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REGULAR PAPER

A System for Optimizing Fertilizer Dosing in Innovative Smart Fertigation Pipelines: Modeling, Construction, Testing and Control

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Abstract

Smart fertigation is a topic of great interest in the effort to optimize different activities involved in local and extensive agriculture for assisting crops, optimizing production by using wireless technologies, data-processing electronic boards and sensors network. With the advent of Agriculture 4.0, similar to Industry 4.0, Information Communication Technology (ICT), associated with mechatronics, is giving an added value to this technique allowing optimization of water, fertilizers, control of water flow in pipes and period of irrigation. This paper intends to illustrate findings related to an innovative low cost system for assisting crops and achieving an accurate farming by investigating on the design, construction, testing and control of dosing system for liquid and granular fertilizers. Four different dosage systems have been designed, realized and tested with different granular and liquid fertilizers; the analysis of an extensive experimental campaign allows to define the characteristic and the mathematical expressions for each analyzed fertilizer and for each dosage system. The accurate modeling allows to control with extreme precision the realized dosing systems after estimating the quantity of fertilizer which the crop needs by means of the smart fertigation system. The obtained results permit the optimization of the fertilizer dosage in terms of quantity, which at the same time translates into lower production costs, greater environmental sustainability and optimization of production in terms of quantity and quality.

Keywords Precision agriculture · Flow measurement · Smart fertigation · Automatic fertilizer dosing · Agriculture 4.0 · Agricultural mechatronics · Sensor networks

1 Introduction

A recent common aim of Industry 4.0 is finding a solution that integrates the modern technologies with the agricultural sector's needs, taking into account low environmental impact by means of renewable energy sources [1, 2]. With the help of Internet of Things (IoT), a huge number of low cost and low power sensors can easily be deployed in farmlands, in order to gather precise climate and soil data. Thereafter, the collected data are then forward, by Internet connection, to the so called on-cloud IoT framework. In this context, some recent examples for agricultural applications are shown [3–7] and a survey of several researches of IoT applied to various agricultural, food production and manufacturing challenges are reported [8–10]. The specific aspect of the characteristics of the Wireless Sensor Network (WSN) used in the applications of smart fertigation has also been widely investigated (i.e. [11–14].). Moreover, recent researches have analyzed and suggested the use of low cost photovoltaic station for powering the entire fertigation system [15–17]. The innovative system, considered in this paper, is an energy self-sufficient fertigation system powered by photovoltaic energy and integrated with a low-cost WSN in order to monitor the crops directly on-field [15]. The smart system aims to guarantee a rational use of fertilizers, water resources and, consequently, a reduction of the environmental impact. The solution allows the integration and optimized management of traditional cropping systems with existing innovative technologies (thanks to the use of low-cost wireless electronic modules). Both receive and process data from connected sensors. The fertigation system calibrates the periodicity and fertilizer amounts to be used in the irrigation and fertilization phases based on sensors data

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related to temperature and humidity of both soil and air. The WSN is directly distributed on the land and acquires the soil and environmental parameters by sending the data to a central control unit. In this paper, the important problem of the fertilizer, granular or liquid, dosing system, is considered, whose accuracy and behavior is a crucial problem for precision agriculture (some specific applications in [18, 19]) and the considered smart fertigation system. The dosing system of the fertigation [15] has been strongly investigated in the manuscript starting from its design. An innovative solution for dosing liquid and granular fertilizers is presented, starting from the details of its design and construction. This also includes a complete experimental testing procedure in order to define a mathematical expression depending on the type of fertilizers useful for accurately controlling the dosing system. Four types of dosing systems have been designed, realized and discussed in the present work; two types for granular fertilizers and two types for liquid fertilizers, with different flow rates characteristics. The norms [20, 21] have served as guideline for the design of the augers (for granular fertilizers) and peristaltic pumps (for liquid fertilizers). The detailed description of the setup, used for testing the four realized dosing systems, with different type of fertilizers and the presentation and analysis of the data obtained constitute the main body of this paper. The final results permit to be confident about a high accuracy of the fertilizer dosage for several types of liquid and granular ones and permit to consider the fertigation system as a suitable possibility for optimizing environmental sustainability and production in terms of quantity and quality.

The paper is organized as follows: Sect. 2 includes a general description of the considered solar powered fertigation system with the low cost WSN used for getting the environmental data. Section 3 shows in detail all the design step of the four dosing systems, the choice of the main components and the realization of the prototypes. Section 4 shows the experimental setup used, Sects. 5 and 6 the results of the experimental tests carried out testing the dosage systems with 3 different types of granular fertilizers (Sect. 5) and 3 types of liquid fertilizers (Sect. 6). In the same section detailed comments about the experiments, the accuracy of the devices, the problems during the tests, generalization of the results and the possible application on the fertigation system are also reported; finally, Sect. 7 shows the conclusions of the research.

2 General Description and Design of the Innovative Fertigation System

The considered system [15] allows the agricultural fields fertilization in automatic way and is powered by a solar energy. Furthermore, its central unit is composed by the following main elements (depicted in Fig. 1 and detailed in Fig. 2): photovoltaic panels, wood container, control panel, batteries, dosing system for the liquid fertilizing with relative storage tank, dosing system for the granular fertilizing, mixture tank, electric pump, pipelines and connection cables for the hydraulic and electrical part.

The necessary power for all the system is generated by photovoltaic panels connected in series to the charge regulator that stabilizes the produced energy to 24 V for charging the batteries. The dosing system is powered with alternate current 230 V 50 Hz obtained transforming the batteries energy by means of a stand-alone solar inverter (Fig. 2a). The control panel (Fig. 2b) is made by a logic

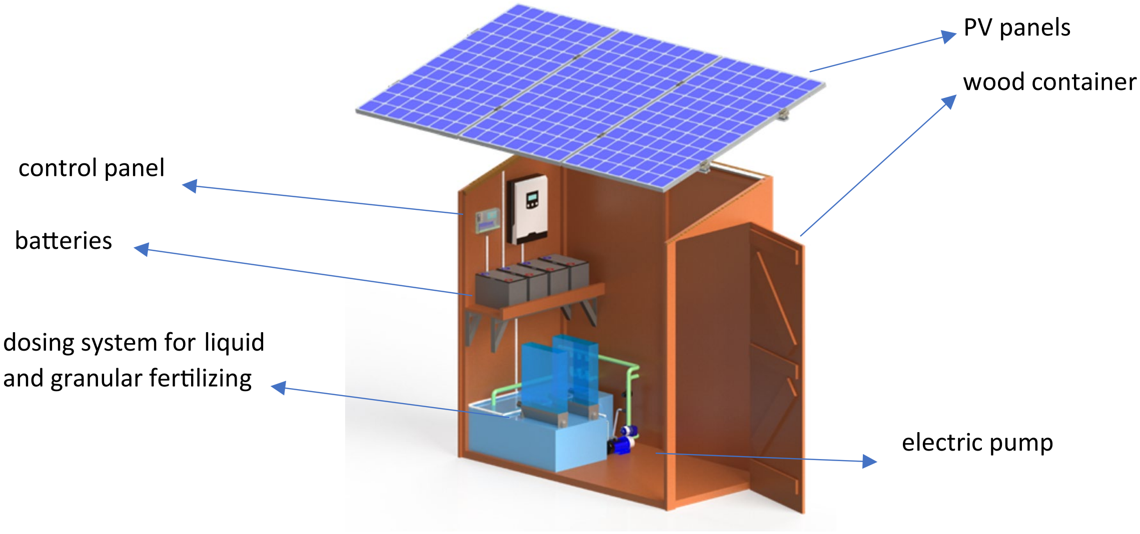

Fig. 1 Design of the fertigation system central unit

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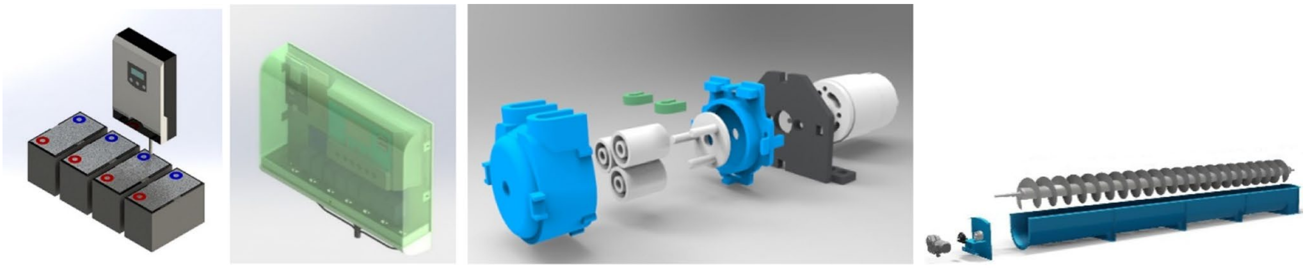
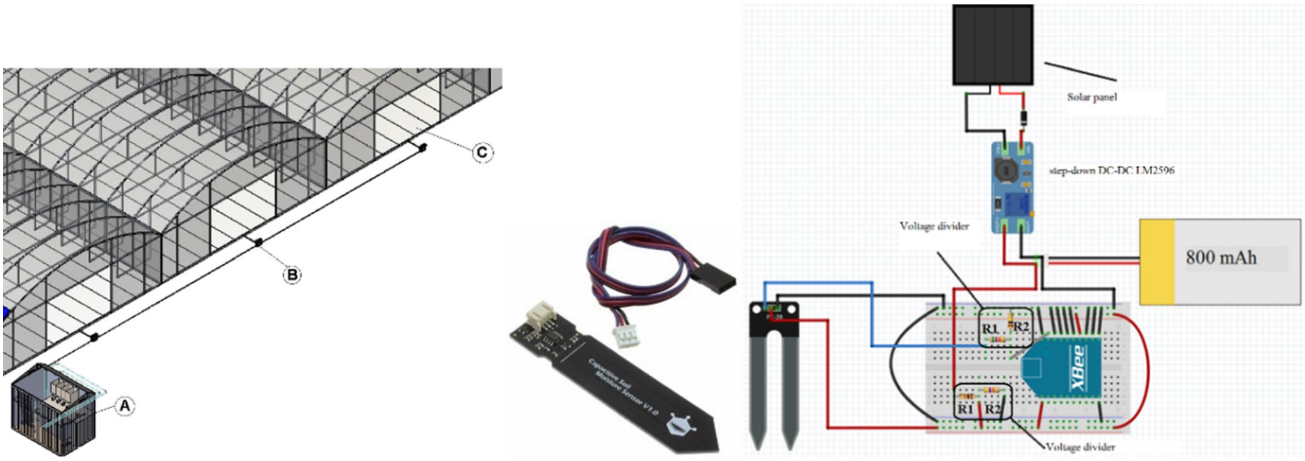


(a) (b) (c) (d)

Fig. 2 **a** inverter and battery, **b** control panel, **c** peristaltic pump, **d** cochlea

board (Raspberry PI 3 model B) that receives the parameters detected by the sensors on the field through the WSN, compares them with the threshold values and, programmed with opportune algorithms that considers the particular farming, controls the drive of the different actuators, the granular dosing, the liquid dosing, the electric pump and the opening of the irrigation electro valves. The liquid fertilizer dosing system is composed by a peristaltic pump that permits the dosing of the fertilizer from the storage tank; the peristaltic pump (Fig. 2c) is made by a rotor where three rollers are applied which, during the rotation, throttles the tube and provoke the fluid advancement. The granular fertilizer dosing system is realized by a dosing cochlea that permits the fertilizer of handling from the collection hopper to the mixture tank. The cochlea (Fig. 2d) is constituted by a shaft that has, on the external surface, a certain number of helixes; the shaft rotation driven by an electric motor handles a quantity of granular fertilizer depending on the velocity and duration of the shaft rotation. The fertigation central unit (A in Fig. 3a) starts up the pump, opens the electro valves of the interested zone (indicated with B, C in Fig. 3a) and holds the other zone close. The system detects through sensor nodes of the WSN physical magnitudes on the field (i.e. humidity and temperature), depending from threshold values locally set or remotely programmed through web server, and automatically controls the drives using programmed electronic boards. The considered sensor node is a ground humidity sensor, Soil Moisture DF Robot (Fig. 3b), that is a capacitive level sensor able to measure the percentage of water in a ground volume. A preliminary configuration of the sensor nodes and of the WSN, of the control electronic boards and transmission devices, will be presented for the completeness of the paper; anyway other studies and improvements of the control system and its hardware are not object of the present research and have been recently published [22, 23]. The data transmission is realized by a xBee (xBee S2) module which is a low cost module that uses a serial communication for (wireless) data transfer at radiofrequency. An appropriate dimensioned photovoltaic panel powers the sensor and the wireless module; the considered panel has an output voltage of 5 V. In the considered setup, a step-down tension converter DC-DC LM2596 decreases and stabilized



(a) (b) (c)

Fig. 3 **a** Scheme of the fertigation system, **b** ground humidity sensor, **c** scheme of each sensor node

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the panel output voltage to a value of 4 V for charging the above lithium battery. Finally, in order to correctly power the xBee S2 module (3.3 V) and the soil moisture DFRobot sensor (1.2 V), two voltage dividers have been realized; a complete scheme of the sensor node configuration is shown in Fig. 3c), where all the considered elements have been indicated.

3 Sizing Dosing Systems

Starting from the analytical sizing, defined by the relative reference standards, the selection of the most suitable components to the subsequent 3D CAD modeling of the dosing systems has been carried out. In total, four devices were designed, two for the dosage of the liquid fertilizer and two for the dosage of the granular fertilizer; for each system, three different types of fertilizer were analyzed.

3.1 Granular Fertilizer Dosage Systems Design

For the transportation of the granular fertilizer, from the loading hopper to the mixing tank, metering augers are used. The dosing auger is a machine commonly used for the transportation of the material, inserted by one or more loading ports, using the thrust of a rotor. The rotor is a tube that carries at its end the helical elements. Therefore, once the fertilizer transported strip is rotated on the bottom and on the helical thrust body, it ensures the displacement of the fertilizer. This happens once the dosing screw has been selected, its dimensional and geometric characteristics have been defined, and the relative reference standard for sizing has been considered, namely the UNI 10,468 standard [20]. The processed volumetric flow rate I_v of the cochlea, considering its geometrical characteristics depicted in Fig. 4a), can be determined by the speed for the auger passage section as expressed in (1),

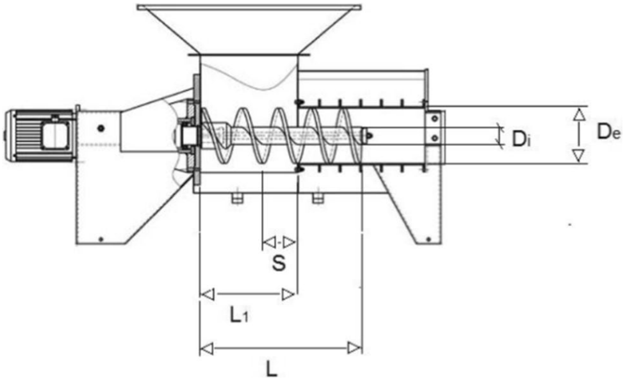

Fig. 4 Geometrical characteristics of a cochlea

$$I_v = v * A \tag{1}$$

where v is the ground speed, expressed by (2), depending on the cochlea step S (Fig. 4a),

$$v = S * \frac{n}{60} \tag{2}$$

and A is the area defined by (3) where D_e and D_i are cochlea geometrical characteristics described in Fig. 4. φ is the filling coefficient that allows to take into account the non-total filling of the cochlea during operation; it is equal to 0.9 for the extraction screw conveyors and between 0.15 and 0.45 for the others.

$$A = \varphi * \frac{\pi}{4} * \left(D_e^{\,2} - D_i^{\,2}\right) \tag{3}$$

In this research two different granular fertilizer dosing systems with different cochlea having different geometrical characteristics and different velocities (n), as reported in Table 1, have been designed, constructed, and tested. The CAD design of the cochlea and all the granular fertilizer dosing systems are reported in Fig. 5a, b respectively for the dosing system 1 and 2 (bigger cochlea).

The mass flow may be calculated by (4), where ρ is the density of the considered granular fertilizer.

$$I_m = \rho * I_v \tag{4}$$

Three different granular fertilizers supplied by the company "Agritecs.r.l." have been considered for each system: "*Idrosoyl 10–40-10 + Micro*" named Fertilizer 1, "*Idrosoyl 15–5-30 + 2MgO + Micro*" named Fertilizer 2, "*Idrosoyl 18–18-18 + Micro*" named Fertilizer 3. The mass flows and the physical characteristics for each fertilizer for the 2 granular dosing systems by considering (4) are reported in Table 2.

The total resistant power P(kW) to ensure the transport of the material is given by (5) [20]:

$$P = P_e + P_h + P_n + P_{st}\ [\mathrm{kW}] \tag{5}$$

in (5) P_e is the resistance due to the extraction motion (kW), P_h is resistance due to the movement of the material (kW),

Table 1 Physical characteristics of the granular fertilizer dosing systems 1 and 2

Geometrical parameter	Granular dosing system 1	Granular dosing system 2
S (mm)	18.5	30
D_i (mm)	8	20
D_e (mm)	22	45
L (mm)	160	300
n (rpm)	55	10.2

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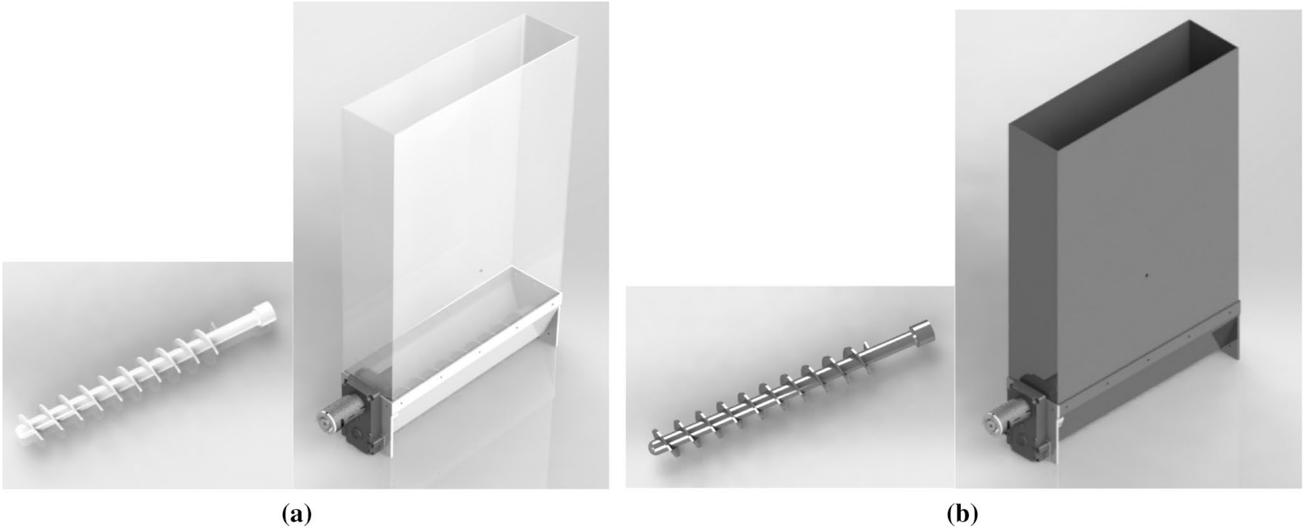
(a) (b)

Fig. 5 In order: **a** dosing system 1: cochlea and complete 3D CAD, **b** dosing system 2: cochlea and complete 3D CAD

Table 2 The mass flows and the physical characteristics for each fertilizer for the 2 granular dosing systems

Fertilizer	Density ρ (kg/m^3)	Mass flow I_m with dosing system 1 (g/s)	Mass flow I_m with dosing system 2 (g/s)
1	1050	5.3	6.56
2	1100	5.5	6.45
3	1012	5.6	6.15

P_n is resistance due to vacuum friction (kW), P_{st} is resistance due to lifting of the material (for inclined screw conveyors) (kW). Applying in (5) the formulas in [20] for the 2 dosing systems, it is possible to estimate a total resistant power of 0.352 W for the first granular dosing system and of 1.35 W for the second one; considering the angular velocity (see Table 2 where the mass flows or the 3 fertilizers are reported) of the 2 dosing systems, from the necessary torque two motor models were chosen for the two systems to satisfy, with a certain margin, the technical specifications of the systems. At this proposal a Kenta motor model K9119600 was chosen for the first system and a Kenta motor model K9119157 was chosen for the second one. A schematic 3D CAD model of the two designed granular dosing system is shown in Fig. 5.

3.2 Liquid Fertilizer Dosing System Design

The device for transporting the liquid fertilizer from its accumulation tank to the mixing tank, where it will be mixed, has been considered a peristaltic pump. Also in this case two different dosing systems have been designed. The following relationships, (6)–(8), were considered for the determination of the flow Q, (6), where in (6) v is the liquid velocity and D the diameter of the tube, of the pump prevalence H (7) [21] where in (7) ρ is the fluid density [kg/m^3], g is the gravity acceleration, p_1 and p_2 the downstream and upstream pressure [Pa], v_1 and v_2 the downstream and upstream liquid velocities [m/s], H_g the height difference, R the load less and of the absorbed power P.(8), where in (8) μ is the pump efficiency.

$$\mathrm{Q} = v \cdot \pi \cdot \frac{D^2}{4} \tag{6}$$

$$\mathrm{H} = \frac{p_2 - p_1}{\rho \cdot g} + H_g + \frac{v_2^2 - v_1^2}{2 \cdot g} + R \tag{7}$$

$$\mathrm{P} = \frac{\rho \cdot g \cdot Q \cdot H}{\mu} \tag{8}$$

During the design, some simplifying hypotheses have been carried out, such as the absence of load, the lack of loss due to the short length of the considered tubes and the possibility of setting the same speed of the fluid in the suction duct and in the delivery duct, considering the fluid speed constant for the ducts having the same diameter. For the liquid fertilizer dosage system 1 it is set equal to v_1=0.45 m/s, while for the dosage system 2 it is fixed equal to v_2 =1.5 m/s. Considering the PVC connecting pipes consist of a transparent plastic tube, diameters were chosen for the first liquid fertilizer dosing system equal to 3/8″, while for the second liquid fertilizer dosing system equal to 1/2″. Since the lengths of these very small pipes are always less than 0.3 m, load losses have been assumed to be negligible. Applying Eq. (6) with the fixed velocities and the diameters

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chosen, an estimated flow of 1.92 l/min for the liquid in the first dosing system and an estimated flow rate of 11.58 l/min in the second one have been valued. Once calculated the flow rates, the peristaltic pump "SingFlo" model "FLO-2401" able to process a volumetric flow rate equal to 2 l/min has been chosen for the first dosing system and the "SingFlo" model "FL-44", able to process a volumetric flow rate equal to17 l/min has been chosen for the second dosing system. The corresponding powers, equal to 21.6 and 134.4 W respectively, is eligible to satisfy the requested powers given by (8) for all the liquid fertilizers and taking into account the technical characteristics of the pumps. A representation of the selected peristaltic pumps with 3D CAD and photo is given in Fig. 6a for the dosing system 1 and in Fig. 6b for the dosing system 2.

Three different liquid fertilizers have been considered for testing each of the two dosing system: "*Fluitek*" named Fertilizer 1, "*Thonerboro plus*" named Fertilizer 2, "*Trys plus*" named Fertilizer 3. The maximum mass flows for the fertilizers referred to the 2 granular dosing systems, by considering (4), are reported in Table 3.

Table 3 The mass flows and the physical characteristics for each fertilizer for the 2 liquid dosing systems

Fertilizer	Density ρ (kg/m^3)	Mass flow I_m with dosing system 1 (g/s)	Mass flow I_m with dosing system 2 (g/s)
1	1250	42	350
2	1350	44	378
3	1850	61	518

4 Experimental Tests

4.1 Experimental Setup for Granular Fertilizer Dosing Systems

Several experimental tests were carried out for analyzing the real behavior of the fertilizer dosing systems designed and realized as shown in the previous sections. The objective of the tests with 3 different granular fertilizers and as many different liquid fertilizers was to investigate on the influence of the chemical-physical fertilizers properties on the accuracy of the dosing system. Moreover, several tests in the same conditions were useful to evaluate the repeatability of the flow rate processed by the system, so as to avoid incorrect measurements. By varying the operating time of the fertilizer handling system, several tests were carried out in order to evaluate the correspondence between the working time of the dosing system and the real flow rate of fertilizers at the dosing system exit. In this way a flow rate-time diagram has been considered evaluating the linearity of the system with respect to different quantities of fertilizers necessary. Each point of the plotted flow rate-time plot is the average of three diverse tests in the same conditions. Finally, considerations about the accuracy of the dosing systems that permits to optimize the control strategy for placing the correct quantity of fertilizer avoiding excesses or lacks of fertilizers; moreover, comparisons with the theoretical values of flow rate previously estimated will complete the extensive experimental campaign of measurements.

Four experimental setups have been realized for the tests; two setups related to the granular fertilizers (one for each dosing system) and other two setups related to the liquid fertilizers. For each type of fertilizer (granular or liquid), the difference is the type of cochlea or pump used. In all setups the motor driving the cochlea or the pumps is powered by 2 batteries of 12 V connected in series in such a way to have a powered voltage of 24 V. The control is made by a low cost digital board 'Arduino 1′ that supplies a relay module at 5 V connected by appropriate cables to the servomotor. A scheme and a photo of the control unit are shown in Fig. 7 where the connections between the electronic digital board (Arduino) and the relays module are shown schematically and with a photo. The setups related to the granular fertilizers with the two different types of cochlea are shown in Fig. 8a, b with a measurement tank placed at the exit of the cochlea for measuring the quantity of deposed fertilizer on a balance; in Fig. 9 the tank at the exit of the cochlea and the subsequent measurement of fertilizer by means of an electronic balance, for the dosing system 1 and the fertilizer 1.


(a)

(b)

Fig. 6 **a** Peristaltic pump for dosing system 1:3D CAD, photo **b** peristaltic pump for dosing system 2: 3D CAD, photo

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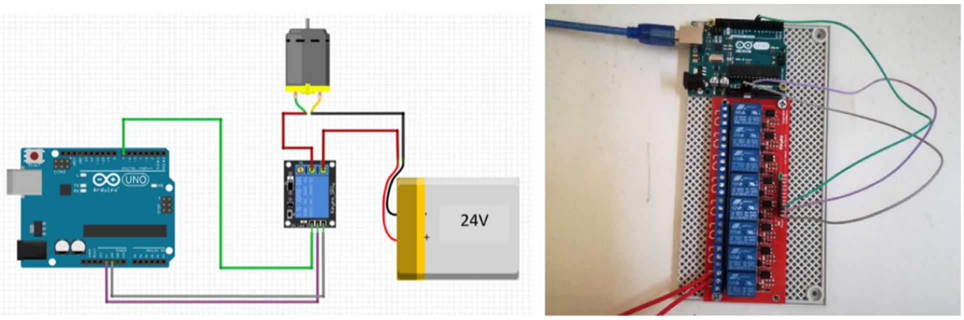

Fig. 7 Scheme and photo of the control board used for all the setups

(a) (b)

Fig. 8 **a** Setup for granular fertilizer dosing system 1, **b** setup for granular fertilizer dosing system 2

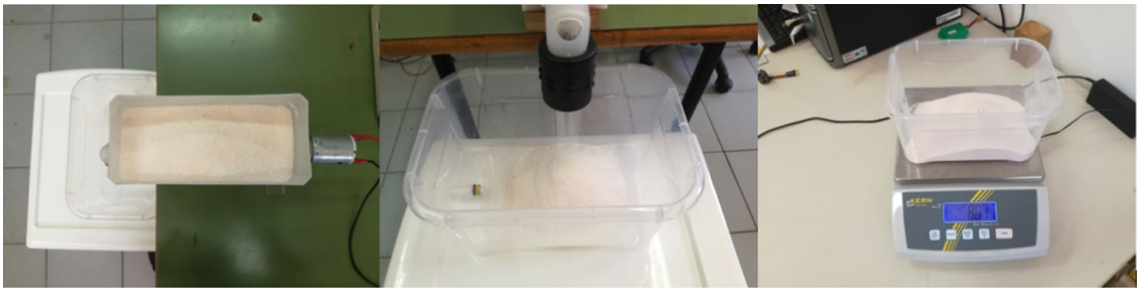

Fig. 9 Test for granular fertilizer 1, dosage system 1

(a) (b)

Fig. 10 **a** Setup for liquid fertilizer dosing system 1, **b** setup for liquid fertilizer dosing system 2

4.2 Experimental Setup for Liquid Dosing Systems

The setup related to liquid fertilizers (as shown in Fig. 10) has, differently from the previous setup, an accumulation tank for the liquid fertilizer at the pump entrance and a measuring vessel for quantifying the deposed fertilizer at the pump exit. The control board is the same used in the previous setup (depicted in Fig. 7 with the relative relays

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module). The complete setup systems are shown in Fig. 10 (view from top), where Fig. 10a) depicts the dosing system 1 (smaller pump) and Fig. 10b the dosage system 2, while Fig. 11 is a photo that shows the top, frontal and lateral view during a test (referred to the liquid fertilizer 1 and the dosage system 2).

5 Granular Fertilizer Dosing System Tests

5.1 Theoretical Aspects

Several tests were carried out considering the two previously dimensioned dosing systems for granular fertilizers. The tests have been carried out by changing the drive time of the cochlea motor; starting from an opening time of 5 s, until a final time of 300 s, with at least 2 repetitions for each test in order to evaluate the process repeatability. In order to have a wider range of data, the step considered is 5 s in the first part and then it is has been increased for the last tests. Considering the almost coincidence of the results obtained with the repetitions, in the results reported in Table 4 only the average value for each test is reported for the 2 dosage systems and for the 3 granular fertilizers with respect to the different opening times. In Fig. 12 a graphical evaluation of the results for the dosage system 1 and in Fig. 13 for the dosage system 2 is reported; it is possible to appreciate the extreme linearity of the behavior of both dosage systems for all the 3 considered fertilizers for all the opening times and the corresponding quantities of deposed fertilizer on the tank. In order to have a more clear idea of the linearity, the determination coefficient R^2 defined by (9) and the fitting straight line equation are reported foe each case.

$$R^2 = 1 - \frac{SQE}{SQD} \tag{9}$$

where in (9), $SQE = \sum_{i=1}^{n} (y_i - f(x_i))^2$ is the sum of the square of the errors between the n experimental points y_i and the corresponding points $f(x_i)$ on the fitting straight line and $SQD = \sum_{i=1}^{n} (y_i - \bar{y})^2$ that is the sum of the square of the errors between the n experimental points y_i and their average value $\bar{y}$. The determination coefficient may permit to have an idea of the real linearity of the proposed dosage systems and, consequently, may give important information about the possibility of easily using the proposed dosing system in the central unit of an automatic an innovative fertigation system (previously described). The large number of tests carried out permits also to understand if, considering the similar density of the considered granular fertilizers, other physical parameters (excluded the density) may substantially influence the dosage system behavior.

5.2 Results Analysis

The following important considerations may be pointed out from the analysis of the experimental tests shown in Table 4 and Figs. 12 and 13:

- the two granular fertilizer dosing systems have an excellent repeatability and a linear behavior for all the 3 different fertilizers considered and the fitting straight lines shoes an error always minor than 1% that means that it is possible with high accuracy to dose the quantity of granular fertilizers to use in all the cases;
- the two dosing systems have a behavior that depends from the type of fertilizer; the dependency is light, it

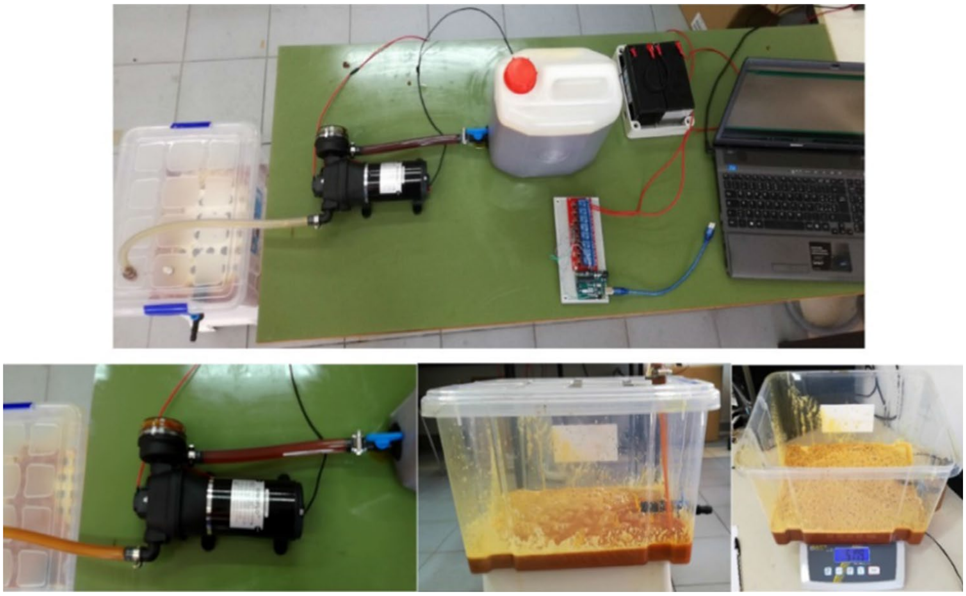

Fig. 11 Test for liquid fertilizer 1, and dosage system 2

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Table 4 Experimental results for granular fertilizer dosage systems 1 and 2

Time (s)	Granular fertilizer dosage system 1			Granular fertilizer dosage system 2		
	Mass of fertilizer 1 (g)	Mass of fertilizer 2 (g)	Mass of fertilizer 3 (g)	Mass of fertilizer 1 (g)	Mass of fertilizer 2 (g)	Mass of fertilizer 3 (g)
5	17.5	19.5	17	21.67	21.67	22.67
10	36	39	34	43.67	43	44
15	54.5	57.5	51.5	63.67	66	70.33
20	72	76.5	68.5	82.33	78.33	88.33
25	87.5	99	86	103.67	111.67	108
30	104	116	104.5	123.67	138	123.67
45	153.5	168.5	155.5	185.67	211.67	184.67
60	205.5	223.5	207.5	249.67	280.33	249.33
75	255.5	275	260.5	318.67	348.67	328.67
90	306	326.5	311.5	381.67	418.33	373
105	354.5	375.5	364.5	443.33	487	438
120	406.5	433.5	416.5	502.33	560	507
150	511.5	552	517	635.67	696.67	–
180	616	660.5	619	763.67	831	–
210	719.5	773.5	727.5	887	960.33	–
240	811	886	823.5	1023.33	1070.67	–
300	1010.5	1106	1016	1316.67	1409.67	–

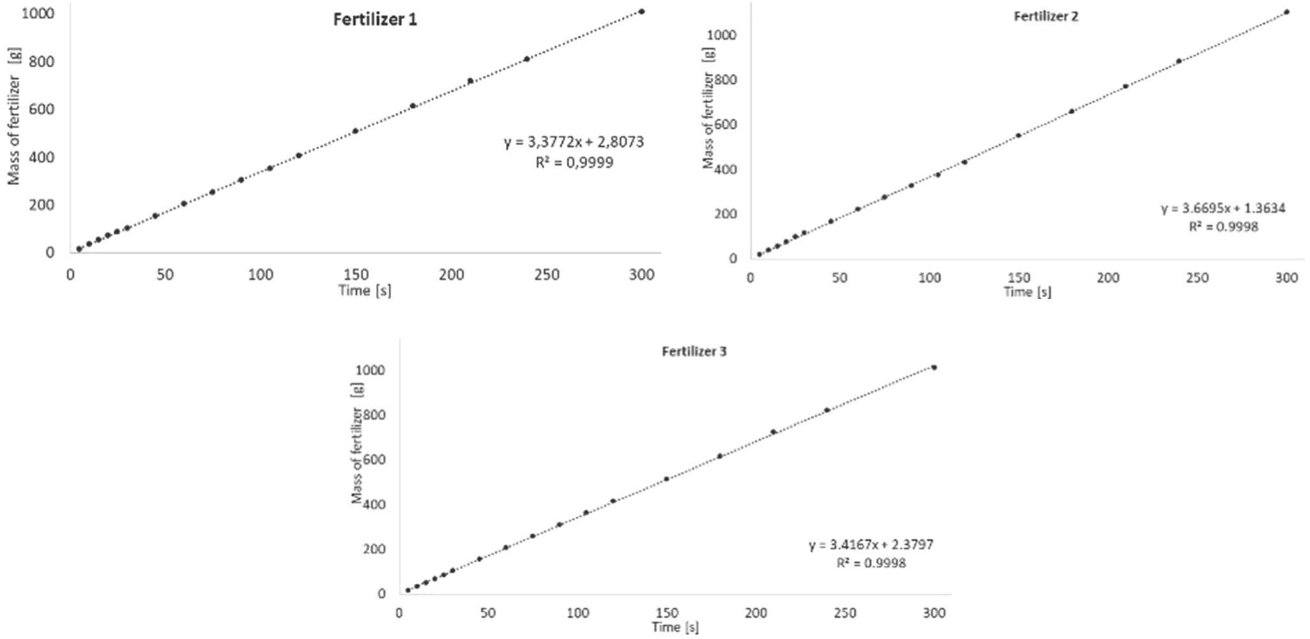

Fig. 12 Analysis of experimental results for the granular fertilizer dosage system 1

may be appreciated for the tests with a big quantity of fertilizer (last rows in Table 4), anyway all the considered fertilizers are included in a range of 10% of the indicated value, and if this accuracy may be considered acceptable, it is not necessary to tune the dosing system for each fertilizer to use. This result is perfectly coherent with the densities of the granular fertilizers, that is quite similar for all 3 the fertilizers with a maximum difference of 10% (see Table 2);

– the tests with fertilizer 3 and dosing system 2 shows a behavior similar to the other fertilizers until the working time of the cochlea overpasses 120 s. When the cochlea

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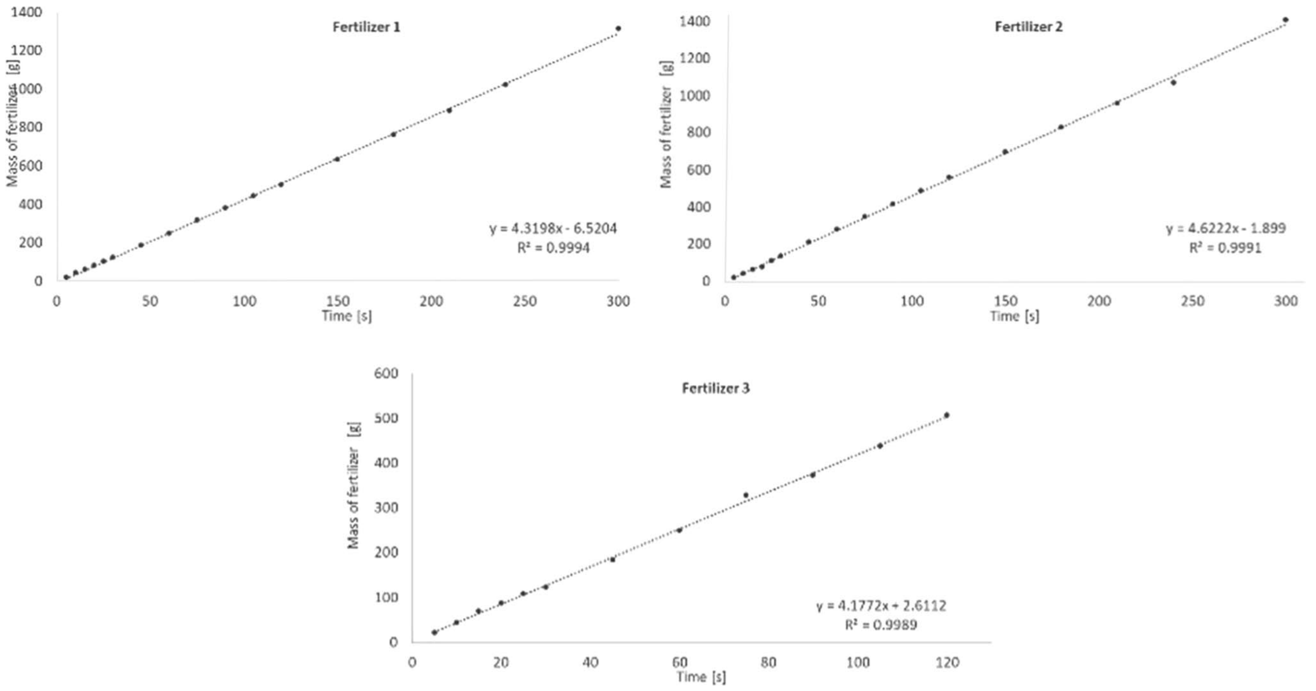

Fig. 13 Analysis of experimental results for the granular fertilizer dosage system 2

working time overpasses 120 s, it was not possible anymore getting experimental data (see Table 4) because, after that time, the cochlea is not anymore able to move the granular fertilizer and the mass flow remains constant. This anomalous behavior is due to the fact that the fertilizer, compacting inside the loading hopper, is not able anymore to be transported and a kind of empty area arise around the cochlea that idles. Figure 14 shows clearly this empty area. During the experiments it has been considered the possibility of reversing the rotation direction of the cochlea after passing 120 s, but with a negative exit due to the big extension of the empty area around the cochlea. There is to underline that, with the same fertilizer, the first dosing device system could work properly without any problem, for its lower mass flow rate;

- in Table 5 a comparison between the theoretical mass flow rates of the designed dosing systems for the 3 fertilizers with the experimental mass flow rates estimated by the tests is reported; the experimental mass flow rate is lower than the theoretical one with a reduction that depends from the reality of the experiments different from the ideal conditions considered in the design phase. Anyway a mass flow of around 80% of the theoretical one is obtained for both the dosing systems and for the 3 fertilizers.

Fig. 14 Empty area around the cochlea for dosing system 2 fertilizer 3 after 120 s

6 Liquid Fertilizer Dosing System Tests

6.1 Theoretical Aspects

The tests carried out on liquid fertilizers considering the two previously dimensioned systems were organized as the tests referred to granular fertilizer. The two liquid fertilizer dosing systems were tested with three diverse liquid fertilizers. At least two repetitions were carried out for each configuration in order to verify the repeatability of the results. Moreover,

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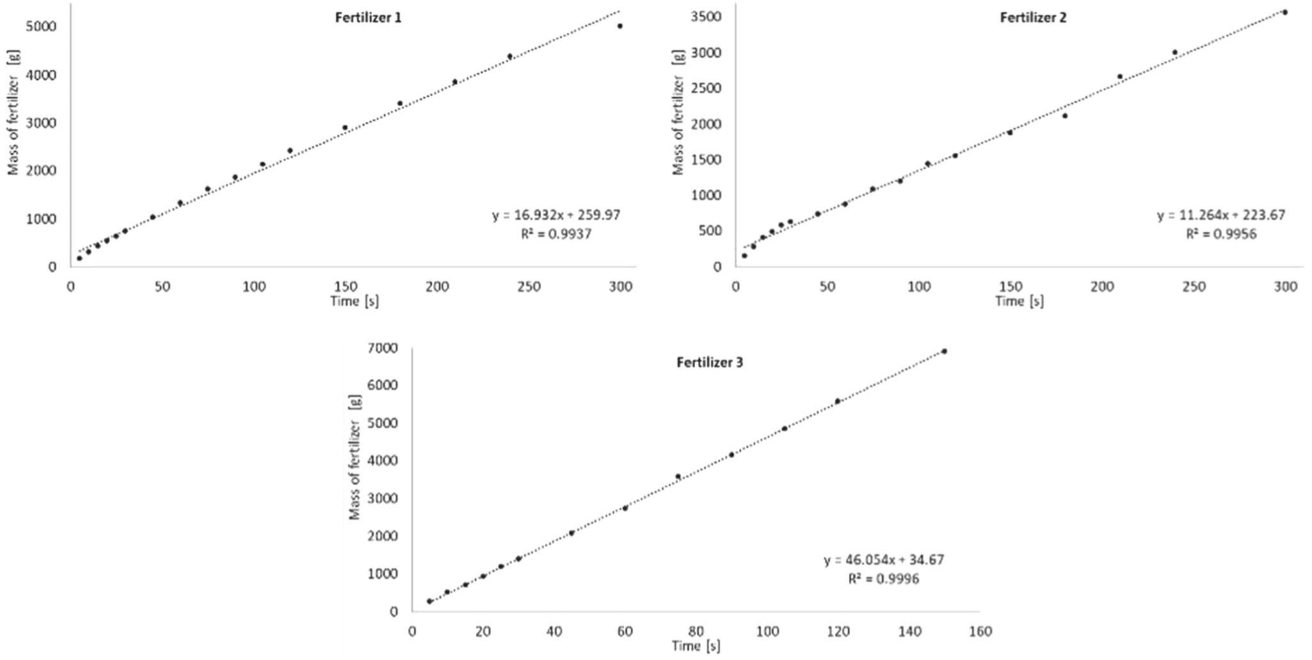

Fig. 15 Analysis of experimental results for the liquid fertilizer dosage system 1

Table 5 Experimental analytical data comparison granular fertilizer systems 1 and 2

Fertilizer	Granular fertilizer dosing system 1		Granular fertilizer dosing system 2	
	Analytical mass flow (g/s)	Experimental mass flow (g/s)	Analytical mass flow (g/s)	Experimental mass flow (g/s)
1	5.3	3.6	6.15	4.6
2	5.5	4	6.45	4.4
3	5.6	3.4	6.56	5

the working time of the motor of the peristaltic pump was increased starting from the value of 5 s, measuring, after the end of each test, the quantity of liquid fertilizer deposed in the tank placed at the exit of the peristaltic pump (see corresponding setup shown in Fig. 11). The results referred to the average value of 2 or 3 tests and to the 3 analyzed fertilizers are shown in Table 6 (dosage system 1 and dosage system 2) and the corresponding plots with the evaluation of the fitting straight lines with their equations and of the determination coefficient R^2 are shown in in Fig. 15 (three liquid fertilizers for dosage system 1 vs the pump opening time) and Fig. 16 (three liquid fertilizers for dosage system 2 vs the pump opening time). As clear from the characteristics of the liquid fertilizers, fertilizer 3 has a higher value of density, so it needs less time to achieve the same value of mass of the other fertilizers, and its characterization can be stopped with lower values of working time for the motor of the pump. Finally, it is important to underline that all the tests were carried out by completely filling of fertilizer the tank located at the entrance of the pump (the white tank in Fig. 10).

7 Results Analysis

The following important considerations may be carried out from the analysis of the experimental tests shown in Table 6 and Figs. 15 and 16:

- also in the case of the dosing systems designed for the liquid fertilizers, the behavior of both the systems has an excellent repeatability and a linear behavior for all the 3 considered fertilizers and the fitting straight line can give with a very low error an excellent model of the systems; for the two dosage systems, in all the cases, the average error is lower than 3%. This error is mainly due to the generation of air bubbles that generate small variations on the processed fertilizer. This low error, that is a bit bigger that the error for granular fertilizers, guarantees that it is possible with high accuracy to dose the quantity of granular fertilizers to use in all the cases. Of course, the behavior of the most powerful second dosing system shows a higher mass flow rate for each considered fertilizer;

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Table 6 Experimental results for liquid fertilizer dosage systems 1 and 2

Time (s)	Liquid fertilizer dosage system 1			Liquid fertilizer dosage system 2			
	Liquid fertilizer 1 (g)	Liquid fertilizer 2 (g)	Liquid fertilizer 3 (g)	Time (s)	Liquid fertilizer 1 (g)	Liquid fertilizer 2 (g)	Liquid fertilizer 3 (g)
5	178	157.5	279	5	808.5	777	1707.5
10	317	280	513	10	1380.5	1314.5	3255
15	429.5	413	705.5	15	1889.5	1783.5	4883
20	541.5	494	937	20	2354	2223.5	6449
25	643	586.5	1201.5	25	2976.5	2763	8084
30	754	631.5	1401	30	3470	3381.5	
45	1036	740.5	2088	35	4166.5	3933	
60	1333.5	880	2735.5	40	4653.5	4447	
75	1626.5	1095.5	3598.5	45	5189.5	4894.5	
90	1868	1204	4171	50	5628	5311.5	
105	2141	1452.5	4859.5	60	6210	6139.5	
120	2424	1554.5	5591.5	70	7505	7021	
150	2909	1881	6910.5	80	8423	7708	
180	3411.5	2114.5					
210	3851.5	2666					
240	4385.5	3011.5					
300	5015	3564					

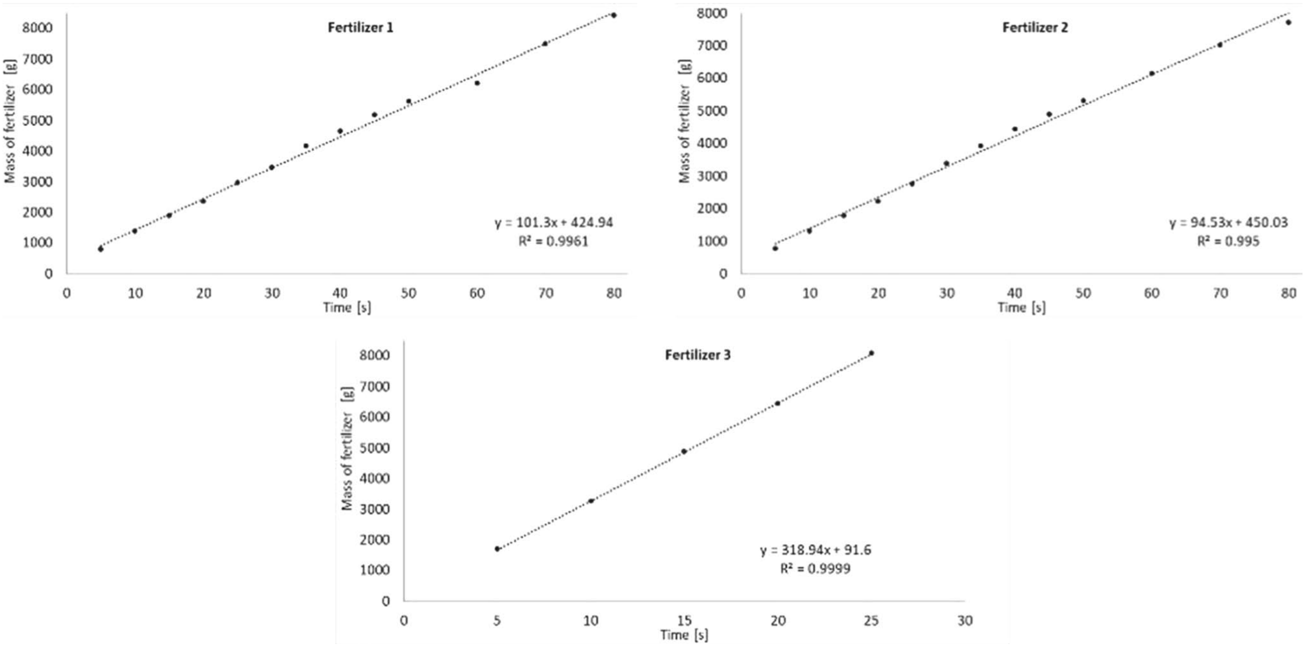

Fig. 16 Analysis of experimental results for the liquid fertilizer dosage system 2

- differently from the case of granular fertilizer, in this case the fertilizers have different physical characteristics (see Table 3) and fertilizer 3 has a density and mass flow rate much higher that the other two liquid fertilizers. The behavior is substantially linear in all the cases, but, considering the different fertilizers, it is possible to observe that it is a more regular for the more dense fertilizer 3 with a linearity error lower than the other 2 fertilizers;
- all the tests in Table 6 were carried out considering a constant quantity of fertilizer in the supply tank, a completely full tank condition. In order to investigate on the importance of this condition, that in operative situations

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Table 7 Experimental results for liquid fertilizer dosage system 1, partially empty supply tank

Time (s)	Liquid fertilizer dosage system 2		
	Liquid fertilizer 1 (g)	Liquid fertilizer 2 (g)	Liquid fertilizer 3 (g)
15	427	388	702
15	419	376	705
30	748	637	1388
30	742	630	1380
45	1019	702	2084
45	997	730	2088

Table 8 Experimental analytical data comparison liquid fertilizer systems 1 and 2

Fertilizer	Liquid fertilizer dosing system 1		Liquid fertilizer dosing system 2	
	Analytical mass flow (g/s)	Experimental mass flow (g/s)	Analytical mass flow (g/s)	Experimental mass flow (g/s)
1	42	37	350	162.8
2	44	32.2	378	156.6
3	61	56.4	518	340.2

may be not always respected, some tests (2 repetitions for each test) were carried out with a partially empty tank. The results are reported in Table 7 for the three liquid fertilizer and the dosage system 1 with partially empty supply tank. Comparing the results with the data in Table 6, it is possible to conclude that the effect of the filling level of the supply tank is not so significant and the mass of deposed fertilizer is analogue with the condition of completely full tank;

- in Table 8 a comparison between the theoretical mass flow rates of the designed dosing systems for the 3 liquid fertilizers with the experimental mass flow rate estimated by the tests for both the dosing systems is reported; the experimental mass flow rate is lower than the theoretical one with a reduction that depends from the dosage system (lower for the dosage system 1 with lower mass flow) and from the fertilizer (lower for the higher density fertilizer 3). This is justifiable by considering that as the velocity of the fluid increases, there is an increase in the energy losses by the system, due to dissipations that generally turn into heat. In this way the dissipations cause changes in the flow of the liquid, generating a reduction in the processed flow rate. This phenomenon is less evident with the fertilizer 3 with higher density that shows a bigger efficiency.

Finally, from all the aforementioned considerations and comments, it is possible to conclude that, with simple linear mathematical relations, we can determine directly and with an excellent accuracy, note the amount of fertilizer required by the crop, the operating time of the system for all the dosage systems designed and realized and for all the fertilizers (granular and liquid) tested.

8 Conclusions

Relying to the concept of precision agriculture, in this work some components have been designed and tested: four automatic fertilizer dosage systems, two for granular fertilizers and two for liquid fertilizers with different flow rates, that may be inserted in an innovative fertilization system powered by solar energy in such a way to optimize, with a high level of accuracy, the mass quantity of fertilizer placed in the ground.

The main aim of the research, besides the preliminary hardware design of an appropriate environmental node sensor hardware, has been the design from scratch, the realization and the testing of automatic dosage systems that may be driven by a control that uses the data of the network of sensors nodes placed in the field.

The several tests carried out and here presented, first of all, have made it possible to verify the correct analytical sizing of the dosing systems; as a result of the tests, it was possible to ascertain the proper functioning, in terms of moving the fertilizer from the loading area to the unloading area. Furthermore, the tests have allowed to determine the repeatability, considering the operating time constant, of the flow rate calculated as a function of the fertilizer and of the type of system under analysis. The analysis of the data made it possible to determine the linear mathematical expression, characteristic for each fertilizer and dosing system, which allows a priori to define, according to the actuation time, the quantity actually processed and the motor working time necessary to get the necessary quantity of fertilizer with high accuracy and very low error. The motor working time can be easily set by a simple digital driving board and a suitable control algorithm.

It has been observed that the granular fertilizers dosing systems have a slightly higher linearity and repeatability than the liquid fertilizer dosing systems, due mainly to the different chemical-physical behavior that, for liquid fertilizer, provoke the generation of air bubbles in the fluid especially at high speed and low density.

Moreover, after designing the dosing systems, the execution of the related experimental tests made it possible to compare the analytical data with those obtained experimentally. This comparison showed the fundamental importance of the calibration process, which allowed to define the trend of experimental data compared to analytical data. In this activity, the analysis was limited to only

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three different fertilizers for each system, however it was observed that the difference between the experimental and analytical data remained roughly constant with the variation of fertilizers, suggesting a similar trend for the others fertilizers commonly used in agriculture.

The setup used for the tests is characterized by its simplicity and economy and from the possibility of directly measuring the amount of fertilizer (liquid or granular) available in the ground, characterizing with a linear mathematical model the dosage system. The designed and tested dosing systems are now available for their use inside the fertigation solar powered systems; future specific developments for refining the research here presented could be related to the possibility of testing other fertilizers in such a way to create a database useful for avoiding for the user any kind of preliminary calibration for getting an accurate dosing. A further specific target for some solid/granular fertilizers (such as granular fertilizer 3) could be that of avoiding the problem of empty area around the dosing cochlea by designing a system for mixing the fertilizer in the hopper during the rotation of the cochlea. Moreover, it should be considered that the fertigation system could be applied in areas where environmental or external factors could heavily influence the necessities of the plants; at this aim a more complex investigation should be carried out including the correlations between the different influencing factors. The factors may be divided in specific factors related to the dosage system behavior (that have considered from the results of the experimental tests in this research), and external factors (environment, pollution, specificity of the plants, specificity of the place, etc.) where a complete and articulated analysis (i.e. [24]. that analyzes the dynamic factors for mitigating air pollution) should be necessary and useful for defining their relative contribution to the process. In the discussed case, the effects of the external factors may be considered inherent the dosage system control of the proposed complete fertigation system, where opportune sensors and control algorithms could take into account, in closed loop, the effect of external factors. Several tools have been recently introduced in the scientific literature [25–28] for supporting the control algorithm choices. The demonstrated extreme linearity of all the proposed low-cost dosage systems is a benefit for easily controlling the external factors and maintain a stable and well controlled behavior of the proposed fertigation system. Other automatic fertilizers (i.e. the system shown in [29]) have shown, in the field tests, a not negligible difference between the prescribed dosage and the applied one. The validation of the entire automatic fertigation system constitute the next research target including a functional analysis of the factors affecting the system performance.

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