RESEARCH PAPER

Assessment of Psychrotolerant Microbial Consortium for Enhanced Paddy Straw Decomposition under Low-Temperature Conditions

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ABSTRACT
Paddy straw management still remains a key issue in the rice-wheat cropping systems of North India, especially during the post-harvest phase because low temperatures limit microbial activity, which leads to delayed straw decomposition. Residue burning, one of the conventional practices followed for quick disposal of straw, greatly impacts the environment, nutrient cycling, and emissions of greenhouse gases. This study assessed the efficiency of using a psychrotolerant microbial consortium for accelerating paddy straw decomposition at low temperatures. The fungal strains were isolated from paddy straw and soil in winter season, and their lignocellulase production capability was screened at 10°C. Three isolates (T. harzianum S14, C. globosum S17, and T. asperellum S20) were chosen after considering their compatibility and efficiency in hydrolysis to prepare the psychrotolerant consortium. Decomposition potential of the consortia was determined by laboratory experiments and validated using in situ field experiments carried out at Amritsar, Punjab, India, at average winter temperatures of about 10°C. The effect of various rates of the consortium (from 2.5 to 10.0 L ha^{-1}) on the decomposition rate was determined. The results indicated significantly higher rates of breakdown of paddy straw in the treatment plots than in control plots, with 30.42% biomass reduction occurring after 21 days from application of the consortia, while in the control plots, it was recorded as 20.62%. Higher biomass reduction was achieved when the highest consortia dose, T5 (10 L ha^{-1}) was applied as indicated by high microbial population, improved soil enzyme activity (dehydrogenase, urease, and alkaline phosphatase), nutrient availability, with maximum available nitrogen (323 kg ha^{-1}), phosphorus (20.97 kg ha^{-1}), and potassium (271 kg ha^{-1}). This study indicate that a combination of psychrotolerant microorganisms provides a promising and environmentally friendly approach to paddy straw management in cold climate conditions, thereby minimizing residue burning without affecting the fertility of the soil.
Keywords: *Nutrient cycling, Psychrotolerant microbial consortium; Low temperature; Residue management; Enzymatic activity, Paddy Straw*
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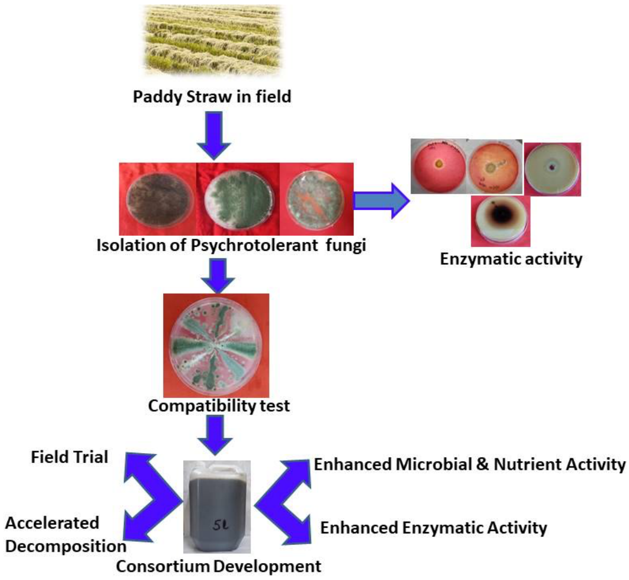
GRAPHICAL ABSTRACT



1. INTRODUCTION

Paddy (*Oryza sativa* L.), which is also known as paddy in India, provides food to about half of the world's population and occupies about 156 million hectares of land across the globe [1]. Paddy straw becomes one of the most common residues from the process of growing rice [2]. The disposal problem and environmental pollution due to the paddy straw become critical especially in the northern parts of India. Another problem associated with rice straw is the relatively high carbon-nitrogen (C:N) ratio of rice straw and slower decomposition [3]. The situation is more critical in temperate and tropical regions, where the decomposition is accelerated only during monsoon season [4]. In view of the generally prevailing cool and dry weather conditions during the beginning of the rabi season in the north Indian region, the decomposition process in the paddy fields takes place very slowly, thus negatively impacting the overall soil condition and agricultural productivity. This problem has been further compounded by the lack of awareness among the farming community about proper waste management techniques. Keeping in mind the above factors, an experiment was designed to test the effectiveness of Psychrotolerant bacteria and fungi in decomposing paddy straw [5]. There are many microbial communities and soil ecosystems that demonstrate significant variety and flexibility. Microbial consortia, which refer to the group of at least two microorganisms that synergistically accomplish a certain goal, have been widely studied in terms of their ability to influence a certain material or environment [6]. The proper selection of microbes from the indigenous population along with scientific research and development of the method of application might be necessary prior to giving ecological validity and effectiveness to the microbial consortium. The adaptability of microbial consortia can be partially utilized depending on the specific microbes, materials, and the methodology applied in the ecosystem [7].

In the Indo-Gangetic Plains of India, particularly in the rice–wheat production systems of Punjab, Haryana, and western Uttar Pradesh, paddy cultivation generates enormous quantities of crop residues every year [8]. Among these, paddy straw constitutes a major fraction, with an estimated several million tonnes produced annually during the post-harvest period [9]. The management of this residue has become a critical environmental and agricultural challenge, especially during October–November when farmers face a narrow window between rice harvesting and wheat sowing [10]. Under these circumstances, open-field burning of paddy residue remains one of the most commonly adopted practices due to its rapid and low-cost nature [11]. However, residue burning results in severe environmental consequences, including emission of greenhouse gases, particulate matter, and other toxic pollutants, deterioration of soil health, loss of valuable plant nutrients, and adverse impacts on human and ecosystem health [12].

Although *in-situ* biological decomposition of crop residues is considered a sustainable alternative to burning, its efficiency is significantly influenced by prevailing climatic conditions [13]. In North India, the post-harvest period coincides with a sharp decline in temperature, often ranging between 5–20°C, accompanied by reduced microbial activity and slower organic matter mineralization. Under such low-temperature conditions, the native mesophilic microbial communities exhibit reduced enzymatic efficiency, leading to delayed decomposition of lignocellulosic biomass such as paddy straw [14]. Paddy straw is inherently resistant to degradation because of its complex structural composition, primarily cellulose, hemicellulose, lignin, silica, and phenolic compounds, which limit rapid microbial colonization and breakdown.

2. MATERIALS AND METHODS

2.1 Compatibility Test between Isolates

Compatibility among selected psychotropic fungal isolates was evaluated to determine their suitability for formulation as a microbial consortium. Actively growing cultures of each isolate were co-inoculated in pairs on Potato Dextrose Agar (PDA) plates by placing agar plugs approximately 3 cm apart.

The plates were incubated at 10 °C and observed periodically for up to 10 days. Interactions between paired isolates were examined for the presence of inhibition zones, overgrowth, or antagonistic behaviour. Isolates showing mutual growth without formation of inhibition zones or abnormal morphological changes were considered compatible. All possible combinations of selected isolates were tested in triplicate.

2.2 Experimental Setup

Relative straw degradation of paddy straw cut into three sizes (3 cm, 6 cm, and unchopped) was evaluated using a modified method of Sruthy et al. [15].

Ten grams of autoclaved paddy straw and 5 mL of psychrotrophic fungal consortium (10^7 conidia mL^{-1}) (Table 3.1) were added to 250 mL Erlenmeyer flasks containing 75 mL of Reese Mineral Medium (RMM). The composition of RMM was as follows: peptone (0.5 g L^{-1}), KH_2PO_4 (2.0 g L^{-1}), $MgSO_4$ (0.3 g L^{-1}), $FeSO_4\cdot7H_2O$ (5 mg L^{-1}), $ZnSO_4\cdot7H_2O$ (1.4 mg L^{-1}), $(NH_4)_2SO_4$ (1.4 g L^{-1}), $CaCl_2$ (0.3 g L^{-1}), $MnSO_4$ (1.6 mg L^{-1}), $CoCl_2$ (2.0 mg L^{-1}), and urea (0.3 g L^{-1}; filter-sterilised and added after autoclaving). The pH was adjusted to 6.0, and the final volume was made up to 1,000 mL with distilled water. Flasks were incubated at 10 °C in triplicate. Samples were collected at 7, 14, 28, and 42 days after inoculation (DAI).

2.3 Relative Straw Degradation Rate (RDR)

After incubation, residual straw was recovered, washed gently with distilled water to remove adhering mycelia and medium, and oven-dried at 65 °C until constant weight.

RDR (%) was calculated using the formula:

$$(\text{RDR } (\%)) = \frac{\text{W0} - \text{W1}}{\text{W0}} \text{X } 100$$

where:

W0: Initial dry weight of paddy straw (g)

W1 = Weight of paddy straw after degradation (g)

3. FIELD EXPERIMENT

3.1 Experimental Area and Location

A field experiment on paddy straw degradation under low-temperature conditions was conducted at Chogawan village, Amritsar district, Punjab, India (31.70481° N latitude, 74.66012° E longitude; 239 m above mean sea level) (Fig. 3.3). The objective of the field trial was to evaluate the bio-efficacy of a psychrotrophic fungal consortium for in situ decomposition of paddy straw.

The experiment was laid out in a Randomised Block Design (RBD) with twelve treatments and three replications. Each plot measured 3 × 3 m^2 and was located on a farmer's field. The *in-situ* decomposition was done to find out the efficiency of psychrotolerant microbial consortium degradation in the most prevalent cultivar of paddy PB1509 after harvesting in the fields,

3.2 Experimental Design and Treatment Application

The experimental layout is presented in Table 3.5, while treatment details are given in Table 3.6. The recommended concentration and volume of inputs are provided in Table 3.4.

The microbial consortium was applied at the rate of 15 L diluted in 150 L of water per acre. Urea was applied at 20 kg ha^{-1} [16]. The inoculum was sprayed uniformly using a 20 L knapsack power sprayer and mixed manually with the straw after application.

Soil and straw samples were collected at 0, 14, 27, and 45 days after inoculation for further analysis.

3.3 Soil Characteristics

Before initiation of the field experiment, composite soil samples (0–15 cm depth) were collected, air-dried, sieved (2 mm), and analysed using standard procedures. The soil was alluvial in origin, coarse to fine textured, and alkaline (pH >7.3) with electrical conductivity of 0.78 dS m^{-1}. Organic carbon content was 0.70%, and available nitrogen, phosphorus, and potassium were 335, 16.97, and 242 kg ha^{-1}, respectively. Micronutrient contents of DTPA-extractable Zn, Cu, Mn, and Fe were 0.63, 0.46, 29.86, and 34.12 mg kg^{-1}, respectively [17].

3.4 Soil Chemical Analyses

Soil samples were collected at appropriate intervals during the decomposition period and analysed for physicochemical properties using standard methods. Electrical conductivity (EC) was measured according to Jackson [18], soil pH using an Elico pH meter [19], organic carbon by the wet oxidation method [20], available nitrogen by alkaline permanganate method [21], available phosphorus by spectrophotometry [22], and available potassium by flame photometry [23]. Available micronutrients (Fe, Zn, Mn, and Cu) were determined using the DTPA extraction method [24].

3.5 Soil Enzymatic Activities

i) Dehydrogenase Activity

Six grams of field-moist soil (in triplicate) were placed in screw-capped test tubes, and 0.1 g $CaCO_3$ was added and mixed thoroughly. One millilitre of 3% aqueous triphenyl tetrazolium chloride (TTC) and 2.5 mL distilled water were added. Tubes were incubated in the dark at 30 °C for 24 h. After incubation, 10 mL methanol was added to each tube, and the contents were filtered through Whatman No. 42 filter paper. The intensity of the pink-coloured triphenyl formazan (TPF) was measured at 485 nm using methanol as blank. Results were expressed as μg TPF g^{-1} soil day^{-1}.

ii) Alkaline Phosphatase Activity

One gram of soil was placed in a 100 mL conical flask. To this, 0.2 mL toluene, 4 mL modified universal buffer (MUB, pH 11.0), and 1 mL p-nitrophenyl phosphate substrate were added. The flasks were incubated at 37 °C for 1 h. After incubation, 1 mL of 0.5 M $CaCl_2$ and 4 mL of 0.5 M NaOH were added. The contents were filtered through Whatman No. 1 filter paper, and the yellow colour intensity was measured at 430 nm. Results were expressed as μg p-nitrophenol g^{-1} soil h^{-1}.

iii) Urease Activity

One gram of soil (in triplicate) was placed in culture tubes, and 500 μL of 0.8 M urea solution was added. Tubes were incubated at 37 °C for 2 h. After incubation, 10 mL of 1 N KCl (in 0.01 N HCl) was added, and tubes were shaken for 30 min. The suspension was filtered, and 1 mL filtrate was mixed with 5 mL each of reagent A (phenol and sodium nitroprusside) and reagent B (NaOH and sodium hypochlorite). After 30 min of colour development, absorbance was recorded at 625 nm.

iv.) Estimation of Soil Microbial Population

Soil microbial populations (aerobic bacteria and fungi) were enumerated using the serial dilution plate technique on nutrient agar (NA) and potato dextrose agar (PDA). Ten grams of fresh soil were suspended in 90 mL sterile water (10^{-1} dilution), shaken at 120 rpm for 10 min, and allowed to settle. Further serial dilutions were prepared. PDA plates were inoculated with 10^{-2} and 10^{-3} dilutions for fungal counts, while NA plates were inoculated with 10^{-5} dilution for bacterial counts. Plates were incubated at 15 ± 2 °C for 2–6 days. Colonies were counted and expressed as colony-forming units (CFU) g^{-1} dry soil [25].

4. STATISTICAL ANALYSIS

Data obtained from various experiments were expressed as mean ± standard deviation (SD) based on three replications. Statistical analysis was performed using R software version 4.3.2. One-way analysis of variance (ANOVA) was applied to test the significance of differences among treatments at a probability level of $p \leq 0.05$. Mean separation was carried out using Duncan's Multiple Range Test (DMRT) to determine significant differences between treatment means.

5. RESULTS

This study shows the effectiveness of Psychrotolerant microbial consortium for their ability to accelerate the rate of decomposition of paddy straw in an *in-situ* environment with a special focus on decomposition rates, soil enzyme activity and its impact on soil health.

5.1. Experiment Design for Field Study

The site was selected in Block Chogawam, District Amritsar where the temperature is found as 10°C on an average during winter season after paddy harvest. Pusa Basmati 1509 residue was taken as test residue for *in-situ* management at farmer's field. There were five treatments in total with RBD having factorial combination of variety of treatments and further three replications for each treatment. The straw and stubble load was found to be 5-7 T ha^{-1} and following treatments were carried at:

T1 Control (PB 1509 (Straw + Stubbles), T2 PB 1509 Straw + Stubbles + MC @ 2.5 litre ha^{-1} , T3 PB 1509 Straw + Stubbles + MC @ 5.0 litre ha^{-1} , T4 PB 1509 Straw + Stubbles + MC @ 7.5 litre ha^{-1}, T5 PB 1509 Straw + Stubbles + MC @ 10.0 litre ha^{-1}

5.1.1. Field trial with SOP for paddy straw management

Field trial with SOP for paddy straw management: SOP followed was in aligned to farmer's practices. After harvesting, the liquid consortium diluted in 500 liters of water was sprayed over the residue and quickly mixed in soil with any machine rotavator. After mixing, a slight irrigation was given in the field, the samples were collected initially at 0, 5, 7, 14, and 21 days. The sowing of next crop wheat was carried out after 15 days of incorporation of straw in the field

5.1.2. Field study.

Acceleration of biomass decay in the treated plots could be explained by increased cellulase and ligninase activities of the microbial consortium allowing fast degradation of complex compounds. The statistical analysis (ANOVA) proved that there were differences in biomass degradation between plots ($p < 0.05$) at each stage. In conclusion, the utilization of psychrotolerant microbial consortia accelerates the decomposition of paddy straw biomass in cold conditions.

5.2. Microbial Consortia Preparation

Soil and paddy straw samples were collected from the cold region during winter season and isolations were carried out for bacteria and fungi. The isolates were screened for lignocellulolytic hydrolytic potential at 10°C and finally three fungi were selected for the development of consortium. *Trichoderma harzianum* S14, *Chaetomium globosum* S17, and *Trichoderma asperellum* S20 were found compatible which is the backbone of consortium. The mass multiplication of fungus was carried out by surface as well as solid state fermentation. The viable spore count of the liquid consortium developed by mixing all three fungal liquid culture in equal proportion was kept at room temperature and the viable count as 10^{12} CFU ml^{-1} initially and maintained 10^{9} CFU ml^{-1} till 180 days.

5.3. Decomposition Rates and Biomass Loss under control condition.

The developed Psychrotolerant culture was studied for decomposition under controlled condition at 10°C. Four treatments were taken in small trays where paddy straw and stubbles were taken from Block chogawam District Amritsar. The samples were analyzed for loss in weight and calculation of decay constant from initial till 21 days after the treatment. At 14 days after inoculation, the amount of biomass lost by consortium treatment plots was

22.07%, while the control plots had shows only 16.80%. At 21 DAI, treatment plots had shows a total loss of 30.42% of their biomass compared to the control plots 20.62%. The result clearly shows the positive effect of microbial cultures for decomposition of paddy residue.

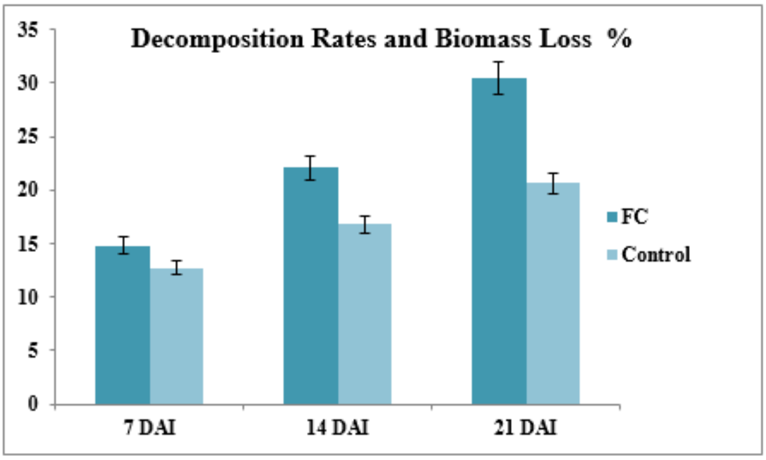


Figure1: Changes in Decomposition rate and biomass loss in the control and fungal consortium

5.4. Microbial Community Dynamics

The behavior of the microbial community demonstrated distinct change in the microbial community including the count. Initially, the soil bacterial count showed 33.97 to 35.11 X $\log_{10}$ CFUg^{-1} and after seven days of incorporation, a variation in the bacterial count was observed in all the treatment as compared to control. The bacterial count was found maximum in the treatment T5 (76.22 x 10cfu g^{-1}) while T2, T3, T4 showed the count at par with each other (38.22 – 74.01) while the control treatment T1, showed the lowest bacterial count 58.81 x $\log_{10}$ CFU g^{-1}. As the decomposition progressed, the same was observed after 14 days and 21 days of incorporation but there was increase in bacterial count throughout the decomposition period including the control treatment.

The fungal count was also carried out for the soil samples during the decomposition period and it was observed that there was around 2.7 to 3.0 $\log_{10}$ CFU g^{-1} fungal counts in the initial same but as the decomposition period extended, similar to bacterial count, the fungal count also showed the same trend. At 7, 14 and 21 days of incorporation the treatment T5 showed the maximum count 3.6-7.9 CFU g^{-1} respectively which was followed by the treatments T3, T4, and T2 almost at par with each other while the control treatment showed the lowest count 5.6 $\log_{10}$ CFU g^{-1}.

Table 1. Enumeration of total soil microbial count (log10 CFU/g)

Treatment	Days			
	Bacteria			
	05	07	14	21
T1	36.91d	43.11d	59.63c	58.81c
T2	38.22cd	45.07c	64.22ab	70.26b
T3	41.57bc	46.31c	60.91bc	71.49b
T4	43.36b	49.81b	62.33b	74.04ab
T5	45.86a	67.57a	68.19a	76.22a
Fungi				
T1	3.3b	3.7b	4.9b	5.6b
T2	3.4b	3.6a	4.5b	5.2b
T3	3.1b	3.8b	5.1b	5.7b
T4	3.4ab	3.8b	4.9b	5.2a
T5	3.6a	4.6a	7.8a	7.9a

5.5. Soil pH and Electrical Conductivity (EC) During Decomposition

The changes in soil pH, EC and moisture content were observed for all the treatments till 21days. The initial soil pH was close to neutral in all the treatments and it was found as 7.18 but as the decomposition accelerated in soil, the treatments showed variation in pH and a small shift from neutral to mild alkaline was observed. After 7 days the treatment T5 showed a shift from 7.18 to 7.42 which was also followed by treatment T4 while after 14 days again the pH for the treatment T5 was observed as 7.57 followed by control treatment T1 as 7.56 the pH was also observed after 21 days of incorporation and T5 showed as 7.63, T1 as 7.52 and T4 as 7.51 respectively. Treatment T2 and T3 also showed a small change from 7.18 to 7.37 and

7.32 respectively. This change in pH of soil may be contributed due to ammonification during accelerated decomposition. While pH levels fluctuated during decomposition, EC values were between 0.60 and 0.67 dS m^{-1}. In 7 days after incubation (DAI), there was change in EC values across treatments, with T5 registering the highest EC value of 0.86 dS m^{-1}, followed by T2 with 0.81 dS m^{-1} and T4 with 0.74 dS m^{-1}, suggesting ongoing decomposition and mineralization of the substrate. There was an increasing trend in EC at 14 DAI, especially in higher consortium treatments, with T5 attaining the highest EC value of 1.03 dS m^{-1}, followed by T4 at 0.89 dS m^{-1} and T2 at 0.84 dS m^{-1}, while T1, which was the control treatment, had the lowest EC value of 0.71 dS m^{-1}. After 21 DAI, although the values slightly stabilized, T5 still registered the highest EC value of 1.00 dS m^{-1}, followed by T4 at 0.84 dS m^{-1} and T2 at 0.82 dS m^{-1}, while T1 remained at the lowest EC value of 0.75 dS m^{-1}.

Table 2: Changes in pH and EC during paddy straw decomposition under different microbial consortium doses

	pH				EC			
Treatments	**5 Day**	**7 Day**	**14 Day**	**21 Day**	**5 Day**	**7 Day**	**14 Day**	**21 Day**
T1	7.24b	7.22c	7.56a	7.52ab	0.63c	0.72c	0.71c	0.75c
T2	7.2b	7.25bc	7.4b	7.37c	0.68b	0.81b	0.84b	0.82b
T3	7.199b	7.24c	7.31c	7.32c	0.5d	0.62d	0.78bc	0.73c
T4	7.235b	7.3b	7.4b	7.51ab	0.69b	0.74c	0.89b	0.84b
T5	7.4a	7.42a	7.57a	7.63a	0.71a	0.86a	1.03a	1.00a

5.6. Soil analysis of Available N,P,K

The soil samples were analysed for various soil physio-chemical changes to study the effect of developed Psychrotolerant consortium. Straw residue acts as a critical supply of organic C for soil when rice-wheat is cultivated. The effect of straw mulch on the composition and quantity of soil organic carbon (SOC) and the activity of soil enzymes was studied under paddy field conditions. Leaving straw under flooded paddy field soil or through conservative rotation can lead to an increase in soil organic N and P, however, such practice needs to be maintained over long periods. The use of psychrotolerant microorganisms for accelerating the decomposition process of paddy straw in situ had effects on soil physiochemical parameters, which affected the decomposition rate and nutrients cycling.

Available N

The available N level was found to increase steadily from initial time till 21st day in all the treatments during the winter season in the field when average temperature was around 10°C. the initial levels of available N in soil was observed in a range 279 to 293 kg ha^{-1} but as the decomposition progressed a slight increase was observed for available N in soil in all the treatments. A significant increase in available N was observed after 14 days after incorporation and the maximum increase was found after 21 days of incorporation and paddy straw and stubbles. Among the treatments, all the treatments showed increase as compared to control but the treatment T5 showed the highest increase 312 kg ha^{-1} in 14 days and 323 kg ha^{-1} in 21 days after incorporation as compared to other treatments, clearly showing the positive effect of newly developed Psychrotolerant consortium for accelerated decay.

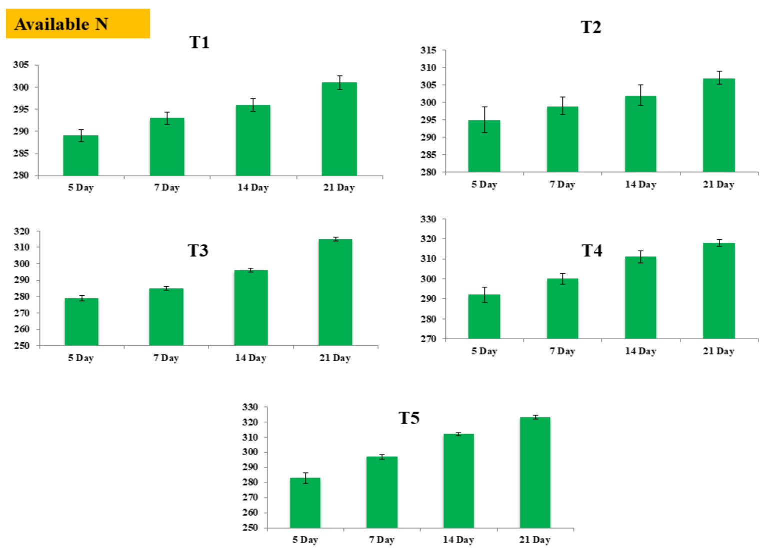


Figure 2: Changes in soil available nitrogen in a period of 21 days of paddy straw decomposition in different microbial consortia

Available P

The available P level was found to increase steadily from initial time till 21st day in all the treatments during the winter season in the field when average temperature was around 10°C. The initial levels of available P in soil was observed in a range 17.4 and 17.76 kg ha^{-1} but as the decomposition progressed a slight increase was observed for available P in soil in all the treatments. A significant increase in available P was observed after 14 days after incorporation and the maximum increase was found after 21 days of incorporation and paddy straw and stubbles. Among the treatments, all the treatments showed increase as compared to control but the treatment T5 showed the highest increase 20.5 kg ha^{-1} in 14 days and 20.97 kg ha^{-1} days after incorporation as compared to other treatments, clearly showing the positive effect of newly developed Psychrotolerant consortium for accelerated decay.

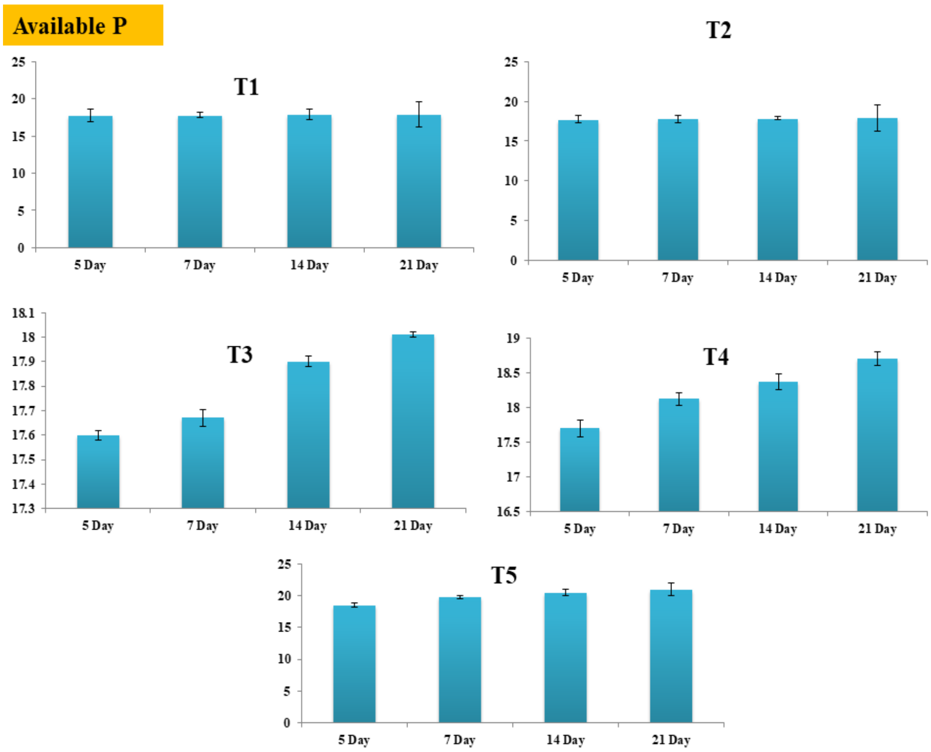


Figure 3: Variation of soil available phosphorus in paddy straw decomposition in psychrotolerant microbial consortia

Available K

The available K level was found to increase steadily from initial time till 21st day in all the treatments during the winter season in the field when average temperature was around 10°C. the initial levels of available P in soil was observed in a range 251 to 262 kg ha^{-1} but as the decomposition progressed a slight increase was observed for available P in soil in all the treatments. A significant increase in available P was observed after 14 days after incorporation and the maximum increase was found after 21 days of incorporation and paddy straw and stubbles. Among the treatments, all the treatments showed increase as compared to control but the treatment T5 showed the highest increase 268 kg ha^{-1} in 14 days and 271 kg ha^{-1} in 21 days after incorporation as compared to other treatments, clearly showing the positive effect of newly developed Psychrotolerant consortium for accelerated decay

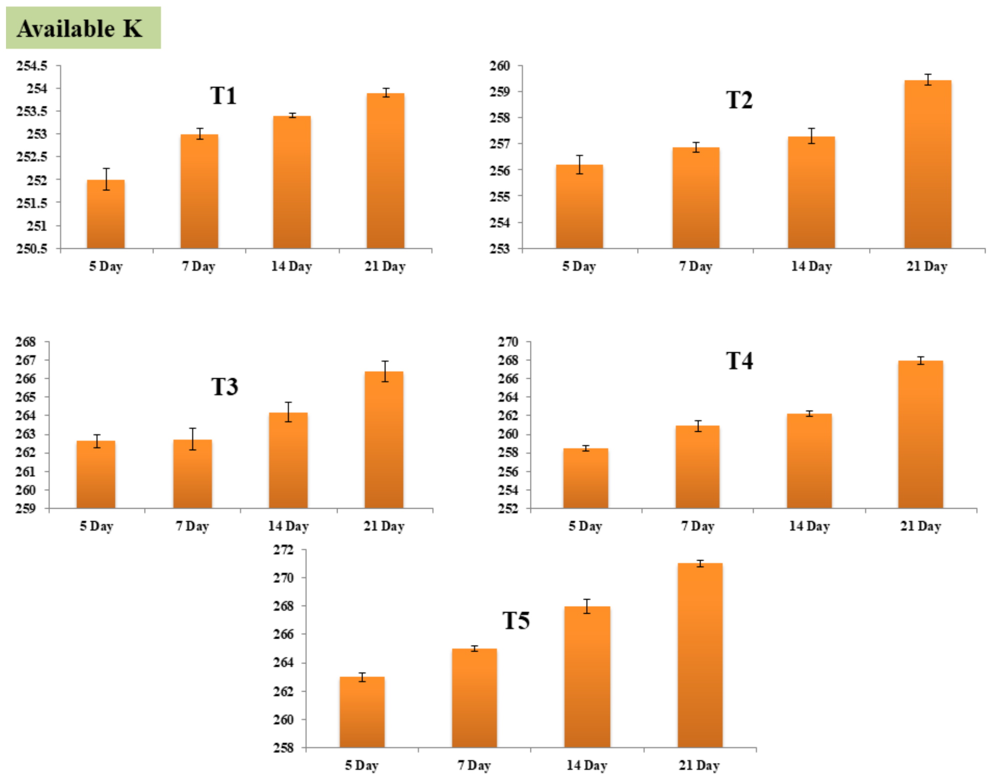


Figure 4: Changes in soil available potassium in low temperatures during paddy straw decomposition

5.7. Soil Enzymatic Study

The enzymatic activities associated with active soil microorganisms present in the field was studied from initial to 21 days of decomposition in all the treatments.

Dehydrogenase Activity (DHA)

The overall microbial activity of the active population present in the soil was analyzed using dehydrogenase activity. The initial soil dehydrogenase activity was observed as 169.86µgTPFg^{-1} and as the decomposition proceeded the soil dehydrogenase activity varied with time and treatment. After seven days of incorporation the treatment T3, T4 and T5 were observed at par showing very little difference among each other with values 216.24, 218.19 and 237.52µgTPFg^{-1} while T2 showed lower dehydrogenase accordingly 192.11 µgTPFg^{-1} and the lowest actively 183.01 µgTPFg^{-1} was observed in control treatment. After 14 and 21 days, the treatment T5 observed the maximum dehydrogenase activity which can be correlated with simultaneous increase in the bacterial and fungal population in the same period. The treatments T2, T3 and T4 also showed an increase in activity as well as population but were lower than T5 and the control treatment showed the lowest increase and activity for the same period.

Alkaline Phosphatase Activity

The overall microbial activity of the phosphorous solubilization population present in the soil with alkaline condition was analyzed using alkaline phosphatase activity. The initial soil alkaline phosphatase activity was observed as 25.76 µg g^{-1} and as the decomposition proceeded the soil alkaline phosphatase activity varied with time and treatment. After seven days of incorporation the treatment T3 and T4 were observed at par showing very little difference among each other with values 36.85, 36.11µg g^{-1} while T2 and T5 showed lower alkaline phosphatase accordingly 31.21and 34.69µg g^{-1} and the lowest actively 30.48µg g^{-1} was observed in control treatment. After 14 and 21 days, the treatment T5, T4 and T3 observed the maximum alkaline phosphatase activity which can be correlated with simultaneous increase in the bacterial and fungal population in the same period. The treatment T2, also showed an increase in activity as well as population but were lower than T5 and the control treatment showed the lowest increase and activity for the same period.

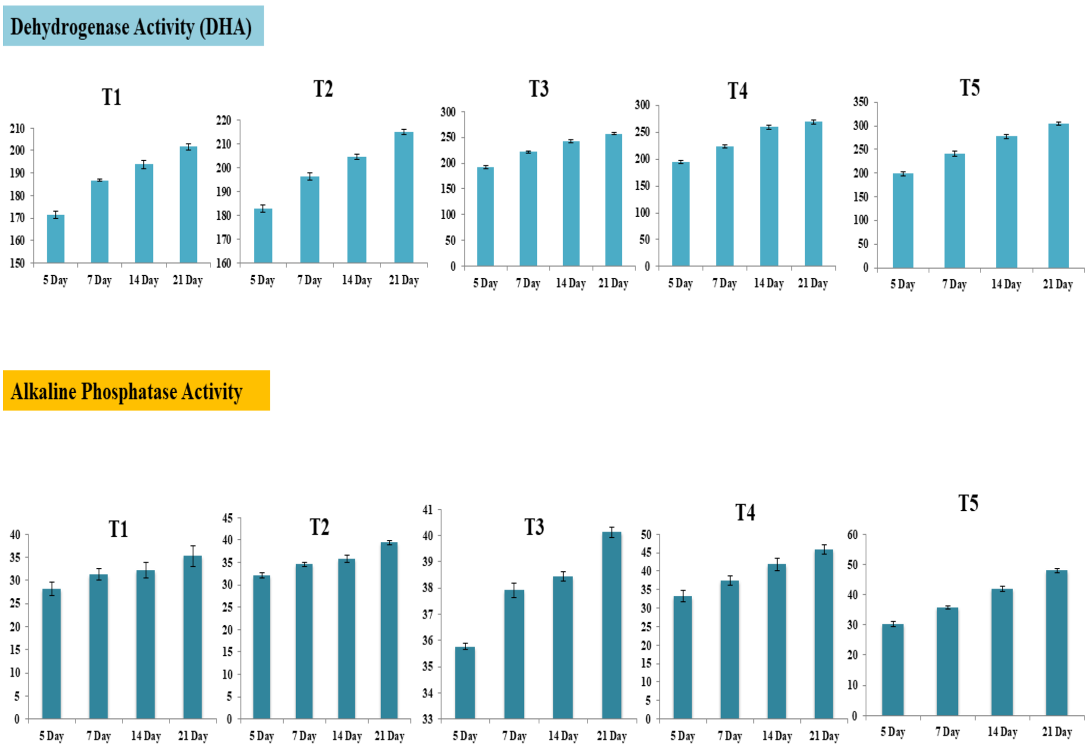


Figure 5: Effect of microbial consortia doses on dehydrogenase activity (DHA) and alkaline phosphatase activity during paddy straw decomposition

Urease Activity

The overall microbial activity of the urea utilizing population present in the soil was analyzed using urease activity. The initial soil urease activity was observed as 32.69 µg g^{-1} and as the decomposition proceeded the soil urease activity varied with time and treatment. After seven days of incorporation the treatment T3 and T5 were observed at par showing very little difference among each other with values 43.77, 43.58µg g^{-1} while T2 and T4 showed lower urease activity accordingly 39.61 and 40.09 µg g^{-1} and the lowest actively 34.86 µg g^{-1} was observed in control treatment. After 14 and 21 days, the treatment T5, T4 and T3 showed a maximum urease activity which can be correlated with simultaneous increase in the bacterial and fungal population in the same period. The treatment T2 also showed an increase in activity as well as population but were lower than T5 and the control treatment showed the lowest increase and activity for the same period.

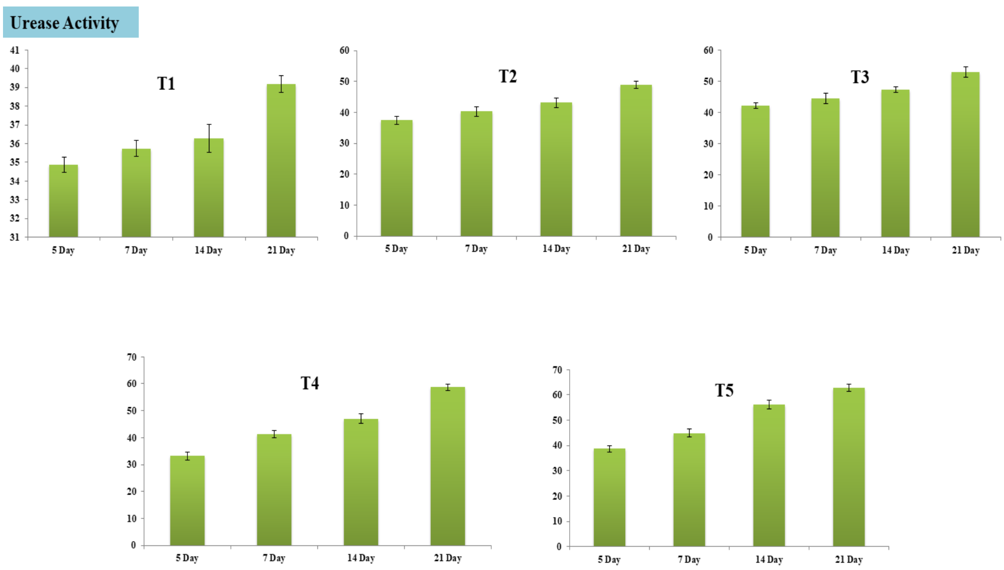


Figure 6: Effect of microbial consortia doses on Urease activity during paddy straw decomposition

6. DISCUSSION

The present study clearly demonstrates that the application of psychrotolerant microbial consortia can significantly accelerate the decomposition of paddy straw under low-temperature field conditions, where natural degradation processes are typically constrained by reduced microbial activity. The cold-adapted fungal strains *Trichoderma harzianum* S14, *Chaetomium globosum* S17, and *Trichoderma asperellum* S20, initially validated under controlled soil microcosm conditions, exhibited strong functional performance under in situ conditions, highlighting their suitability as bio-inoculants for residue management in cold agro-ecosystems.

The enhanced decomposition observed in consortium-amended plots can be attributed to the synergistic action of lignocellulolytic enzymes, which are central to the breakdown of complex plant polymers such as cellulose, hemicellulose, and lignin. The sustained increase in enzymatic activities, including dehydrogenase, urease, and phosphatase, indicates an overall stimulation of microbial metabolism and nutrient cycling. Notably, the coordinated expression of these enzymatic systems suggests that the introduced strains were metabolically active and functionally compatible under low-temperature stress, enabling efficient substrate utilization. A rapid increase in microbial population following field inoculation further confirmed the effective colonization ability of the psychrotolerant consortia. The early peak in microbial abundance, coupled with enhanced enzyme activities, indicates that the introduced strains quickly established functional dominance and initiated decomposition processes. This rapid colonization is particularly important under cold conditions, where native microbial activity is inherently limited. The sudden increase in the population of microorganisms after field inoculation proved the efficient colonizing abilities of the psychrotolerant consortium. The quick establishment of dominance by the introduced strains was evidenced by the swift rise in microorganism abundance and improved enzyme activities. The significance of this quick colonizing process is even more pronounced in cold environments, where the indigenous microbial population is restricted. Nevertheless, the decreasing trend of introduced microorganisms over time indicates that even though they had some functional advantages initially, they could not dominate in the presence of indigenous microbes. This is because of competitive exclusion and adaptation to environmental conditions by native microbes, which are more adapted to surviving in the field environment. This phenomenon has been seen in previous studies where microbial inoculants become less effective over time because of competition with native microbes. However, even at lower levels of biomass degradation, it is evident that an increased level of microbial activity in the first stages is sufficient to stimulate decomposition, as indicated by the changes in nutrient balance (N, P, and K) and enzyme activity. Moisture control, nutrition addition, or chemical pretreatment of residues can help in improving the performance of added microorganisms. Therefore, it can be concluded from the above results that the addition of psychrotolerant microbial consortia to decompose paddy straw is quite effective. The higher efficiency of the consortia at a higher dose shows its potential as an eco-friendly tool for management of plant residues.

7. CONCLUSION

This study demonstrates that presence of psychrotolerant microorganisms in consortia greatly accelerated the breakdown of paddy straw, solving one of the significant challenges in managing residues. Cold-adapted strains showed quick colonization and continuous metabolic function, which facilitated faster degradation of lignocellulose and improved biological activity in the soil. There was also a substantial increase in enzymatic functions (dehydrogenase, urease, and alkaline phosphatase) and nutrients available (N, P, K). Treatment T5, which involved the application of 10 liters of microbial consortia, produced the best results, with the highest enzymatic function and nutrients available (N: 323 kg ha^{-1}, P: 20.97 kg ha^{-1}, K: 271 kg ha^{-1}). Overall, the combination of psychrotolerant microorganisms in consortia with the addition of nitrogen is a viable and environmentally friendly approach to effective residue management. The optimal result achieved in treatment T5 underscores its potential in enhancing residue decomposition and soil fertility.

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9. AUTHORS' CONTRIBUTIONS

Conceptualization, S.K.S; L.S; and S.S.; methodology, S.K.S; L.S.; S.S., S.K., A.K.; software, S.K.S.; S.K., validation, S.K.S; L.S.; S.S., A.K.; formal analysis, A.K.; investigation, A.K., L.S.; resources, S.K.S., L.S.,; data curation, S.K.S; L.S.; S.S., S.K., A.K.; writing—original draft preparation, S.K.S; L.S.; S.S., S.K., A.K.; writing—review and editing, S.K.S; L.S.; S.S., S.K., A.K.; visualization S.K.S; supervision, L.S.; A.K.; S.S.;. All authors have read and agreed to the published version of the manuscript.

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11. CONFLICT OF INTEREST
The authors declare that there is no conflict of interest in this work.

12. ETHICAL APPROVAL
This study does not involve experiments on animals or human subjects.

13. DATA AVAILABILITY
All datasets generated or analyzed during this study are included in the manuscript.

14. USE OF ARTIFICIAL INTELLIGENCE (AI) ASSISTED TECHNOLOGY
The authors confirms that there was no use of artificial intelligence (AI) assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

15. PUBLISHER'S NOTE
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