceedings of the IEEE International Conference on Circuits and Systems (ICCS)*, Thiruvananthapuram, 2017, pp. 186-190.

[5]. Toda M., Ono T., Liu F., Voiculescu I., Evaluation of bimaterial cantilever beam for heat sensing at atmospheric pressure, *Review of Scientific Instruments*, Vol. 81, Issue 5, 2010.

[6]. Macronutrients and Macronutrients for Soil (https://emeraldlawnsaustin.com/macronutrients-micronutrients-soil/).

[7]. M. L. Vitosh, N-P-K FERTILIZERS, (https://www.canr.msu.edu/field_crops/uploads/archive/E0896.pdf).

[8]. Toda M., Inomata N., Ono T., Voiculescu I., Cantilever beam temperature sensors for biological applications, *IEEJ Trans. Electr. Electron Eng.*, Vol. 12, Issue 2, 2017, pp. 153-160.

[9]. Laxmi C. Gavade, A. D. Bhoi, N, P, K Detection & Control for Agriculture Applications using PIC Controller: A Review, *International Journal of Engineering Research & Technology (IJERT),* Vol. 06, Issue 04, 2017, pp. 638-641.

[10]. Etayash H., Thundat T., Microcantilever Chemical and Biological Sensors (Encyclopedia of Nanotechnology), Ed. Bhushan B., *Springer*, 2015.

[11]. Akhil Nair, Alok Verma, Nitrogen, phosphorous and potassium detection in soil using MEMS sensor, in *Proceedings of the 6th International Conference on Sensors Engineering and Electronics Instrumentation Advances (SEIA'2020)*, Porto, Portugal, 23-25 September 2020, pp. 171-173.