Integrating modified sheet-pipe technology in rice field subsurface water management

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Abstract. The development of subsurface irrigation and drainage technology offers a sustainable solution for agricultural water management and enhances efficiency and environmental resilience. This study focuses on the implementation of a sheet pipe for a subsurface water management system designed to optimise water usage while mitigating excess runoff and soil saturation. The system features perforated pipes enveloped by calcite-reinforced sand, making it particularly suitable for narrow or hard-to-access farmlands. Comparative flow capacity tests revealed that the sheet-pipe (SP-C) and perforated PVC pipe (PP-C) systems with calcite-reinforced sand achieved a discharge accumulation of 12,000 g within 90 s and 100 s, respectively, which were faster water flow rates than geotextile-covered alternatives. Further experiments integrated the sheet-pipe system with the cultivation of eight rice varieties developed by breeders at IPB University. The results demonstrated that the average water productivity based on evapotranspiration was 1.4 $kg.m^{-3}$ and total water input was 0.1 $kg.m^{-3}$. The findings underscore the potential of the sheet-pipe system to enhance irrigation practices, offering scalable and efficient water management solutions for various agricultural contexts.

1 Introduction

Efficient water management is a critical component of modern agriculture, particularly in regions where water resources are scarce or unevenly distributed. Traditional surface irrigation methods often result in significant water loss and can contribute to issues such as soil erosion and nutrient leaching. The development of subsurface irrigation and drainage

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systems presents a promising alternative, offering improved water use efficiency and greater environmental sustainability [1]. In this context, the current study explored the application of modified sheet-pipe technology designed to optimise water delivery and drainage in rice fields.

By focusing on the integration of calcite-reinforced sand, this system addresses the structural challenges associated with subsurface filters. Reinforcement often achieved through microbially induced calcite precipitation (MICP)—is essential for maintaining hydraulic conductivity and preventing sand migration under varying saturation levels [2]. Furthermore, the application of innovative pipe configurations and automated installation methods allows for the deployment of these systems in narrow or difficult-to-access farmlands, where heavy machinery is impractical.

Rice lines developed at IPB showed strong resilience across contrasting water regimes, maintaining growth and yield even when drought reduced plant height, root volume, and other physiological traits. One IPB-bred line demonstrated particularly robust root development and consistently produced the highest yield components under both lowland and upland conditions [3]. IPB's systematic screening identified doubled-haploid rice lines that remain stable and productive under deep-water submergence, strengthening adaptation to increasingly flood-prone environments [4]. These results highlight the effectiveness of the IPB breeding program in generating rice materials with stable productivity and strong adaptation to limited water environments. Therefore, it is the right choice for observation of sheet-pipe land.

Beyond operational efficiency, these advanced drainage technologies play a vital role in mitigating waterlogging and stabilizing rice yields in challenging soil environments [5]. The objective of this study was to investigate whether integrating modified sheet-pipe technology with calcite-reinforced sand can provide subsurface irrigation and obtain water productivity in rice cultivation, while also evaluating its adaptability to different field conditions and its potential for broader agricultural applications. By providing a more controlled root zone environment, this approach supports the development of more resilient and productive agricultural systems.

2 Materials and methods

The study implemented a subsurface water management system utilizing sheet-pipe [6] and perforated PVC pipe technologies. Both systems featured perforated pipes encased in calcite-reinforced sand, a material chosen for its ability to enhance the filtration and promote uniform water distribution. The making of calcite-reinforced sand was based on the method for soil stabilization with calcite precipitation [7].

Comparative flow capacity tests were conducted to evaluate the performance of the sheet-pipe system (SP-C) (Fig. 1) and the perforated PVC pipe system (PP-C) covered with calcite-reinforced sand against geotextile-covered systems. PP-C was the same as SP-C but used perforated PVC pipes with an orifice density similar to that of SP-C. The test was conducted by immersing the pipes in water and allowing the water to seep through the pores and flow out of one end of the pipes. Water discharge was measured and recorded, with particular attention to the time required to reach a specified discharge accumulation.

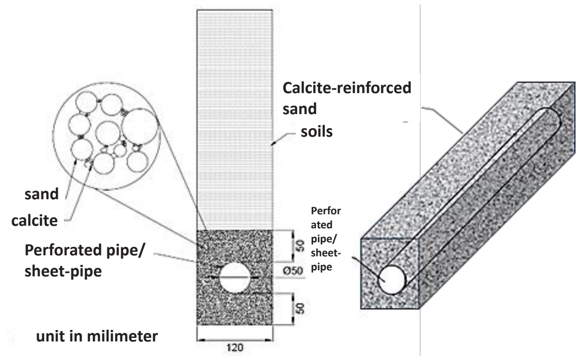

Fig. 1. Calcite-reinforced sand-covered sheet pipe.

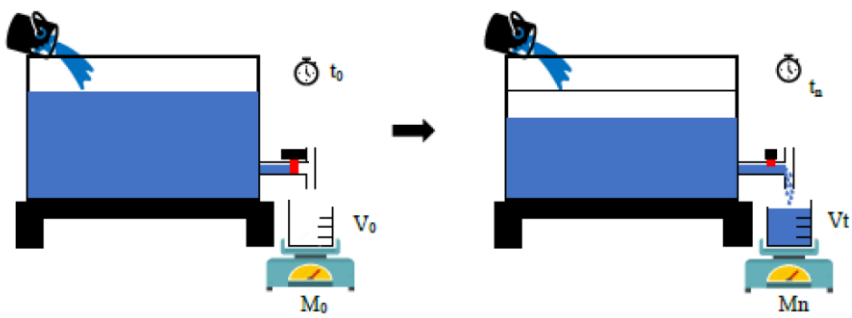

Fig. 2. Discharge test for modified sheet-pipe and perforated PVC pipe.

Fig. 3. Sheet-pipe experimental field

The discharge test was based on the combined falling-head principle (Fig. 3). In this method, water is poured onto the sample and allowed to flow downward through the soil, causing the hydraulic head to decrease gradually. This approach is suitable for fine-grained soils. Water was poured onto the sample, and the outflow at the end of the pipe was measured based on the weight and volume per unit time. The pipe outlet was modified to ensure that the discharged water flowed vertically, making the measurements easier and more accurate.

The sheet-pipe system with calcite-reinforced sand was integrated into rice cultivation trials, in which six new rice varieties developed by breeders at IPB University (IPB V01-06: 3S, 9G, 12S, 13S, 14S, 15S) and two national varieties (Nat V01-02: INPARI 32, INPARI 30) were grown. The experiment was carried out on land measuring 25 m × 12 m, with a sheet-pipe system at a depth of 40 cm underground (Fig. 3). Sheet pipes were installed lengthwise at a distance of 4 m from each other. This installation is a modification of the standard installation to adjust to conditions in narrow lands. Measurements were conducted using automatic weather stations, water level sensors, and flow meters. Water productivity was assessed by calculating yield based on both evapotranspiration (WPETc) and total water input (WPIR) [8].

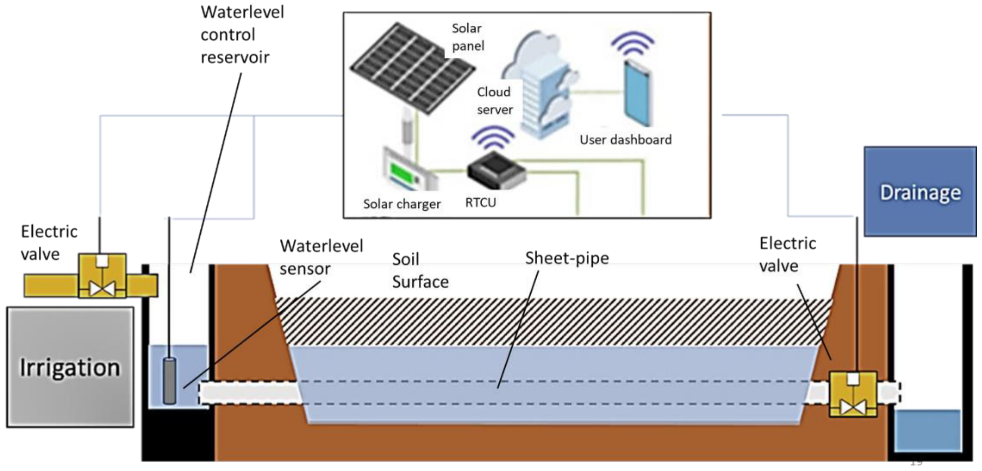

Fig. 4. Sheet-pipe smart irrigation and drainage system scheme.

Fig. 4 illustrates the sheet-pipe smart irrigation and drainage system powered by solar energy and managed via IoT technology, with automated valves controlling both water input and drainage to optimise water levels. The system uses a solar panel, router, cloud server, and device for remote monitoring, enabling farmers to manage irrigation and drainage efficiently and sustainably from afar. This system was set up, but for this case, we conducted the experiment manually to supply water from beneath.

3 Results and discussion

The flow capacity tests (Fig. 5) revealed that both the SP-C and PP-C systems with calcite-reinforced sand significantly outperformed the geotextile-covered alternatives in terms of water flow rates. Specifically, the SP-C system achieved a discharge accumulation of 12,000 g within 90 s, whereas the PP-C system reached the same threshold in 100 s. These results indicate faster and more efficient water movement through the subsurface system, which is essential for maintaining optimal soil moisture levels and preventing waterlogging. This graph compares the total water discharge over time for the four experimental setups combining different pipe types and reinforcement materials. The x-axis shows the time in seconds (0–120), whereas the y-axis shows the total discharge in grams (0–14,000). Among the setups, the sheet pipe with calcite-reinforced sand (SP-C) produced the highest discharge, followed by perforated PVC with calcite (PP-C), sheet pipe with geotextile (SP-G), and perforated PVC with geotextile (PP-G). The inset zoomed-in plot highlights the early discharge dynamics, showing that SP-C also had the fastest initial flow. Overall, calcite-reinforced sand enhanced the discharge performance more effectively than geotextiles, especially when paired with sheet-pipe systems.

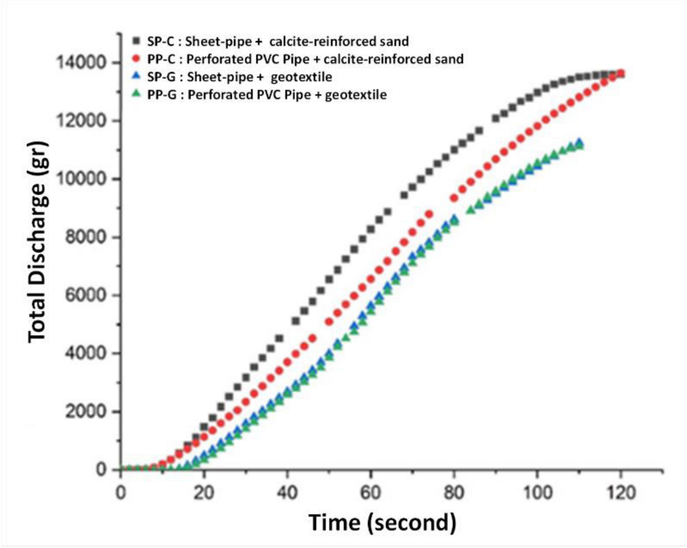

Fig. 5. Flow capacity experimental results**.**

Crop evapotranspiration (Etc) was calculated based on the reference evapotranspiration and paddy crop coefficient. Fig. 6 shows the fluctuation of Etc as well as the water level during the observation. This figure illustrates the relationship between crop evapotranspiration (ETc) and water level over a 91-day period after rice transplantation. The green vertical bars represent the daily ETc (in mm/day), showing the fluctuating water demand of the crop, while the blue line tracks the water level (in cm), which varies from submergence (negative values) to above-ground ponding. The graph highlights the dynamic interactions between crop water use and field water conditions, which are useful for assessing irrigation timing, drought stress, and submergence management in rice cultivation.

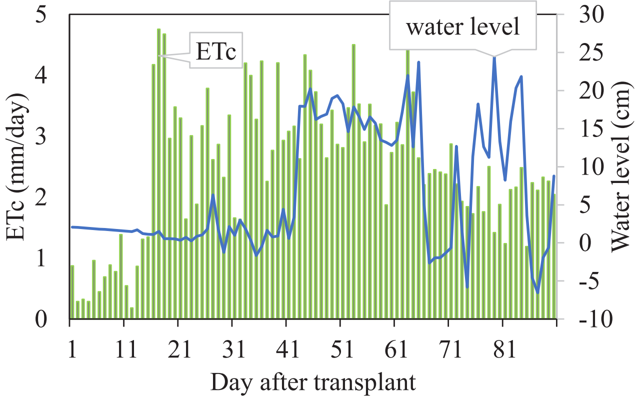

Fig. 6. Evapotranspiration and water level fluctuation

Rice cultivation trials demonstrated that the sheet-pipe system consistently improved water productivity across a range of varieties, with WPETc values spanning from 1.0 to 2.0 kg/m³ and WPIR values from 0.1 to 0.2 kg/m³. Notably, several varieties achieved yields above 6 kg, with the highest reaching 9.1 kg, indicating that the system effectively supports high-yield performance, even under limited water input (Table 1). These results reinforce the sheet-pipe system's role in optimizing water use efficiency, making it a promising solution for sustainable rice farming in areas with constrained irrigation access or challenging field conditions.

Table 1. Yield and water productivity

Variety	Yield (kg)	WP_{ETc} (kg.m^{-3})	WP_{IR} (kg.m^{-3})
IPB V01	4.5	1.0	0.1
IPB V02	5.3	1.1	0.1
IPB V03	5.9	1.3	0.1
IPB V04	5.0	1.1	0.1
IPB V05	9.1	2.0	0.2
IPB V06	6.9	1.5	0.1
Nat V01	6.0	1.3	0.1
Nat V02	8.7	1.9	0.2

4 Conclusions

This study demonstrates that integrating modified sheet-pipe technology with calcite-reinforced sand presents a viable and effective approach for subsurface water management in rice cultivation. The superior flow rates and positive impact on water productivity of this system highlight its potential to optimise irrigation efficiency and support sustainable agricultural practices. Given its adaptability to different field conditions and crop varieties, the sheet-pipe system offers a scalable solution for improving water management in diverse farming contexts in the future. Future studies should explore its long-term benefits, economic feasibility, and potential integration with other sustainable agricultural technologies.

References

1. M. Jafari-Talukolaee, H. Ritzema, A. Darzi-Naftchali, A. Shahnazari, Subsurface drainage to enable the cultivation of winter crops in consolidated paddy fields in Northern Iran. Sustainability (Switzerland). **8**, 3 (2016). https://doi.org/10.3390/su8030249
2. L. Cheng, R. Cord-Ruwisch, M.A. Shahin, Cementation of sand soil by microbially induced calcite precipitation at various degrees of saturation. Can. Geotech. J. **50**, 81-90 (2013). https://doi.org/10.1139/cgj-2012-0023
3. S.S. Yuwono, I. Lubis, M. Ghulamahdi, E.R. Palupi, Morphological, physiological and rice yield in lowland and upland under drought stress. Aust. J. Crop Sci. **19**, 4 (2025). https://search.informit.org/doi/10.3316/informit.T2025052400009401451501889
4. M.F. Anshori, B.S. Purwoko, I.S. Dewi, W.B. Suwarno, S.W. Ardie, Systematic selection to adaptive doubled haploid rice lines under different environments of submergence screening methods. J. Agric. Food Res. **14**, 100775 (2023). https://doi.org/10.1016/j.jafr.2023.100775
5. B. Qi, S. Yang, D. Li, D. Qin, X. Zheng, J. Hu, X. Zhou, H. Liu, Effects of drainage technology on waterlogging reduction and rice yield in mid-lower reaches of Yangtze River. Agronomy. **15**, 4 (2025). https://doi.org/10.3390/agronomy15040905

6. S.K. Saptomo, M.Y.J. Purwanto, C. Arif, B.I. Setiawan, K. Tamura, H. Matsuda, Implementation of sheet-pipe subsurface drainage system in Indonesia: Enhancing soil aeration and water management, in Proceedings of the Frontier in Sustainable Agromaritime and Environmental Development Conference (FiSAED 2024), Bogor, West Java, Indonesia, December 19-20, 2024 (2025). BIO Web Conf.
7. L. Lofianda, H. Putra, E. Erizal, S. Sutoyo, H. Yasuhara, Potentially of soybean as bio-catalyst in calcite precipitation methods for improving the strength of sandy soil. Civil Engineering and Architecture. **9**, 2317 (2021). https://doi.org/10.13189/cea.2021.090719
8. D. Molden, R. Sakthivadivel, Water accounting to assess use and productivity of water. Int. J. Water Resour. Dev. **15**, 55 (1999). https://doi.org/10.1080/07900629948934