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Learning Innovation Together with Community: Inventing and Commercializing Slow-Release Organic Nano Fertilizer Pellets for Healthy and Sustainable Rice Agriculture

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Abstract The village of Jagaraga, located in the Sawan district of Buleleng Regency, Bali Province, had significant potential in both culture and agriculture, particularly in rice farming. More than half of the village's land area was rice fields, and over two-thirds of the villagers were rice farmers. However, ensuring healthy soils and crops through effective fertilizer solutions remained a major challenge. The aim of the community development initiative was to empower the village farmers to become innovative through collaborative learning and by inventing and commercializing a slow-release nano fertilizer. A participatory action and learning approach was used to engage the rice farming community. The Subak Babakan farmer organization and the local rice milling enterprise, PB Suwela Amertha, were involved in the empowerment activities, which included information sessions, training, technology application, guidance, evaluation, and sustainability planning. As a result, four formulas of slow-release organic nano fertilizers in pellet form were successfully developed. Additionally, a four-helix partnership involving academicians, the farmer community, enterprises, and the government was established to build a business platform for commercializing the innovation. Through this collaboration, academicians and community farmers successfully learned to address the primary challenges in rice agriculture innovatively while promoting sustainable practices to maintain the health of the land and the well-being of the villagers.

1. INTRODUCTION

The community empowerment initiative was carried out to develop Jagaraga Village, District of Sawan, Regency of Buleleng, Bali Province, Republic of Indonesia, as an innovation-based techno-park village, where the villagers were intended to be developed as creative and innovative individuals, ensuring their better quality of life and sustainable future. Jagaraga Village covers an area of 338 hectares, with land use distributed as follows: (a) Residential land: 20.002 hectares, (b) offices/schools: 0.10 hectares, (c) fields/moorlands: 6.22 hectares, (d) rice fields: 262.874 hectares, and (e) cemeteries: 0.41 hectares. Thus, rice fields make up 77.22% of the village's land area. The livelihood and income of Jagaraga Village residents remain predominantly tied to the agricultural sector, particularly rice farming.

An intensive observation of the paddy's farmers was already conducted and showed a vital information about the land soil and paddy's plant problems. Some causes of the problems had been mentioned by the interviewed farmers, particularly the rice field soil treatment before planting and the use of inorganic fertilizers as well as chemicals for combating pests and rice plant diseases. Two most feared

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problems of rice farmers are: (1) harvesting fail because the rice plants collapse just before harvesting time due to wind and rain and (2) the damage to rice paddy land soils that are difficult to repair. Meanwhile, the farmers have not yet confidently moved on the organic agriculture as currently promoted intensively by other stakeholders such as academicians, governments officers and non-governmental organizations that are concerned with organic agricultures. They need to be empowered to address their agricultural challenges independently, drawing motivation and determination from within themselves. A well-designed program is essential to help the village initiate steps toward realizing their hopes and achieving their goals.

There are four key community elements driving the motivation to develop Jagaraga Village as a techno-park, implementing green innovation for the sustainable development of rice agriculture: Jagaraga villagers, governmental village officials, village-owned enterprises (BUMDesa Jagaraga), and the Suwela Amertha rice mill enterprise. From the perspective of the Jagaraga villagers, most of the people are in urgent need of stable jobs that guarantee their livelihoods; thus, they require increased knowledge and life skills that can be acquired for free or at an affordable cost. In addition, the villagers need continuous coaching to empower the village's potential, with the farming community of Subak Babakan as the primary target group for this initiative. From the side of village officials, both the official government apparatus, led by the Head of Jagaraga Village and his staff, and the customary government apparatus, headed by the Traditional Chairman of Pekraman Jagaraga and his staff, show strong motivation to develop the village, aligning their efforts with the vision and mission of Jagaraga Village. The synergistic harmony between these groups is a crucial factor in the success of village development. The BUMDesa Jagaraga exhibits a high level of motivation to play an active role in improving the welfare of the community through various productive initiatives that empower village resources, generate added value, and enhance the village's original income. In addition to focusing on the economic sector, particularly in providing for the basic needs of the community, BUMDesa Jagaraga requires coaching to further develop productive businesses by utilizing human, natural, spiritual, cultural, and socio-economic resources unique to Jagaraga Village. Meanwhile, the Suwela Amertha Rice Mill (PB. Suwela Amertha), owned and led by Mr. Nyoman Partha, plays a pivotal role in sustaining the largest rice production enterprise in eastern Buleleng, employing 53 workers with a production capacity of 10–15 tons per day. The enterprise heavily relies on grain drying and milling technology, which is critical in determining the quantity, quality, and consistency of production, alongside the quality and quantity of rice harvested by farmers. Collectively, the harmonious collaboration among these four elements significantly determines the success of Jagaraga Village's development as an innovation-based techno-park focused on sustainable rice agriculture.

The community empowerment program aimed to enhance the innovation capacity of rice farmers in solving agricultural challenges effectively and sustainably, with a strong emphasis on maintaining healthy soils and rice plants. A notable example of this effort involved a collaborative package of activities—combining farmers, academicians, government officials, and local enterprises—that focused on the invention and commercialization of a slow-release organic nano fertilizer in pellet form. The pellet fertilizer comprises silica-carbon nanocomposites and nano silica powders derived from rice husk ashes, nano calcium phosphates from slaughterhouse bone waste, nanoparticles of magnesium, copper, and zinc oxides synthesized via green methods, and organic matter from fermented goat and sheep manure. This innovative fertilizer was supported by scientific research and prior art, including patents and studies. Karyasa et al. (2018) patented silica-carbon nanocomposites from rice husk ashes and highlighted silicon's role in agriculture, showing that combining nanocomposites with rice husk charcoal can reduce ion forms of N, P, and K. Green synthesis methods for oxide nanoparticles were referenced from Rotti et al. (2023). Dissolved silicon in paddy water, as reviewed by Souri et al. (2021), improves soil health and mitigates biotic and abiotic stress in rice plants. Ogunyemi et al. (2024) demonstrated copper oxide nanoparticles (CuO-NPs) as an effective tool against bacterial leaf blight in rice, while Ali et al. (2024) showed that MgO-NPs enhance plant resistance to both biotic and abiotic stresses through structural, biochemical, and molecular pathways. The impact of ZnO-NPs on soil microorganisms and plant growth, especially in promoting nitrogen fixation and microbial activities, was studied by Strekalovskaya et al. (2024). Additionally, the availability of free silica in paddy soil and water was identified as crucial for rice growth, health, and productivity (Ahmad & Hassim, 2024; Haruni et al., 2024; Surendar et al., 2024). By combining these nanoparticles—nano silica, nano calcium phosphate, silica-carbon nanocomposites, and organic fertilizers—the program provided an innovative solution to longstanding agricultural challenges, paving the way for sustainable advancements in rice farming.

2. METHOD

Participatory action and learning together approach were conducted to empower rice farmer community by including village officers and private rice mill enterprise as well as village-owned enterprise through learning together in solving problems of farmers in their rice agricultural area. The participatory action and learning together approach were adopted from several related studies (Cornish et al., 2023; Kusumawati et al., 2024; Situmeang et al., 2024). The information session, training, applying technology, guiding and evaluating, and sustaining the program were conducted to invent and to commercialize a slow-release organic nano fertilizers in forms of pellets for solving the problems of rice field soils as well as to strengthen rice plants in combating against biotic and abiotic stresses. Those steps of community empowerment were adopted

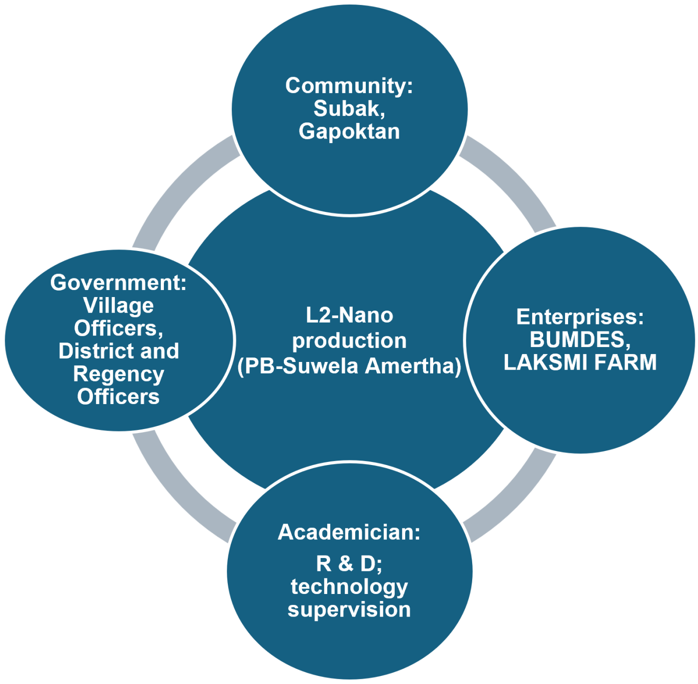

Figure 1 . Four-helix flatform for producing and commercializing the L2-Nano fertilizer pellets

from the national guidance of community service program (Direktorat Riset, Teknologi, dan Pengabdian kepada Masyarakat, 2024).

In the first step, the communication of the program was conducted to the community empowerment targeted members comprising of five selected farmer community members of Subak Babakan Jagaraga, two head local enterprises of BUMDES Jagaraga and PB. Suwela Amertha that showed interested in involving the program. In the second step, the appropriate technology of making L2-Nano organic fertilizer pellets was introduced and trained to the community empowerment targeted members by learning together in formulating of the fertilizer pellets beginning with making organic fertilizer powders from goat and sheep manures, nano calcium phosphate from bovine bone waste powders, nano composite of silica-carbon from black carbonized rice husk, bio-charcoal fine powders from bamboos stems, and nanoparticles of MgO, CuO and ZnO by applying green synthesis using green extract of mango leaves and salt powders of MgCl2, CuCl2, and ZnCl2 respectively and making the pellets.

Thirdly, the applying of technology step, the farmers and the academicians worked together in making L2-Nano organic fertilizer pellets in four compositions, namely Batukaru-01 (BTK-01), Batukaru-02 (BTK-02), Batukaru-03 (BTS-03), and Batukaru-04 (BTS-04), and in applying the fertilizer pellets for paddy's plantation in a demonstration plot where the experiment was performed. The demonstration plot consisted of five rice fields (each field area was 20 m2) comprising of experiment groups of A (rice plants with L2-Nano fertilizer pellets of BTK-01), B (rice plants with BTK-02), C (rice plants with BTK-03), D (rice plants with BTK-04) and K (rice plants with normal condition and conventionally conducted paddy's plantation)).

Fourthly, the guidance and evaluation steps were conducted by caring together of the paddy's plants on the demonstration plot and measuring the nitrogen (N), phosphorus (P), potassium (K) and conductivity of the respective rice field soils of the five rice fields in the demonstration plot by using the instrument of RS485 soil NPK PH EC Temp humidity Sensor tester 7 in 1 soil available in Jayapurateknik (JPT) via online market place. Finally, the fifth step was a sustaining program, in which a focus group discussion was conducted to construct a four-helix partnership flatform of production and commercialization of the invented L2-Nano fertilizer pellets.

Furthermore, a four-helix partnership involving academicians, the farming community, enterprises, and government was established to create a business platform for producing and commercializing the invention, as illustrated in Figure 1. The participation levels of the targeted community members were observed and analyzed descriptively, using the framework of participation levels outlined by Vaughn & Jacquez (2020). Additionally, measurement data from five rice field soils on the demonstration plot were evaluated to determine how the academicians and community farmers collaboratively engaged in innovative problem-solving for rice agriculture. This collaborative effort not only addressed key agricultural challenges but also promoted sustainable practices to maintain the health of the land and the well-being of the villagers.

3. RESULT AND DISCUSSION

Four slow-release organic nano fertilizers in pellet form were developed, each with distinct formulas. The main ingredients include goat and sheep manure compost as the base organic material, silica-carbon nanocomposite as a slow-release agent, nano silica powder as a source of free silica for rice field soils and waters, and nano calcium phosphate as a source of calcium and phosphate ions, both released slowly alongside nitrogen and potassium from the compost. Additionally, nanoparticles of CuO-NPs, MgO-NPs, and ZnO-NPs are incorporated as functionality enhancers. These four fertilizer pellets are named Batukaru-01 (A), Batukaru-02 (B), Batukaru-03 (C), and Batukaru-04 (D), as shown in Figure 2.

In Figure 2, farmers faced difficulties distinguishing between the A, B, C, and D fertilizer pellets due to their black color and uniform appearance. In Figure 3, farmers and academicians collaborated in a rice field experiment using the four types of organic nano fertilizer pellets. The experimental groups applied 5 kg of pellets per 20 m² of prepared field, while the control group used conventional inorganic fertilizers. After 25 days, the differences between the experimental and control groups were evident in the performance of the rice plants.

Ten targeted community members participated actively in the program. These included five rice farmers, the head of the rice farmer community (Subak Babakan Jagaraga), the head of the local village enterprise (BUMDesa Jagaraga), a representative from PB Suwela Amertha, a representative from Laksmi Farm, and a Jagaraga village official. These participants were involved in various activities: formulating and producing the L2-Nano fertilizer pellets (as shown in Figure 2), applying the fertilizer in five rice fields within the demonstration plot (as shown in Figure 3), guiding and evaluating the results, and building a four-helix collaboration platform for producing and commercializing the L2-Nano fertilizer pellets.

Observation data on participation levels, based on Vaughn & Jacquez (2020), are depicted in Figure 4. The findings showed that 100% of the participants received information or training on the technology, 80% provided input during consultations, 60% engaged directly with researchers or academicians, 55% collaborated with researchers or academicians, and 40% were empowered to lead further processes, achieving program goals and securing resources for sustaining the initiative.

Figure 2 . Four pellets of slow-release organic nano fertilizers

Figure 3 . Experiment together using the fertilizer pellets

Figure 4 . Participation levels and their achievement percentages of targeted community members

Table 1 . Measurement data of pH, N, P, K and electrical conductivity of rice field soils

Group Code		pH	N (mg/Kg)	P (mg/Kg)	K (mg/Kg)	Electrical Conductivity (us/cm)
A	A1	7	30	43	86	427
	A2	7	34	48	95	464
	A3	7	33	46	92	455
	Average	7.00	32.33	45.67	91.00	448.67
	Deviation	0	2.08	2.52	4.58	19.30
B	B1	6.66	33	44	95	461
	B2	6.54	31	46	89	447
	B3	6.67	38	48	107	537
	Average	6.62	34.00	46.00	97.00	481.67
	Deviation	0.07	3.61	2.00	9.17	48.43
C	C1	7	33	46	92	462
	C2	6.86	34	48	97	486
	C3	6.7	32	46	92	470
	Average	6.85	33.00	46.67	93.67	472.67
	Deviation	0.15	1.00	1.15	2.89	12.22
D	D1	7.14	21	16	53	166
	D2	7.14	29	41	62	416
	D3	7.57	24	34	69	346
	Average	7.28	24.67	30.33	61.33	309.33
	Deviation	0.25	4.04	12.90	8.02	128.97
K	K1	7.49	12	13	36	124
	K2	7.66	18	28	46	279
	K3	6.55	21	21	44	220
	Average	7.23	17.00	20.67	42.00	207.67
	Deviation	0.60	4.58	7.51	5.29	78.23

The farmers also expressed interest in testing the pH, nitrogen (N), phosphorus (P), potassium (K), and electrical conductivity (EC) of the rice field soils in both the experimental and control groups. Using four-probe sensors available in the online marketplace, they collected the data, which are presented in Table 1. The data in Table 1 revealed significant differences between the control and experimental groups. The availability of N, P, and K in the rice field soils indicated that the fertilizers released nutrients slowly, and the composition of the fertilizer components influenced the release rates of N, P, and K.

From the data in Table 1, the farmers and researchers observed the following:

1. The pH of all five rice field soils was quite similar and near neutral.
2. Average N content followed the order: B > C > A > D > K (control).
3. Average P content followed the order: C ≈ B > A > D > K.
4. Average K content followed the order: B > C > A > D > K.
5. Average EC values followed the order: B > C > A > D > K.

These findings indicate that the B pellets (Batukaru-02 or BTK-02) exhibited the highest performance in maintaining optimal pH, nitrogen (N), phosphorus (P), potassium (K), and electrical conductivity (EC) in the rice field soils. Additionally, all experimental pellets (BTK-01, BTK-02, BTK-03, and BTK-04 L2-Nano fertilizers) demonstrated superior performance in fertilizing the soils compared to the conventional fertilizers used in the control group.

The ratios of N:P and N:K of A, B, C, D, and K groups of rice field soils can be briefly described as follows. The ratios of N:P of A, B, C, D and K groups of rice field soils are 0.708; 0.739; 0.707; 0.813; and 0.822, respectively. The ratios of N:K of A, B, C, D and K groups of rice field soils are 0.355; 0.351; 0.352; 0.402; and 0.405, respectively. The ratios mean that the free availability P contents of the rice field soils are higher than that of N contents, the smaller the ratios mean the higher of P content than that of N content. As reported before, free phosphate (P) in soils participates in the formation of cellular membranes and in various metabolic processes and promotes plant growth and physiological metabolism (Roychowdhury et al., 2023), thus for rice plant growth, content of P need to be high in the rice field soils. In terms of K contents for growing of rice plants the higher content of K because with increasing K application, the growth condition of rice was improved and flowering earlier as reported by Ye et al. (2019). Furthermore, as shown in Table 1, the electrical conductivities of rice field soils of B > C > A > D > K. It means that the B group has the best soil electrical conductivity among them, meanwhile electrical conductivity is an important indicator of soil salinity and physicochemical properties, where empirically found before that the higher electrical conductivity of the rice field soil is, the higher microbial diversity, soil enzyme properties, and nutrient contents available in the soil (Kumar et al., 2021). In conclusion, the B rice field soil or the use of BTK-02 slow-release nano fertilizer pellet can preserve prospectively better nutrients and microbials diversity for rice plant growth and yield, thus the involved farmers in this field experiments can ensure to use the BTK-02 composition as a slow-release fertilizer for recovering their rice field and better growing their rice plants.

The impacts of the learning and experimenting activities on the farmers are evident in their increased understanding of the factors causing differences in rice plant performance among the experimental groups. Through direct observation and hands-on experience, the farmers learned that organic fertilizers enriched with nanoparticles provide a promising transition from inorganic to organic fertilizers, demonstrating the potential of nanochemistry in agriculture. Consequently, these activities enhanced not only the farmers' knowledge and rice cultivation skills but also their innovation capabilities.

The local rice milling enterprise, PB Suwela Amertha, aligns well with the production of organic nano fertilizers due to the abundant availability of rice husks—a significant byproduct of the rice milling process. These rice husks can be repurposed to create nano silica, silica-carbon nanocomposites, and biochar, adding considerable value to the waste. Meanwhile, the village-owned enterprise (BUMDesa Jagaraga), as a representative of the village government, can play a key role in marketing and promoting the use of these organic nano fertilizers.

Furthermore, academicians can contribute by refining the fertilizer prototypes and conducting further feasibility studies. This collaboration among farmers, local enterprises, village officials, and academicians fosters a sustainable and innovative approach to addressing agricultural challenges, ultimately benefiting the entire community.

4. CONCLUSION

The field experiment involving the application of slow-release nano fertilizer pellets in rice field demonstration plots successfully demonstrated that the BTK-02 fertilizer pellets outperformed others in preserving free available nitrogen (N), phosphorus (P), and potassium (K) in the soil, as well as maintaining soil electrical conductivity—factors critical for rice plant growth and yield. This collaborative learning innovation with the farming community resulted in valuable practices not only for rice farmers but also for academicians, village government officials, and local enterprises. These stakeholders gained experience in joint invention and commercialization, fostering innovation capabilities among all involved. Notably, the farmers have begun confidently addressing challenges in rice agriculture by adopting eco-friendly advanced materials. This indicates that the collaborative experiment has enhanced farmers' capacity for innovative problem-solving, enabling them to tackle agricultural challenges wisely and effectively while prioritizing sustainable soil health and rice crop growth.

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CONFLICT OF INTERESTS

The authors declare there is no conflict of interest.

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