On the Use of Encapsulated Phase Change Materials Pebbles and Pellets as Freeze Protection Method for Low-Stature Plants/Crops

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The use of phase change materials (PCMs) in encapsulated pebbles or pellets as freeze protection method for low-stature plants/crops is proposed and discussed at the conceptual level. Utilizing a simplified geometrical model, it is shown that, for practical applications, small encapsulated-PCM pebbles/pellets of 1-cm sized could provide the necessary heat to prevent the freezing during typical freezing time. Taking into account the balance between the loss of energy on a typical frost night and the latent energy stored in the encapsulated PCMs-pebbles/pellets, the amount of such pebbles/pellets per unit of soil-area was calculated and resulting in the use of less than 2% of the soil-area. The preliminary results at conceptual level are encouraging, however, additional work and R&D is require before its real practical efficacy can be put to test. The choice of the suitable crops, the specific environmental conditions during the freezing time, the manufacture recyclability and environmental impact of the pcm-pebbles/pellets are some of the aspects which must be carefully addressed.

Keywords. *Freeze Protection Crops. Phase Change Materials-PCMs*

I. INTRODUCTION

Damage to crops by freezing temperatures causes important crop yield losses worldwide every year. In the USA, there are more economic losses to frost damage than to any other weather-related phenomenon. In a recent report from the National Oceanic and Atmospheric Administration NOAA, [2] on the weather and climate billion-dollar disasters to affect the U.S. from 1980-2014 show losses on 26 billion dollars. Consequently, considerable effort to reduce damage is expended.

Nowadays, a number of different methods are used for preventing freeze damage to crops. The methods are described in terms of passive and active techniques, [1]. Passive methods are those which are used well in advance of the freeze and include proper scheduling of planting and harvesting within the safe freeze-free period such as (1) Site selection; (2) Land clearing; (3) Crop management; (4) Soil management; (5) Chemicals (growth regulators and Cryoprotectants and antitranspirants) ; (6) Plant Covers ; and (7) Evaporative Cooling among others. Active methods are those which are used when the danger of a freeze is present and takes place just before and during the occurrence of the frost after a warning has been issued in the weather forecast. They are usually only effective under radiative frost conditions when winds are light or calm, and are most suitable in low-lying, the most common active methods are (1) Covering ; (2) Fog or smoke clouds; (3) Wind machines ; (4) Sprinkling ; and (5) Heaters.

The object of this work was to analyze a novel and economical affordable approach for frost protection with particular reference to low-stature plants/crops by the use of phase change materials (PCMs) encapsulated as pebbles or pellets units. The present work is developed at a very conceptual level and the theoretical estimations reported result from general idealizations and are therefore not intended to give a definitive assessment of the applicability of the concept for any particular plant/crop. This should not be misconstrued as an attempt to present definitive quantitative values but rather illustrative results which somehow permit a rough general view of the possibilities of the idea. The thermal aspects treated in this work must be coupled with the specific plant/crop physiology, specific climate and environmental conditions, as well as whether it is safe both for humans as well as environment. Therefore, a lot more work and R&D is required before its real practical efficacy can be put to test, and

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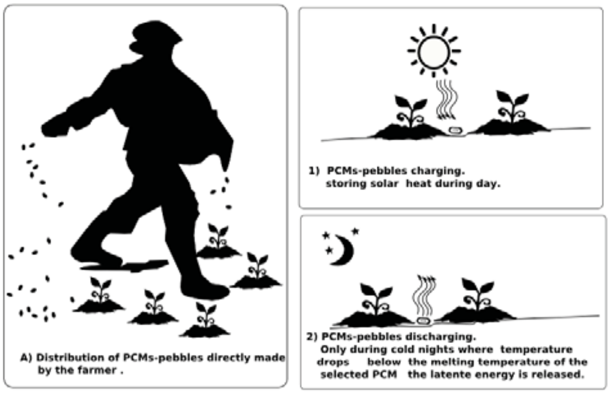

FIG. 1: The conceptual idea. **Left side:** Farmers can distribute the PCMs-pebbles by a simple sowing method (left side). The PCMs-pebbles/pellets can stay during all the year as a passive method. **Right side:** (1). During the day, PCMs-pebbles are charged by sun heating, and (2) during the freezing nights, the stored energy is release by the PCMs-pellet.

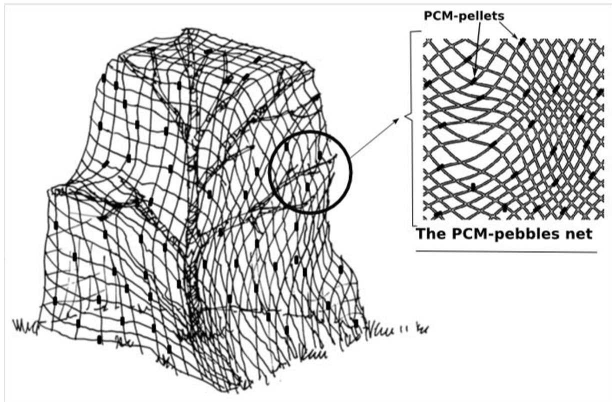

FIG. 2: Encapsulated PCMs Pebbles/Pellets nets. One practical application might be in the use of nets where a more optimal and controlled distance between pebbles/pellest could be ensured as well as the external thermal charging of the PCMs nets owing to its easy removal nature in comparison with the direct sowing method depicted in Fig. 1.

in this way this paper can be considered as first step.

A. The use of encapsulated PCMs as freeze protection method for crops

A Phase Change Materials or PCM is a substance with a high heat of fusion which, melting and solidifying at a certain temperature, is capable of storing and releasing large amounts of energy. This heat is absorbed or released when the material changes from solid to liquid and vice versa, and then, PCMs are properly classified as latent heat storage (LHS) units. However, although water can be classified as LHS if change of phase occurs (liquid$\rightleftharpoons$gas, or, solid$\rightleftharpoons$liquid) and its latent heat is used, nevertheless, in this paper we understand by PCM a material which has been deliberately designed for this purpose and almost exclusively to liquid $\rightleftharpoons$ solid phase change systems. [3].

The idea of using LHS as freeze protection method for crops is not new, it was already used through water irrigation (sprinkling water) prior to frost occurrence. In this case, the added moisture has the beneficial effects of increasing the capacity of the soil to store heat and improving conduction of heat to the surface. The heating of the soil during day time is reduced because increased evaporation uses up heat energy and the moisture may also change the critical temperature which is needed to cause freeze damage to a crop. However,

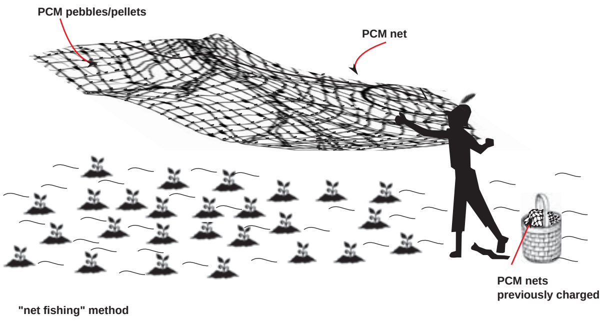

FIG. 3: Net fishing method.

the method has associated a certain complexity. For instance, when using sprinklers for freeze protection, the sprinklers should be started and stopped when the wet-bulb temperature (T_w) is above the critical damage temperature (T_c) and the air temperature to start the sprinklers must be estimated by first measuring the dew point (T_d) temperature, the application rate required for over-plant sprinkling depends on the sprinkler rotation rate, wind speed, and -as aforementioned, the dew point temperature which must be previously calculated. Finally, sprinklers need to provide constant and uniform coverage, [1].

II. THE USE OF ENCAPSULATED PCMS-PEBBLES/PELLETS FOR FREEZE CROP PROTECTION

The fundamental idea proposed in this manuscript based in the use of encapsulated PCMs-pebbles/pellets is schematically depicted in Fig. 1. Fig. 2 and Fig. 3 are two possible variations of the core idea showing the versatility of the concept. In summary, pellets or pebbles containing an encapsulated PCM inside - See Fig. 4, are used as solar thermal storage system. During the day the thermal solar energy is stored as latent heat by melting the PCM (phase change: solid→ liquid) and hence this time could properly referred as *"charging-time"*. Then, during the cold nights this latent heat is slowly released to the environment (phase change: liquid→ solid) and likewise might properly referred as *"discharging-time"*.

Thus, the PCMs-pebbles/pellets will be charged by the solar energy during day and only during cold nights when the temperature drops below of its melting temperature the energy will be released. This cycle of charging-discharging will be repeated every day -after freezing nights, for months or even years being the life-time or recyclability of the pebbles/pellets only limited by the degradation of cladding and the PCM itself. One of the attractiveness of the proposed use of encapsulated PCMs is the very large spectrum of melting temperatures available in the current PCM market, being conspicuous the organic PCMs because their melting temperatures are in the range required for soil protection, [3]. Organic PCMs also are unexpensive materials and then reducing the cost of production of the pebbles/pellets to the cladding materials

Because the simple nature of the concept, encapsulated PCMs-pebbles/pellets could be scattered in the soil directly by the farmer as is schematically depicted in Fig. 1 (left side) this method might be referred as *"PCM-sowing"*. In this case, the heat source must be necessary the sun because would be economically impractical a daily removal of the pebbles/pellets. In the "PCM-sowing" method one of the most important aspects to be considered is the cladding -see Fig. 4, which must prevent the release of the PCM into the soil while is being exposed to critical changes of temperature, rain, moisture, etc., and without showing any sign of degradation over very long periods (months or even years). Likewise in the case of accidental rupture of the cladding, the PCM must be compatible with the soil as possible, and then, certain features as PH or the biodegradability of the PCM which have not been considered so far in conventional application of PCMs (e.g., domestic hot water) must be investigated and then opening a new interesting line of research. Moreover, in the most ideal case for advanced designs, one can envisage the design of a PCM not only as a soil friendly material in case of accidental release, but also endowed with certain fertilizer properties and then accomplishing a double task in such a way that the degradation of the cladding with the time and then the release of the PCM into the soil will result in a certain fertilization.

Nevertheless, as was pointed out before, the *"sowing-method"* depicted in Fig. 1 implies almost certainly the use of solar energy as heat source. However, in some situations, places or specific environments, the sun can not be a reliable heat source during the day (e.g., during cloudy days), and then the charging of the PCMs pebbles/pellets could be jeopardized. For this situation, an attractive alternative is envisaged in Fig. 2 by the use of nets which allow the control not just of the space between pebbles-pellets -which is important as we will see in next sections, but also a daily removal of the nets and then opening the possibility of using of other source of energy for charging the encapsulated PCMs, for example, by using hot air blowers driven by electrical or fossil fuels. Once the nets are charged (i.e., the inside PCM is molten), they might be applied to the crops by the farmer as schematically depicted in Fig. 3. This method might be referred as *"net fishing"* method.

In the next section, we will develop the thermal analysis of the encapsulated PCMs pebbles/pellets units, but before, it is important to identify the main constraints that must be simultaneously satisfied, namely:

- **(1)** PCMs pebbles/pellets must be small with diameters no larger than ≈ 1 cm or thereabouts
- **(2)** Solidification time of the PCMs must be compatible with the typical freezing times. Minimum 2 hours.
- **(3)** Stored latent heat in the pebbles/pellets must be large enough to permit the use of a reasonable reduced number of pebbles/pellets per unit of soil-area.

A. Time of solidification

For the sake of simplicity, let us consider a spherical pebble as depicted in Fig. 4 as geometrical model for the solidification process. For cylindrical pellets, the same theoretical treatment is valid but with modification of certain constants as will see.
The time that the front of solidification needs to advance a distance **s** away from the surface of boundary at **R**, might be written as first estimate as, [3]

$$t = \frac{h \cdot \mathbf{s}^2}{2\kappa \cdot (T_{pc} - T_s)} f(\mathbf{s}^+, \beta) \qquad ; \mathbf{s}^+ = \frac{\mathbf{s}}{\mathbf{R}} \tag{1}$$

where h is the volumetric latent heat of fusion, κ the thermal conductivity, T_{pc} and T_s are the molten PCM and front of solidification temperature, respectively., **s**

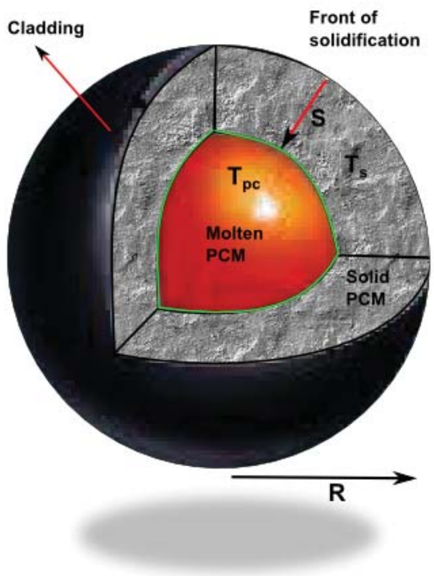

FIG. 4: Geometrical model for PCM-pebble/pellet thermal calculations.

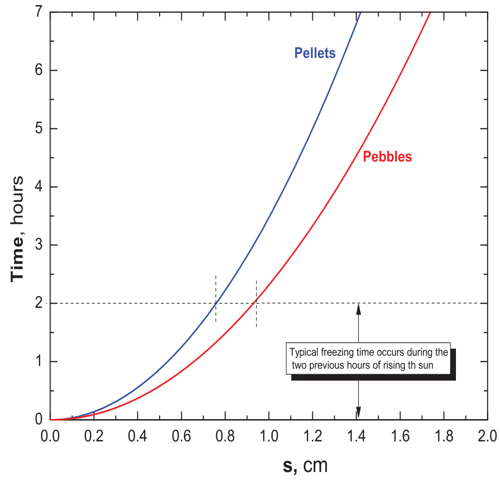

FIG. 5: The solidification time for cylindrical pellets and spherical pebbles for typical characteristic values of organic PCMs

is the front of solidification, $\mathbf{R}$ is the geometrical radius of the cylinder or sphere, f is a dimensionless number which takes into account the deviation from plates and β is a parameter taking into account boundary effects. For our specific case, β can be approximated to zero, [3] and then solutions for f for spherical (pebbles) and cylindrical (pellets) considering $\mathbf{s} = \mathbf{R}$, i,.e, $\mathbf{s}^+ = 1$ and $\beta = 0$ yield, [3]

$$f(\mathbf{s}^+, \beta) = \frac{1}{3} \qquad \textit{pebble} \tag{2}$$

$$f(\mathbf{s}^+, \beta) = \frac{1}{2} \qquad \textit{pellet} \tag{3}$$

which inserting into Eq.(1), one obtains for the solidification time,

$$t = \frac{h \cdot \mathbf{R}^2}{4\kappa \cdot (T_{pc} - T_s)} \qquad \textit{pellet} \tag{4}$$

$$t = \frac{h \cdot \mathbf{R}^2}{6\kappa \cdot (T_{pc} - T_s)} \qquad \textit{pebble} \tag{5}$$

The physical parameters in the above equations, i.e., h, κ, T_{pc} and T_s are specifics for a specific PCMs, however, in order to get a first estimate about the solidification times we can consider typical average values for organic PCMs as most suitable material for soil applications. For the latent heat, h are between $1.5 \times 10^8 J/m^3 \geq h_m \leq 2.5 \times 10^8 J/m^3$, so let us take an average value of $h = 2.0 \times 10^8 J/m^3$. Thermal conductivity are between $0.1 W/mK \geq \kappa \leq 3.1 W/mK$, so, let us take an average value of $\kappa = 1.6 W/mK$. Typical temperature differences $T_{pc} - T_s$ between the solidified and the molten PCM at the front of solidification are on 0.5 K or thereabouts. The resulting curves are shown in Fig. 5. Considering that the freezing of crops generally happen during the two previous hours of the rising of the sun, then with 2 hours for discharging, PCMs-pellets with radius $\approx$ 0.7 cm or spherical pebbles with radius $\approx$ 1 cm can be used

So far, constraints **(1)** and **(2)** have been satisfied. On one hand, the sizes of the pebbles or pellets are withing reasonable values around 1-cm, and on the other hand, the solidification time from using these sizes are within the typical periods of freezing.

Finally, we need to calculate how many encapsulated pebbles or pellets are needed by unit of soil-area in order to assess the technical and economical feasibility of the proposed concept.

B. The number of encapsulated pebbles-pellets

In order to calculate the number of pebbles or pellets per unit of soil-area, firs of all, we need to know the average net energy loss from the crop during a typical radiation frost, and on the other hand, we need to know the energy flux of each pebble/pellet projected into the soil-area.

During radiation frost conditions, energy is lost

TABLE I: Average energy fluxes during a radiation frost

Energy Transfer	**Flux Density**
	Watts per square meter
Conduction (from the soil)	+28
Convection (from the air)	+39
Downward Radiation (from the sky)	+230
Upward Radiation (from the orchard)	-315
Net Energy Loss from the crop	**-18**

through radiation upward from the surface. Energy is gained by downward radiation from the sky, by conduction of heat upward through the soil, and by convection of warmer air to the colder plants. Under clear skies, more heat is lost than gained in this process. Table 1 shows a typical nighttime energy balance for citrus, and the values are similar for other crops, [1].

From Table 1, the net loss of energy is in the order of $\mathbf{w} = -18W/m^2$ during a typical frost night.

For the calculation of the projected heat flux from the pebble or pellet into the soil, an average heat flux from the pebble or pellet may be defined as

$$\bar{\Phi} \approx \frac{h}{t} \cdot \left[\frac{V_{pc}}{A_{\parallel}}\right] \tag{6}$$

where again h is the PCM volumetric latent heat (J/m^3), t the solidification time (s), V_{pc} and $A_{\parallel}$ are the volume and the projected soil-area of the pebble or pellet, respectively. For a spherical pebble, $V_{pc} = \frac{4}{3}\pi\mathbf{R}^3$ and $A_{\parallel} = \pi\mathbf{R}^2$, and for a cylindrical pellet, with length equal to $2\mathbf{R}$ we have $V_{pc} = 2\pi\mathbf{R}^3$ and $A_{\parallel} = 4\mathbf{R}^2$. Then, taking into account Eq.(4) and Eq.(5) for the solidification time, the heat flux for pebbles and pellets per unit of soil-area yields,

$$\bar{\Phi} = 8\kappa\frac{(T_{pc} - T_s)}{\mathbf{R}} \qquad \textit{pebble} \tag{7}$$

$$\bar{\Phi} = 2\pi\kappa\frac{(T_{pc} - T_s)}{\mathbf{R}} \qquad \textit{pellet} \tag{8}$$

Finally, considering the previously calculated net energy loss from the crop (from table.I), $\mathbf{w}$, by a balance of energy, the area to be covered by pebbles or pellets A_{pc} giving an area of soil A_s is given by

$$A_{pc} = A_s\frac{\mathbf{w}}{\bar{\Phi}} \tag{9}$$

Therefore, the number of pebbles or pellets, $\mathbf{N}$ per unit of soil-area is given by

$$\mathbf{N} = \frac{1}{A_{\parallel}}\frac{\mathbf{w}}{\bar{\Phi}} \tag{10}$$

or

$$\mathbf{N}_{pebbles} = \frac{\mathbf{w}}{8\pi\kappa(T_{pc} - T_s) \cdot \mathbf{R}} \tag{11}$$

$$\mathbf{N}_{pellets} = \frac{\mathbf{w}}{8\pi\kappa(T_{pc} - T_s) \cdot \mathbf{R}} \tag{12}$$

Using $\mathbf{w} = 18W/m^2$ (see Table.I), and typical values for organic PCMs as $\kappa = 1.6W/mK$, $T_{pc} - T_s = 1.0K$ and using pebble or pellets of radius $\mathbf{R} = 1cm$, we have $\mathbf{N}_{pebbles} = \mathbf{N}_{pellets} \approx 60$ pebbles or pellets per m^2 of soil representing just between 1% to 2% of the soil-area.

III. DISCUSSION

In previous section it was demonstrated that, at least, at a very conceptual level, the use of encapsulated pebbles or pellets for frost-protection is a feasible and attractive technology. However, the proposed concept seems potentially more useful for low-stature plants/crops, such as strawberries, but not citrus or ornamental shrubs. And even with relatively small plants, one has to demonstrate the loss of exothermic heat from the pebbles (via dissipation) before it has a chance to provide any meaningful warming to the plant canopy. Such loss would be exacerbated under somewhat breezy conditions. Rhizosphere might get better warming effect than the above ground parts but roots are already insulated by the soil profile and even more so under a snow cover.

On the other hand, one needs to be also cognizant of the fact that preventing freezing of plant tissues is not necessarily always a good thing. Because, plants in temperate climates routinely freeze and thaw and survive as long as freezing stress is under the tolerance threshold. But, preventing freezing may result in supercooled plant cells which are quite vulnerable to intracellular freezing which is always lethal. However, the proposed method is preventing freezing by keeping a warmer local environment but without altering the solidification temperature -contrariwise with the use of chemical additives preventing freezing by reducing the solidification temperature. Then, intracellular freezing cannot occurs before freezing.

It must also be recognized that any such technology would only be embraced provided it had no deleterious effect on the soil health and plant's ability to take nutrients and water from the soil. And that how well and fast it is naturally decomposed; whether it is safe both for humans as well as environment. The preliminary results reported in this work are encouraging, however, additional work and R&D is required before its real practical efficacy can be put to test.

IV. SUMMARY OF RESULTS AND CONCLUSIONS

An alternative freeze protection concept for crops based in the use of PCMs encapsulated in pebbles or pellets has been proposed and discussed.
The concept is intended for easy application by farmers as well as an inexpensive and ecological method eliminating the need of previous complex calculations or in-situ surveillance during the freezing period and offering a long duration protection for months or years only limited by the cladding degradation of the pebbles/pellets.
Using a simplified geometrical model, it was shown that only a 1% to 2% of the soil-area should be covered by pebbles or pellets o with radius on 1 cm.

NOMENCLATURE

A = area
$A_{\|}$ = projected soil area
h = volumetric latent heat, J/m^3
N = number pellest/pebbles per unit of soil-area
R = radio of pebble or pellet
s = front of solidification
t = time
T = temperature
V = volume
w = net energy loss from the crop, (W/m^2)

Greek symbols

β = parameter for boundary effects
κ = thermal conductivity
Φ = soil-projected latent heat flux from pebble or pellet, (W/m^2)

Subscripts

pc = phase change material
s = surface of pellet

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