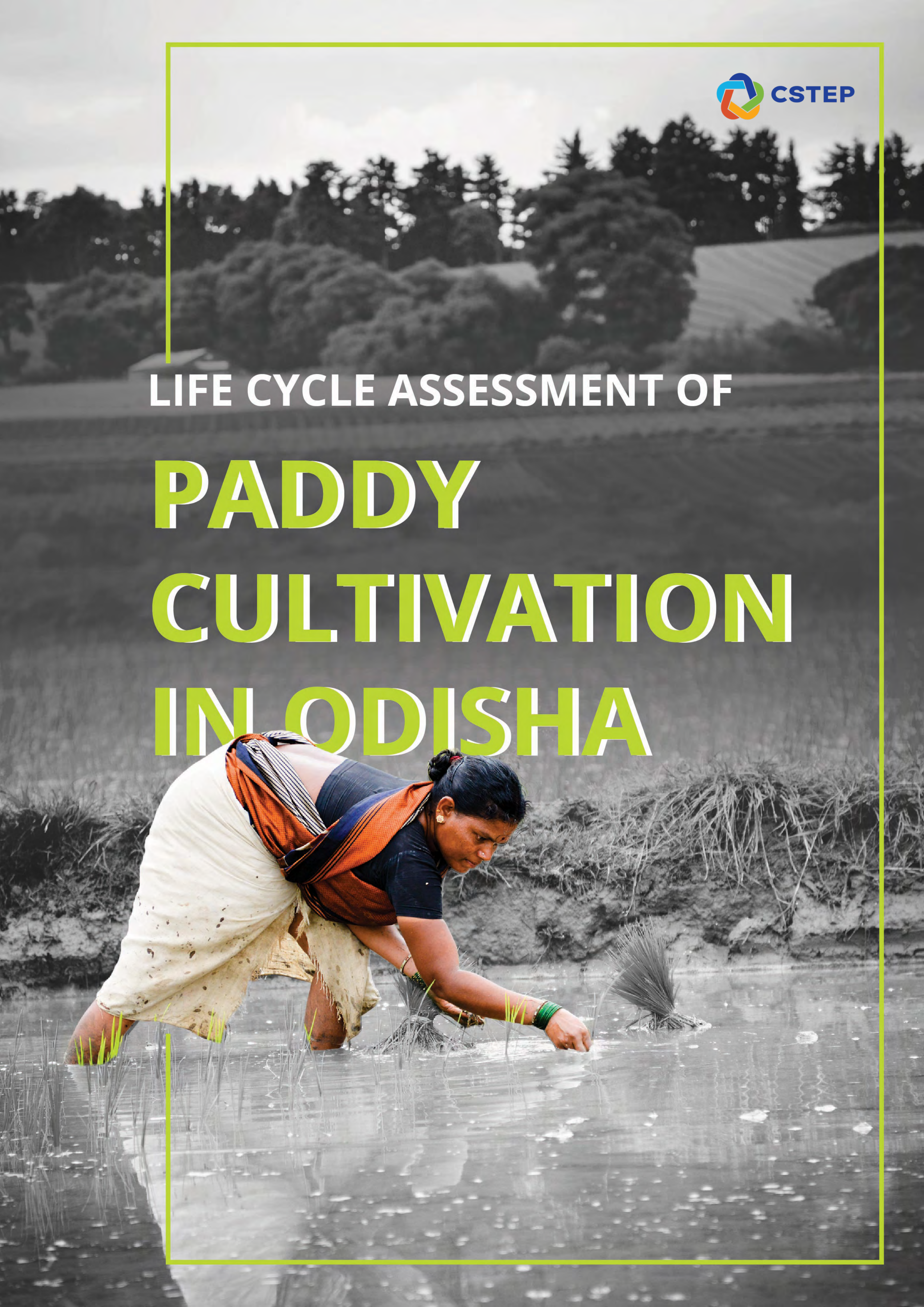

CSTEP

LIFE CYCLE ASSESSMENT OF PADDY CULTIVATION IN ODISHA

Life Cycle Assessment of Paddy Cultivation in Odisha

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Center for Study of Science, Technology and Policy (CSTEP)

June 2026

Edited and Designed by CSTEP

Disclaimer

Generative AI statement

No generative AI tools were used in the preparation of this document.

Suggested citation: CSTEP. 2026. *Life cycle assessment of paddy cultivation in Odisha* (CSTEP-RR-2026-04).

June 2026

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Acknowledgements

The authors are thankful to the Management Committee at the Center for Study of Science, Technology and Policy (CSTEP) for providing the opportunity to conduct this study.

We extend our heartfelt gratitude to the Climate Resilience Cell (CRC), Department of Agriculture and Farmers' Welfare (DA&FW), Government of Odisha, particularly, Shri Shubhranshu Mishra (Additional Secretary), Dr Sangram Keshari Pattanaik (Deputy Director), and Shri Nagendra Kumar Malik (Assistant Director), for their support and guidance in coordinating with various departments and preparing this report.

We thank Professor Tushar Mohanty (Odisha University of Agriculture and Technology [OUAT]) for reviewing the report and providing his valuable feedback. We also extend our sincere gratitude to Mr Thirumalai NC (Sector Head, Strategic Studies, CSTEP) and Dr Indu Murthy (Sector Head, Climate, Environment and Sustainability, CSTEP) for their valuable insights that helped shape this study. We would also like to thank Dr Arup Nandi (Former Chief of Research, CSTEP) for his unwavering support in facilitating the partnership with Catalyst Management Services. We are also grateful to Dr Bhavin Gohel and Dr Sachin Venkatrao (Senior Associates, Adaptation and Risk Analysis, CSTEP) for their assistance in data collection, validation, and coordination with DA&FW and OUAT. We thank the Adaptation and Risk Analysis team at CSTEP for their collective efforts in making this report a reality.

We thank our Communications and Policy Engagement (CPE) team, particularly Ms Shayantani Chatterjee (Editor, CPE, CSTEP) for the editorial support and Ms Bhawna Welturkar (Senior Manager-Communications Design, CPE, CSTEP) for the design inputs.

Finally, we express our deep gratitude to the Gates Foundation for their financial support.

Executive Summary

Paddy cultivation is the central pillar of agriculture in Odisha, both economically and culturally. The state has a predominantly agrarian economy, with 46% of its gross cropped area dedicated to paddy. The state has a diverse agro-climatic landscape that supports both kharif (monsoon) and rabi (winter) paddy, with kharif accounting for the majority of its production.

However, paddy is highly emission-intensive and a resource guzzler. It requires extensive amounts of water and fertiliser for cultivation, posing sustainability challenges, especially in regions facing water scarcity. Flooded paddy fields release large amounts of methane (CH_4) in the atmosphere owing to the anaerobic respiration of bacteria in the water. The large amounts of nitrogen-containing fertilisers applied to the soil release nitrous oxide (N_2O) through nitrogen volatilisation, which then leaches or runs off into water bodies. Irrigation power and fuel usage in agricultural machinery also contribute to emissions.

Given the enormous scale of rice production in the state, climate-smart practices must be adopted to ensure its sustainability. The current study primarily focused on natural farming. This climate-smart practice promotes a mix of locally sourced and low-cost practices for managing nutrients, pests, water, and soil and avoids the use of inorganic inputs. Further, direct-seeded rice (DSR), another climate-smart farming technique, was examined in the context of rainfed cultivation to evaluate its resource efficiency and environmental benefits.

To assess the sustainability of these farming techniques, a comparative analysis was conducted for the proposed climate-smart interventions and conventional farming using life cycle assessment (LCA). LCA was used to evaluate each farming practice based on resource use and its management, farm inputs, and environmental impacts. It considers the entire farm life cycle, including material extraction, manufacturing, distribution, and on-farm use. The results of the LCA quantified impacts across various categories, including resource scarcity and damage to ecosystems and human health, using indicators such as global warming potential (GWP), terrestrial acidification potential (TAP), and water consumption.

This holistic assessment can benefit both farmers and the environment through reduced resource usage, improved soil fertility, and lowered emissions.

Table ES1 summarises the environmental impacts of these cultivation techniques across various parameters.

***Table ES1**: Environmental impact of the selected cultivation techniques*

Impact category	Conventional farming	Natural farming	Direct-seeded rice cultivation
Global Warming Potential (kg CO_{2eq})	4,460	2,838	3,829
Terrestrial acidification potential (kg SO_{2eq})	10.10	6.9	7.54
Freshwater eutrophication potential (kg P_{eq})	2.97	2.18	2.09
Marine eutrophication potential (kg N_{eq})	0.19	0.22	0.16
Terrestrial ecotoxicity potential (kg 1,4-DCB_{eq})	6,338	3,411	5,270
Freshwater ecotoxicity potential (kg 1,4-DCB_{eq})	91.49	59.25	68.83
Marine ecotoxicity potential (kg 1,4-DCB_{eq})	129.52	83.89	97.23
Abiotic depletion potential - Minerals (kg Cu_{eq})	2.85	0.66	2.72
Abiotic depletion potential - Fossil fuels (kg oil_{eq})	787.61	538.96	574.80
Water consumption (m^3)	5,072	3,704	3,555
Yield (tonnes)	2.02	1.21 (post maturity = 2.14)	1.62

Table ES2 shows the key results of the comparison of the impact assessment parameters across the selected cultivation techniques.

***Table ES2**: Comparison of the impact assessment parameters against conventional farming*

Parameter per acre	Natural farming	Direct-seeded rice cultivation
Overall emissions	36% ↓	14% ↓
Water consumption	27% ↓	30% ↓
Mineral usage	77% ↓	5% ↓
Fossil fuel usage	31% ↓	27% ↓
Yield	40% ↓ (post maturity = 5.85% ↑)	20% ↓

While these climate-smart cultivation techniques offer a significant reduction in environmental impact compared to conventional cultivation, they result in notable yield reductions.

This study estimated emissions from paddy cultivation across the state at 16.6 million metric tonnes (MMT) of CO_{2eq}, with 8.2 MMT from on-field emissions. The value of on-field emissions aligns with the value of emissions estimated by the GHG Platform India. However, the additional 8.4 MMT of CO_{2eq} from off-field sources, such as irrigation and raw material production, should also be taken into account to obtain a realistic picture of agricultural emissions.

The projected impact of adopting climate-smart agricultural interventions in areas irrigated through lift irrigation (tanks, wells, and bore wells) was also assessed in this study. The base scenario assumes that all lift-irrigated areas under paddy cultivation in Odisha follow conventional cultivation. Scenario 1 considers 75% of these areas under conventional cultivation, 12.5% under natural farming, and 12.5% under DSR cultivation. The land allotment followed in the studied scenarios is described in Table ES3.

Table ES3: *Study scenarios with land allotment under the studied cultivation techniques*

Scenario	Conventional cultivation	Natural farming	Direct-seeded rice cultivation
Base Scenario	100%	0%	0%
Scenario 1	75%	12.5%	12.5%
Scenario 2	50%	25%	25%
Scenario 3	25%	37.5%	37.5%
Scenario 4	0%	50%	50%
Scenario 5	0%	100%	0%
Scenario 6	0%	0%	100%

Scenario 4 showed a 25% drop in GWP and a 30% drop in yield from the Base Scenario. A 100% natural farming scenario (Scenario 5) showed a 36% drop in GWP and a 40% drop in yield from the Base Scenario. Similarly, a 100% DSR cultivation scenario (Scenario 6) showed a 14% drop in GWP and 20% drop in yield from the Base Scenario. These aspects need to be carefully considered when strategising how much area should be covered by climate-smart solutions in the state.

This study addresses the limited quantitative evidence on the environmental impacts of cultivation practices by employing LCA. Through a comparative approach, it provides a holistic perspective that links greenhouse gas emissions, yield, and water and resource use, thereby generating insights of direct relevance to both policy and practice. While climate-smart agricultural practices offer notable on-plot benefits, their adoption must also account for potential yield reductions and the trade-offs in emissions and water use per unit output.

By integrating these dimensions, this study serves as a decision-support guide, enabling the design of more realistic and context-specific targets for emission mitigation, water management, and cultivation strategies that can support sustainable farming, enhance farmer livelihoods, and inform long-term state-level agricultural planning.

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Abbreviations

ADP	Abiotic depletion potential
AWD	Alternate wetting and drying
CH_4	Methane
CO_2	Carbon dioxide
CSA	Climate-smart agriculture
Cu	Copper
DAP	Diammonium phosphate
DCB	Dichlorobenzene
DSR	Direct-seeded rice
EF	Emission factor
F/MEP	Freshwater/Marine eutrophication potential
FETP	Freshwater ecotoxicity potential
FU	Functional unit
FYM	Farmyard manure
GHG	Greenhouse gas
GWP	Global warming potential
h	Hour
ha	Hectare
hp	Horsepower
K	Potassium
kg	Kilogram
LCA	Life cycle assessment
LCI	Life cycle inventory
MEP	Marine eutrophication potential
T/F/METP	Terrestrial/Freshwater/Marine ecotoxicity potential
ml	Millilitre
MMT	Million metric tonnes
MOP	Muriate of potash
N	Nitrogen
N_2O	Nitrous oxide
P	Phosphorus
SO_2	Sulphur dioxide
TAP	Terrestrial acidification potential
TETP	Terrestrial ecotoxicity potential

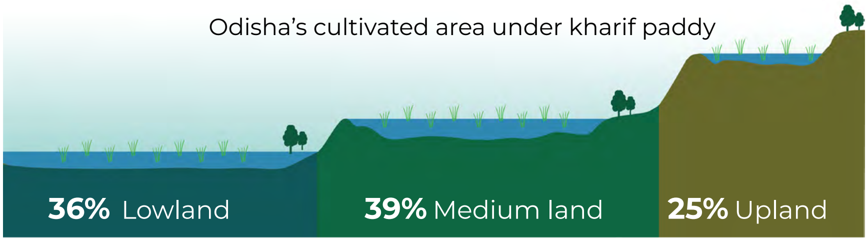
1. Introduction

The Odisha Agricultural Statistics 2023–24 report shows that 45% of Odisha's gross cropped area is under paddy cultivation, making paddy one of the most widely cultivated crops in the state. Historical evidence suggests that rice cultivation has been practised in the state for thousands of years. It also features prominently in local rituals, festivals, and cuisine (Dash, 2021). A significant portion of Odisha's population is dependent on paddy cultivation for their livelihoods and food security. The crop supports millions of small and marginal farmers, as well as seasonal labourers, millers, and others involved in the supply chain. For many, paddy cultivation is crucial not because it provides adequate returns but because it provides farmers with subsistence (Sarkar et al., 2022).

However, paddy cultivation faces several challenges, such as erratic rainfall, declining soil fertility, poor irrigation infrastructure, improper farming practices, and post-harvest losses. These issues affect crop productivity and the long-term sustainability of paddy cultivation in the state. Thus, there is growing interest in making paddy cultivation more sustainable and resilient by adopting farmer-centric and environmentally friendly climate-smart agricultural practices. Further, such practices need to be critically evaluated to determine their sustainability. The specifics related to paddy cultivation methods and sustainability assessment techniques are discussed in the following sub-sections.

1.1. Paddy cultivation

Paddy cultivation can be classified into various categories based on several factors, including land characteristics, soil type, rice variety, season, rainfall intensity and distribution, irrigation source, and labour availability. According to the International Rice Research Institute (n.d.), kharif paddy cultivation coverage can be classified as follows based on the terrain and water regimes:



Puddled cultivation is one of the most common methods of paddy farming in Odisha, accounting for 75% of the total area under kharif paddy cultivation. In this method, seedlings are grown in a nursery for 18–30 days, depending on the variety. They are then transplanted into the main field and maintained in water at a depth of 3–5 cm (Naik et al., 2015). Nutrients are supplied through inorganic fertilisers and organic manures. Inorganic fertilisers supply nitrogen (N), phosphorus (P), and potassium (K) to the crop and are applied at various stages of crop growth, as per the recommended Package of Practices (a set of suggested crop-specific cultivation practices to maximise productivity and sustainability while optimising resource use). The NPK nutrients are supplied through a mix of urea, diammonium phosphate (DAP), and muriate of potash (MOP). Manures supply essential nutrients to the crop, in addition to improving soil structure and water retention. This method of cultivation involving the use of inorganic fertilisers and pesticides is referred to as conventional cultivation in this report. Although this is the most popular method of cultivation across India, it has several environmental drawbacks, including high water usage, associated methane (CH_4) emissions, and high fertiliser usage and associated leaching.

Recently, natural farming has emerged as an alternative practice to tackle these shortcomings. Natural farming is a technique in which chemical inputs are replaced with natural concoctions (Beejamrutham, Ghana Jeevamrutham, Dravajeevamrutham, natural pesticides, and growth promoters) (NITI Aayog, 2021). These concoctions are prepared from materials, such as cow dung, cow urine, neem leaves, and bund soil, that are available in the vicinity of farms. Additionally, the practice considers water and soil management through alternate wetting and drying (AWD). Under this process, irrigation is applied at specific intervals to aerate the soil and ensure moisture retention, adhering to the Whapasa principle (the balance between moisture and air content in soil pores). Soil aeration allows the growth of beneficial microbes and aids root development. This technique of regulating water supply to the soil is referred to as AWD and uses 25%–30% less water than conventional cultivation (Carrijo et al., 2017). Natural farming also significantly improves soil health and structure.

Direct-seeded rice (DSR) cultivation is another practice to overcome the common disadvantages associated with puddled cultivation. While generally followed in rainfed uplands, DSR can be employed as a climate-smart practice in the lowlands. In DSR, seeds are directly planted in the soil rather than transplanted as seedlings. DSR comes with a host of advantages, including reduced water usage, lower CH_4 emissions, reduced labour requirement, improved seedling emergence, and reduced lodging (Kumar et al., 2024).

Table 1 summarises the differences among the three types of paddy cultivation approaches.

Table 1: *Comparison of inputs and process requirements of the three cultivation approaches*

Required inputs/processes	Conventional cultivation	Natural farming	Direct-seeded rice cultivation
Ploughing	✓	-	✓
Nursery	✓	✓	-
Transplanting	✓	✓	-
Inorganic fertilisers	✓	-	✓
Inorganic pesticides	✓	-	✓
Manure	✓	✓	✓
Continuous irrigation (flooding)	✓	-	-
Machinery	✓	-	✓

While the environmental impacts of these cultivation approaches are qualitatively recognised, only a limited number of studies have quantified them. This study addresses this gap by applying life cycle assessment (LCA). By providing a holistic quantification of these impacts, it aims to support decision-making on prioritising cultivation practices to achieve adequate yields while minimising environmental burdens. This report presents the quantification and comparison of the environmental impacts of these approaches using LCA.

1.2. LCA

This analysis helps quantify the impact of a system on the environment over a given timeframe based on its input requirements, energy sources, and intrinsic processes. In the context of paddy cultivation, LCA can be applied to assess greenhouse gas (GHG) emissions at each stage of the rice production chain with respect to farm inputs and farming practices. This includes upstream processes (such as fertiliser production); transport of inputs; on-field emissions (such as CH_4 emissions from flooded fields and nitrous oxide [N_2O] emissions from fertilised soils); and energy use during land preparation, harvesting, and irrigation. By quantifying emissions across these stages, LCA can help compare different farming practices and inform technological or policy interventions for sustainable rice cultivation. LCA measures impacts across various categories, which are discussed in detail below.

1.3. Impact assessment

Impact assessment is a crucial step under LCA that translates the life cycle inventory (LCI) into potential environmental impacts. LCI comprises data on resource use, farm inputs, farming processes, energy consumption, waste generation, and emissions. This step helps evaluate the impact of a chosen process on human health, ecosystem health, resource scarcity, and various environmental impact categories. By identifying key impact areas, this assessment enables stakeholders to make informed and sustainable decisions. To conduct and interpret impact assessment, the estimated emissions and identified resource flows in LCI are categorised into various impact categories, such as global warming potential, acidification, and eutrophication. Each category is defined by a characterisation factor, which reflects its contribution to a specific impact. Some of these impact assessment factors are given below:

1. **Global warming potential (GWP)**: This measures the contribution of GHGs to global warming and is expressed in kilograms of carbon dioxide equivalents (kg CO_{2eq}). As a hypothetical example, if producing a plastic bottle released 1 kg CO_2, its GWP would equal 1 kg CO_{2eq}.

2. **Terrestrial acidification potential (TAP)**: This measures the potential of emissions to cause acid rain, which harms soil and plants, and is expressed in kg of sulphur dioxide equivalents (kg SO_{2eq}). For example, emissions from burning fuel in agricultural machinery contribute to terrestrial acidification.

3. **Freshwater eutrophication potential (FEP)**: This measures the release of nutrients into freshwater bodies, which can cause excessive algal growth and harm aquatic life. It is expressed in kg of phosphorus equivalents (kg P_{eq}). For example, fertiliser run-off from agriculture contributes to freshwater eutrophication.

4. **Marine eutrophication potential (MEP)**: This measures the impact of nutrient pollution (mainly nitrogen) in marine environments, causing algal blooms and dead zones. MEP is expressed in kg of nitrogen equivalents (kg N_{eq}). For example, agricultural runoff entering the oceans introduces excessive nitrogen, which promotes marine eutrophication. Fertiliser run-off also contributes to marine eutrophication.

5. **Terrestrial ecotoxicity potential (TETP)**: This measures the potential harm to land-based organisms from toxic chemicals and is expressed in kg of 1,4-dichlorobenzene equivalents (kg 1,4-DCB_{eq}). For example, pesticides used in agriculture that leach into soil contribute to terrestrial ecotoxicity.

6. **Freshwater ecotoxicity potential (FETP)**: This assesses the potential harm to freshwater ecosystems from toxic chemicals and is also expressed in kg 1,4-DCB_{eq}. For example, chemical runoff from industrial waste into rivers can cause freshwater ecotoxicity, harming fish and aquatic plants.

7. **Marine Ecotoxicity Potential (METP)**: This measures the impact of toxic chemicals on marine environments and is also expressed in kg 1,4-DCB_{eq}. For example, oil spills and the dumping of hazardous wastes into the ocean contribute to marine ecotoxicity.

8. **Abiotic depletion potential - Minerals (ADP Mineral)**: This represents the depletion of mineral resources and is measured in kg of copper equivalents (kg Cu_{eq}). For example, the production of a smartphone requiring substantial copper contributes to mineral resource scarcity.

9. **Abiotic depletion potential - Fossil fuels (ADP Fossil)**: This measures the depletion of fossil fuels and is typically expressed in kg of oil equivalent (kg oil_{eq}). For example, if a factory uses oil for energy, its contribution to fossil resource scarcity is calculated based on the quantity of oil consumed.

10. **Water consumption**: This measures the amount of freshwater consumed during the life cycle of a product or process and is expressed in cubic metres (m^3).

2. Methodology

The following steps were undertaken to conduct LCA in this study:

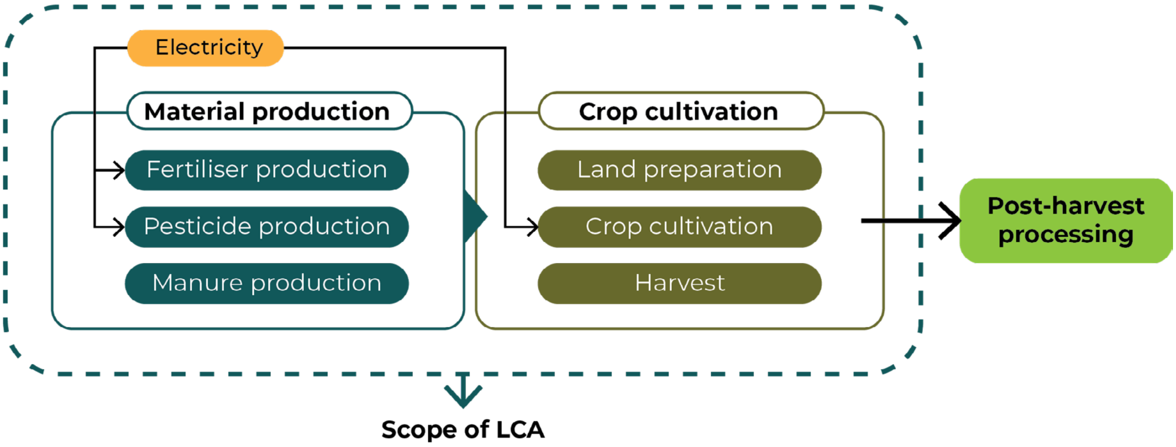
1. Setting the goal and scope of the LCA
2. Choosing the functional unit of the LCA
3. Creating an LCI based on the goal and scope of the LCA
4. Processing the data inputs suitable to feed into the LCA software for impact assessment
5. Analysing results of the simulation

After LCA was performed for each cultivation technique, the emissions from conventional paddy cultivation in Odisha were estimated. To estimate the impact of climate-smart interventions, a scenario analysis was performed wherein different percentages of land were allocated to each cultivation technique.

2.1. Goal and scope of LCA

This step lays the basis for performing an LCA, clarifying the purpose and extent to which the analysis must be performed. In the case of paddy cultivation, particularly when considering adopting climate-smart practices, the first step would be to assess the environmental impact of these practices compared to conventional cultivation. Hence, the goal of the LCA conducted in this study was to quantify the environmental impact of cultivating a paddy plot under different scenarios. The scope of the LCA covered the cradle-to-farm gate (from raw material extraction to the point at which the agricultural product leaves the farm). It includes the mining of the materials, production of material inputs, transportation, other farm inputs, energy requirements, and the processes required for crop production until harvest, as shown in Figure 1. This boundary is chosen because the farmer has the greatest influence over these inputs and processes. Although the farmer is primarily involved in the crop production phase, the type and quantity of material inputs used (e.g. fertilisers, pesticides, source of irrigation power, and seeds), as well as the farming practices followed (water management, soil management, type of ploughing), are bound to influence the environmental impact. Hence, both material production and crop production have been modelled in this analysis. Post-harvest processing has not been modelled because it involves industrial machinery that the farmer may not own or transport to market.

Figure 1: *Scope of the life cycle assessment (LCA)*



2.2. Functional unit (FU) of LCA

FU is the reference unit in an LCA that allows results to be presented under various scenarios for better comprehension. In this study, two FUs were considered: one acre of paddy cultivated and one tonne of paddy harvested. The comparison of scenarios with different cultivation techniques based on the plot area (one acre) gives an idea of the absolute emissions and other environmental impacts. The other FU provides the measure of resources and inputs used and their environmental impact to produce one tonne of harvested paddy. Hence, comparing scenarios with two different FUs would provide more holistic insights.

2.3. LCI

It is a collection of all inputs (material and energy) required and outputs (by-products, wastes, and emissions) generated within the considered scope. For this study, an LCI was created for the lowland cultivation of the 'Pooja' variety, which takes 150 days to mature (National Rice Research Institute, 2021). It is a popularly grown variety in Odisha and was selected as it can be grown under all cultivation approaches considered (conventional farming, natural farming, and DSR). The following inputs formed the LCI for the current LCA:

- Land parcel size
- Seed requirement
- Water requirement for irrigation
  - Energy required to pump the water
- Fertilisers (a mix of urea, DAP, and MOP in the case of conventional farming and natural concoctions in the case of natural farming)
- Farmyard manure (FYM)
- Pesticides (synthetic and organic as deemed fit to the practice)
- Growth regulators
- Machinery for agricultural operations
  - Energy required to power these operations

The outputs generated from cultivation included produce yield, straw, husk, other agricultural residues, and emissions associated with various processes and inputs used for crop production. The emissions were classified as 'off field' and 'on field' in this report, based on the stage at which they were emitted. Straw, husk, and other agricultural residues were not included in the impact assessment, as they are commonly repurposed as fodder in Odisha, and residue burning is negligible in the state (Indian Council of Food and Agriculture, 2018).

2.3.1. Off-field emissions

These emissions are generated from material extraction, production of material inputs, and the electricity required to power these processes and irrigation. The farmer has minimal control over these emissions; however, they can regulate the quantities of these materials to be used. Off-field emissions from conventional paddy cultivation include emissions from the production of seeds, water for irrigation, fertilisers, FYM, pesticides, and growth regulators.

In the case of natural farming, these emissions additionally include those from the preparation of the following inputs:

- Beejamrutham (a concoction that protects seeds and seedlings from soil-borne diseases)
- Ghana Jeevamrutham (an organic fertiliser that promotes soil health)

- Dravajeevamrutham (an organic fertiliser that promotes soil health and growth of beneficial microbes)
- Natural pesticides such as Brahmastra, Neemastra, and Agniastra (natural concoctions to protect the plant from pest infestation)
- Growth promoters such as Panchagavya, egg amino acid, Sapthadhanyankura Kashayam (natural concoctions that promote plant growth and supply nutrients)

2.3.2. On-field emissions

These emissions are generated during the crop production phase. Unlike off-field emissions, these can be controlled by the farmer.

- Emissions from flooding: These mainly include CH_4 emissions that are released when organic matter in flooded paddy fields is decomposed by bacteria under anaerobic conditions (Dhingra et al., 2019).
- Emissions from soil drainage: These include N_2O emissions that are released from nitrification and denitrification processes in the soil. In flooded paddy fields, these emissions are close to zero, but in drained soils, N_2O emissions are significant due to nitrogen mineralisation from organic matter decomposition (Evans et al., 2013).
- Emissions from fertiliser/FYM application: These include N_2O emissions from the N content of fertilisers and FYM applied to the soil (Klein et al., 2006).
- Emissions from fertiliser application: These include SO_2 and PO_4^{3-} emissions from the application of urea and MOP (Selvaraj et al., 2021).
- Emissions from fertiliser/FYM leaching: These include N_2O emissions that are released when the N content of fertilisers and FYM is leached or runs off into water bodies in the form of nitrate (Klein et al., 2006).
- Emissions from fertiliser/FYM volatilisation: These include N_2O emissions that are released when the N content of fertilisers and FYM are volatilised into ammonia (NH_3) and nitrogen oxides (NO_x) and are deposited as ammonium and nitrate ions on soils and surfaces of water bodies (Klein et al., 2006).
- Emissions from urea application: These include CO_2 emissions that are released when urea is applied to the soil (Klein et al., 2006).
- Emissions from machinery usage: These include CO_2 emissions from the use of machinery for agricultural processes. For the studied techniques, only a diesel-powered tractor was assumed to be used for ploughing and carrying. Hence, only emissions from diesel combustion were considered.

2.4. Simulation

Following LCI preparation, the data were fed into SimaPro, an LCA software. This software was selected for its popularity in LCA-related research and its access to a wide range of emission databases and impact assessment methods. All processes that contribute to off-field emissions, except the preparation of FYM and concoctions for natural farming, were modelled using the Ecoinvent database. The preparation of FYM and the other concoctions was modelled separately based on emissions associated with the production of cow dung (with contributions from enteric fermentation and manure management) and other inputs used for the preparation of natural concoctions, as explained in the Appendix. Emissions from water management (continuous flooding vs AWD) and soil management were also separately modelled. In other cases where country-specific emission factors were not available, emission factors from the Ecoinvent database were considered. Further, the impact assessment was performed using the ReCiPe 2016 Midpoint (Hierarchist, H) method.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3. Results

This section discusses the LCI compiled for the selected cultivation approaches (conventional farming, natural farming and DSR) and assesses their impacts through LCA.

3.1. LCI compilation

Tables 2–4 present the LCI prepared for the three paddy cultivation approaches. For conventional and DSR cultivation, data from the Odisha University of Agriculture and Technology (2023) were used, as they represent the contextual data for Odisha. For natural farming, the Package of Practices prescribed by the Rythu Sadhikara Samstha (2021), Indian Institute of Millet Research (2022), and CSTEP (2020) was used. In the initial years of natural farming, yields are considerably lower than those from conventional cultivation. However, after a period of 1 year, yields are 5.85% higher than those from conventional cultivation (Institute for Development Studies AP, 2021). The period during which yields from natural farming exceed those from conventional farming is referred to as 'post-maturity'.

Table 2: *Life cycle inventory for conventional cultivation*

Inputs	Quantity per acre
Seeds	20 kg
Water for irrigation*	5059 m^3
Urea*	56.8 kg
Diammonium phosphate*	28.4 kg
Muriate of potash*	27 kg
Farmyard manure	2.2 tonnes
Pesticide	8 kg
Diesel usage by tractor*	15.35 litres
CH_4 emissions*	26.57 kg
N_2O emissions*	0.23 kg
SO_2 emissions*	495.28 g
PO_4^{3-} emissions*	38.76 g
Yield	2.02 tonnes

**: Components whose quantities were estimated separately (refer to the Appendix)*

Source: Odisha University of Agriculture and Technology, 2023

Table 3: *Life cycle inventory for natural farming*

Inputs	Quantity per acre
Seeds	20 kg
Water for irrigation*	3,668 m^3
Beejamrutham*	5 litres
Ghana Jeevamrutham*	400 kg
Dravajeevamrutham*	2000 litres
Brahmastra	10 litres
Neemastra	10 litres
Agniastra	100 litres
Panchagavya	4 litres
Egg amino acid	200 ml per 100 litres
Sapthadhanyankura Kashayam	250 ml per 100 litres
CH_4 emissions*	3.21 kg
N_2O emissions*	1.32 kg
Yield	1.21 tonnes (2.14 tonnes post-maturity)

**: Components whose quantities were estimated separately (refer to the Appendix)*

Source: Rythu Sadhikara Samstha, 2021; Indian Institute of Millet Research, 2022; CSTEP, 2020

Table 4: *Life cycle inventory for direct-seeded rice cultivation*

Inputs	Quantity per acre
Seeds	20 kg
Water for irrigation*	3,541 m^3
Urea*	56.8 kg
Diammonium phosphate*	28.4 kg
Muriate of potash*	27 kg
Farmyard manure	2.2 tonnes
Pesticide	8 kg
Diesel usage by tractor*	15.35 litres
CH_4 emissions*	21.52 kg
N_2O emissions*	1.43 kg
SO_2 emissions*	495.28 g
PO_4^{3-} emissions*	38.76 g
Yield	1.62 tonnes

**: Components whose quantities were estimated separately (refer to the Appendix)*

Source: Odisha University of Agriculture and Technology, 2023

3.2. Impact assessment

Table 5 summarises the environmental impact of each considered paddy cultivation technique per acre, as obtained from the simulation. For the impact assessment, various parameters were selected to quantify the impact on emissions (GWP), water quality (FEP, MEP, FETP, and METP), land quality (TAP and TETP), and resource use (ADP Mineral, ADP Fossil, and water consumption).

***Table 5:** Estimated impact (per acre) for the three cultivation techniques*

Impact category	Conventional farming	Natural farming	Direct-seeded rice farming
Global warming potential (kg CO_{2eq})	4,460	2,838	3,829
Terrestrial acidification potential (kg SO_{2eq})	10.10	6.9	7.54
Freshwater eutrophication potential (kg P_{eq})	2.97	2.18	2.09
Marine eutrophication potential (kg N_{eq})	0.19	0.22	0.16
Terrestrial ecotoxicity potential (kg 1,4-DCB_{eq})	6,338	3,411	5,270
Freshwater ecotoxicity potential (kg 1,4-DCB_{eq})	91.49	59.25	68.83
Marine ecotoxicity potential (kg 1,4-DCB_{eq})	129.52	83.89	97.23
Abiotic depletion potential - Minerals (kg Cu_{eq})	2.85	0.66	2.72
Abiotic depletion potential - Fossil fuels (kg oil_{eq})	787.61	538.96	574.80
Water consumption (m^3)	5,072	3,704	3,555

3.2.1. Impact assessment per acre of cultivation

An assessment of the environmental impact per acre for each cultivation technique shows that conventional cultivation has the highest impact on all parameters, except MEP. Table 6 shows the reduction in these impact assessment factors owing to natural farming and DSR cultivation.

Table 6: *Comparison of impact assessment factors to conventional cultivation*

Impact category	Natural farming	Direct-seeded rice farming
Global warming potential (kg CO_{2eq})	36.4% ↓	14.1% ↓
Terrestrial acidification potential (kg SO_{2eq})	31.7% ↓	25.3% ↓
Freshwater eutrophication potential (kg P_{eq})	26.6% ↓	29.6% ↓
Marine eutrophication potential (kg N_{eq})	15.8% ↑	15.8% ↓
Terrestrial ecotoxicity potential (kg 1,4-DCB_{eq})	46.2% ↓	16.8% ↓
Freshwater ecotoxicity potential (kg 1,4-DCB_{eq})	35.2% ↓	24.7% ↓
Marine ecotoxicity potential (kg 1,4-DCB_{eq})	35.2% ↓	24.9% ↓
Abiotic depletion potential - Minerals (kg Cu_{eq})	76.8% ↓	4.5% ↓
Abiotic depletion potential - Fossil fuels (kg oil_{eq})	31.6% ↓	27% ↓
Water consumption (m^3)	26.9% ↓	29.9% ↓

The only anomalous trend is that natural farming has a higher MEP per acre (16%) than conventional farming. MEP is affected by excess nutrients in marine water, specifically nitrogen. Since natural farming involves the use of large quantities of natural concoctions that eventually leach into seawater, it may result in high MEP.

Figure 2 and Figure 3 compare the GWP and water consumption of each cultivation technique, respectively. These parameters have been emphasised because they are major indicators of emissions and resource use associated with paddy cultivation. It can be inferred that natural farming and DSR cultivation result in 36% and 14% lower emissions, respectively, and consume 27% and 30% less water, respectively, than conventional cultivation. Thus, conventional cultivation had the highest impact on GWP and water consumption per acre among the three cultivation techniques.

Figure 4 depicts the on-field and off-field emission contribution of each cultivation technique. It can be inferred that natural farming results in significantly lower on- and off-field emissions than conventional farming.

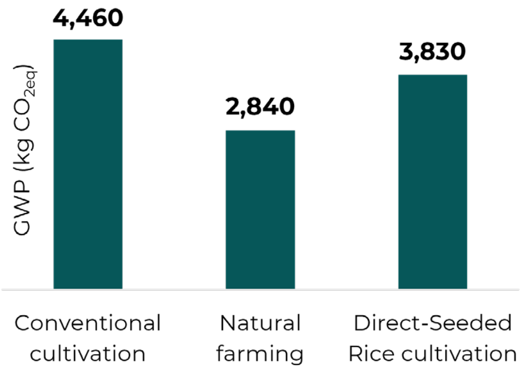


Figure 2: *Comparison of global warming potential (GWP) per acre*

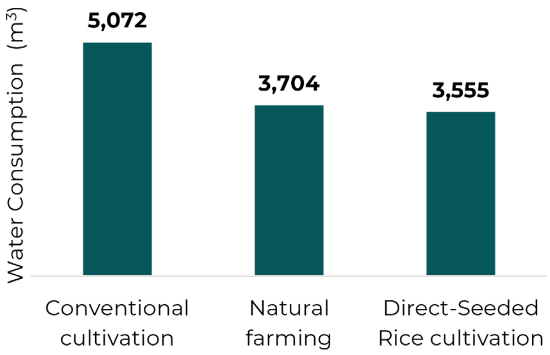
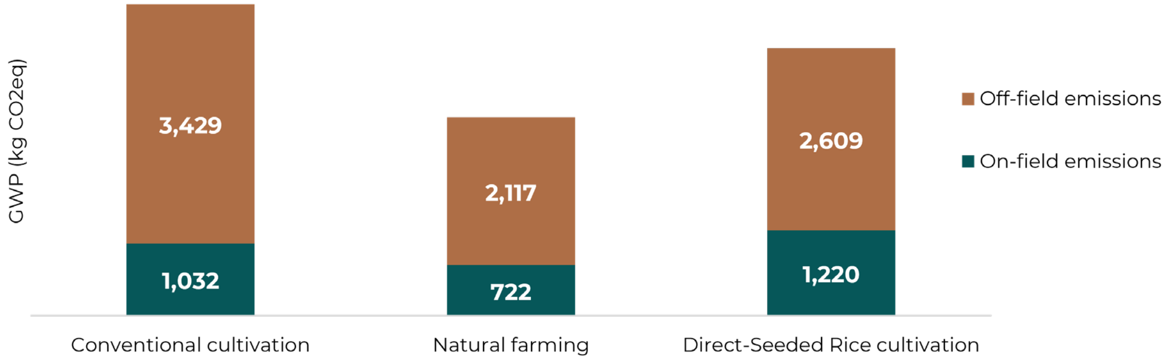


Figure 3: *Comparison of water consumption per acre*

Figure 4: *On- and off-field emission contributions to global warming potential (GWP) per acre for each cultivation technique*



3.2.2.Impact assessment per tonne of yield

The environmental impact per tonne of yield for each cultivation technique was assessed in this study because the yield varies with each technique, as shown in Figure 5. Natural farming and DSR cultivation show 40% and 20% reductions in yield compared to conventional cultivation, respectively. Compared to conventional cultivation, post-maturity natural farming yields increased by 5.8%.

Notably, an impact assessment per acre can inform decisions on how much land can be cultivated with each technique while minimising negative impacts. In contrast, impact assessment per tonne of yield informs planning of the proportion of total yield from each cultivation technique, aiming to ensure maximum yield with minimum impact.

Figure 5: *Comparison of the yield from each cultivation technique*

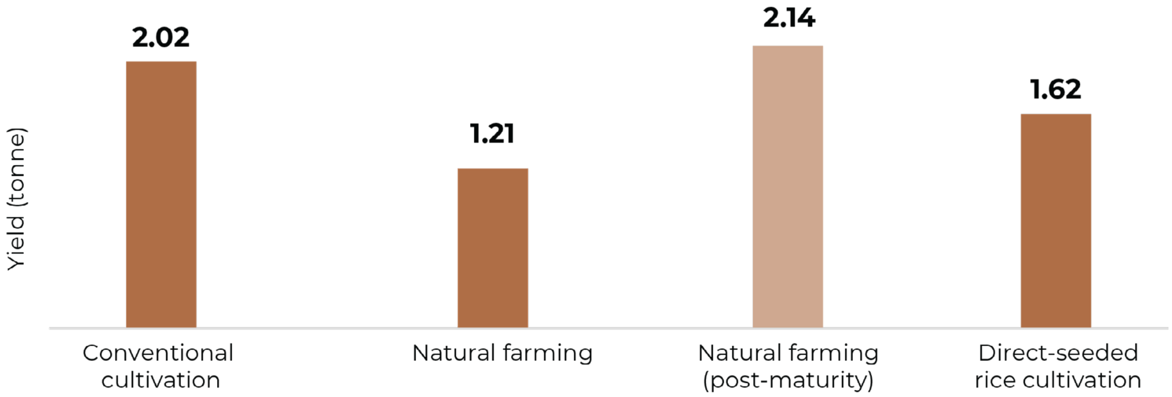


Figure 6 and Figure 7 compare the GWP and water consumption of each cultivation technique, respectively. While the GWP per tonne of produce is the highest for DSR cultivation, water consumption per tonne of produce is the highest for natural farming.

Figure 6: *Comparison of global warming potential (GWP) per tonne of produce*

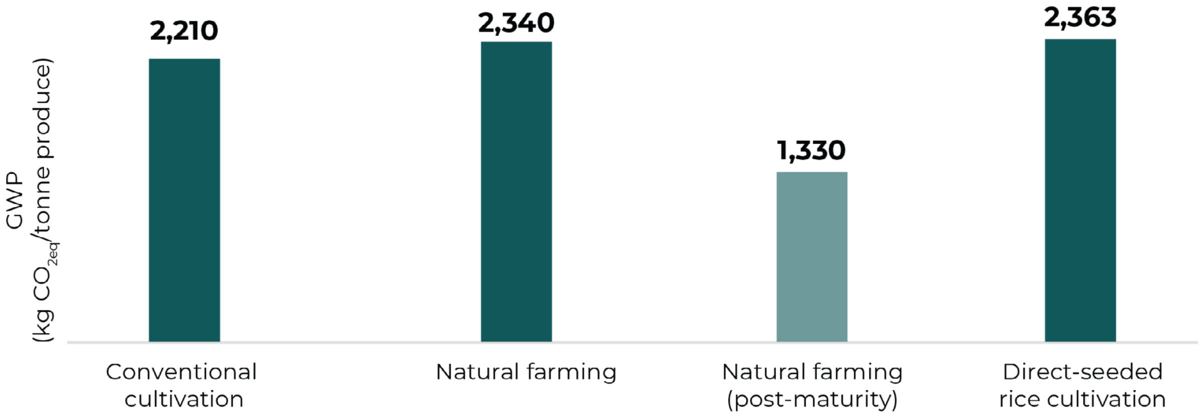
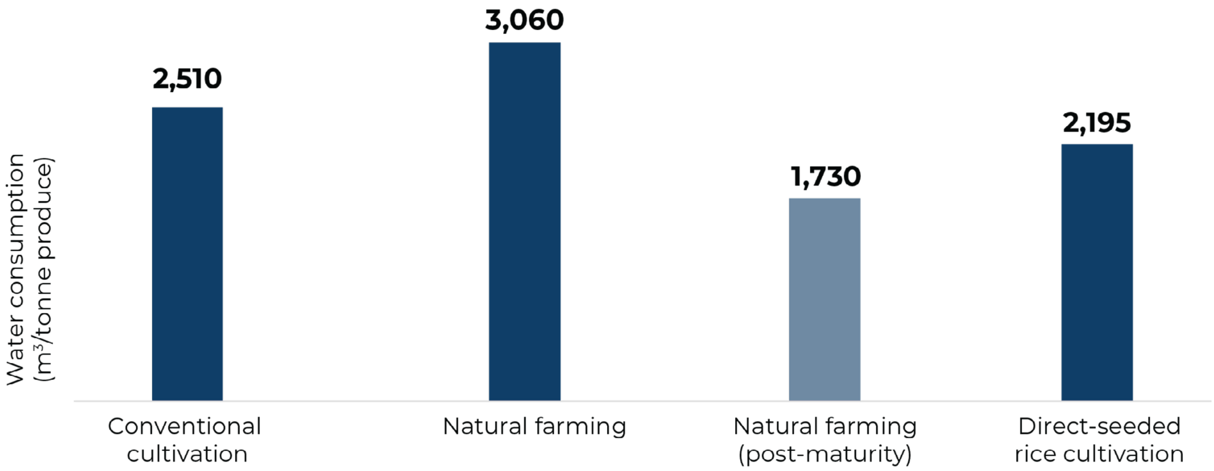


Figure 7: *Comparison of water consumption per tonne of produce*



3.3. Projected impact of adopting climate-smart agriculture (CSA)

To visualise the impact of adopting CSA practices in irrigated areas, this study considered seven cases of land allocation for conventional cultivation, natural farming, and DSR cultivation. Table 7 summarises the various scenarios considered, where each percentage indicates the lift irrigation area allotted under each cultivation technique. The base scenario assumes that all lift-irrigated areas under paddy cultivation in Odisha follow conventional cultivation. Scenario 1 considers 75% of these areas under conventional cultivation, 12.5% under natural farming, and 12.5% under DSR cultivation. This assessment was performed only for areas under lift irrigation owing to the lack of data on surface irrigation.

Table 7: *Scenarios allotting various percentages of irrigated land to each cultivation technique*

Scenario	Conventional cultivation	Natural farming	DSR cultivation
Base Scenario	100%	0%	0%
Scenario 1	75%	12.5%	12.5%
Scenario 2	50%	25%	25%
Scenario 3	25%	37.5%	37.5%
Scenario 4	0%	50%	50%
Scenario 5	0%	100%	0%
Scenario 6	0%	0%	100%

Figure 8 and Figure 9 indicate the predicted impact of adopting these scenarios on the GWP over a single harvest (150 days), while Figure 10 describes the impact on the yield over the same duration. Moving away from conventional cultivation leads to a significant drop in GWP and yield. As shown in the figures, Scenario 4 shows a 25% reduction in GWP and a 30% reduction in yield relative to the Base Scenario. Scenario 5 (100% natural farming) shows a 36% drop in GWP and a 40% drop in yield from the Base Scenario. Similarly, Scenario 6 (100% DSR cultivation) shows a 14% drop in GWP and a 20% drop in yield from the Base Scenario. The percentage allotment will need to be strategically planned to balance the benefits of adopting CSA practices with adequate yields.

Figure 8: *Net global warming potential (GWP) under each scenario*

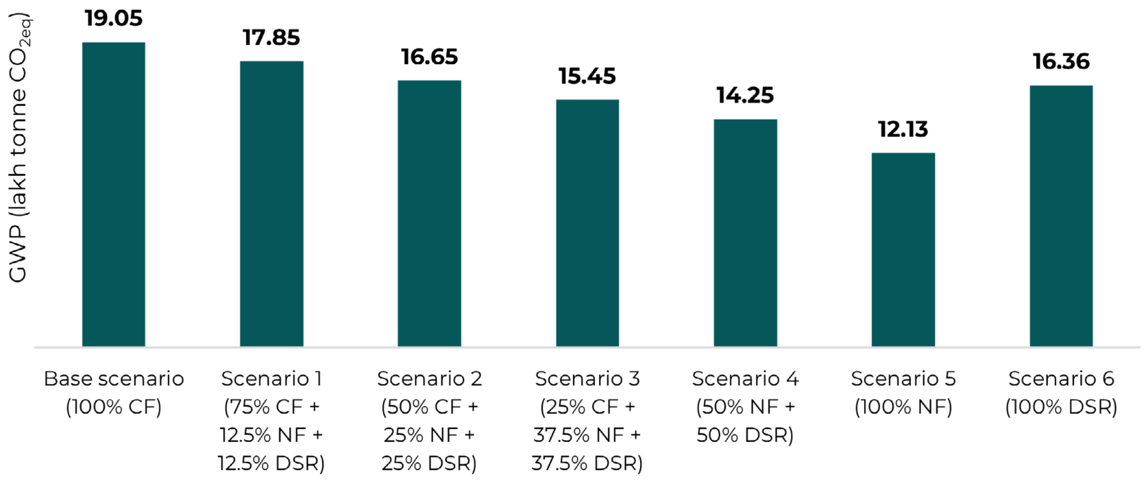


Figure 9: *On-field and off-field emissions under each scenario*

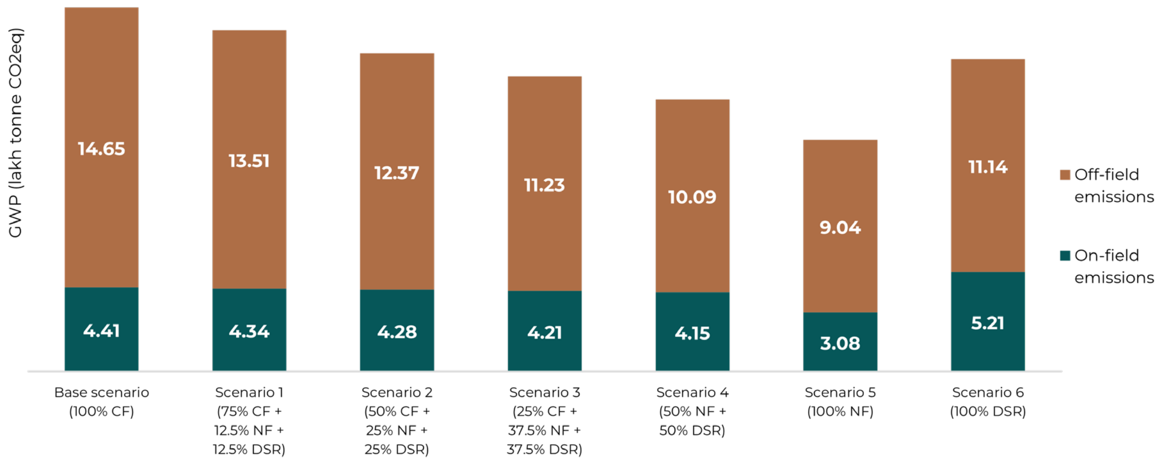
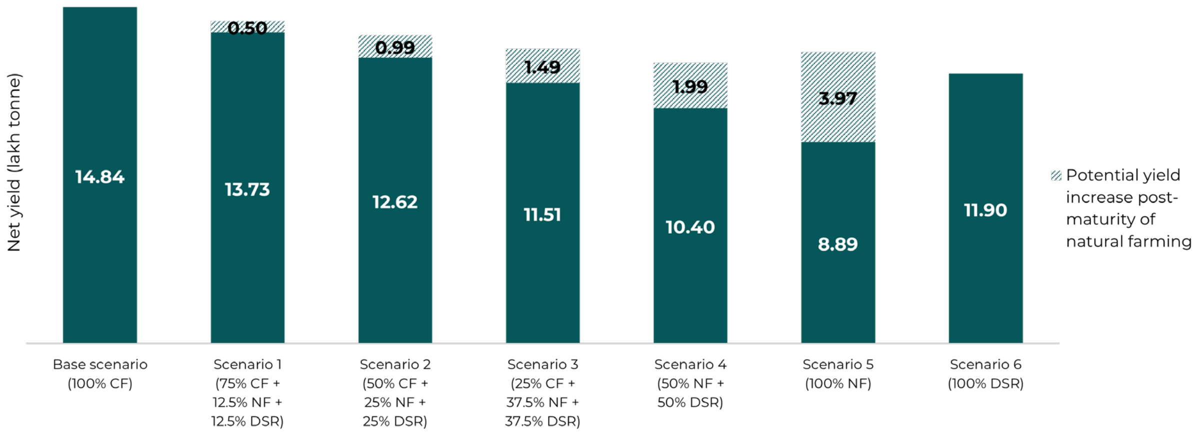


Figure 10: *Net yield under each scenario*



4. Discussion

4.1. Environmental impact and emission estimation

Paddy is cultivated in 39 lakh hectares across Odisha (Department of Agriculture and Farmers' Empowerment, 2025), 35% (13.5 lakh hectares) of which is irrigated. The remaining cultivated area (25 lakh hectares) comprises rainfed and deep-water paddy cultivation. Currently, conventional flooded cultivation is the dominant practice across irrigated areas, while DSR cultivation is dominant across rainfed areas. Natural farming is assumed to be practised in a negligible percentage of cultivated area.

Among the three cultivation techniques, conventional cultivation had the highest GHG impact (or GWP) per acre. While natural farming had the lowest GWP per acre, it also yielded the least, implying a higher GWP per tonne of produce. In addition, natural farming consumes more water per tonne of produce. In contrast, DSR offers a middle ground between GWP per acre and water consumption per tonne of produce. Although natural farming shows long-term positive effects, the abovementioned factors must be considered while strategising climate-smart solutions for Odisha. This comparison provides a more holistic understanding of the environmental impacts of these cultivation techniques. This allows additional thinking along the intersection of GHG emissions, yield, water, and resource usage.

The remaining cultivated area (25 lakh hectare) is a combination of rainfed and deep-water systems. Emissions from these areas are calculated in Appendix 7.3. These areas are estimated to generate 8.6 million metric tonnes (MMT) of CO_{2eq}.

Among irrigated areas, 12.8% is irrigated using tanks, wells, and borewells (Singh et al., 2021), which are assumed to be powered by electric pumps. Hence, these areas can be approximated to generate 1.9 MMT of CO_{2eq}. Further, a mix of diesel and electric pumps is used to irrigate the remaining area (87.2%). According to a recent report by CSTEP, 5% of the total irrigation pumps in Odisha are diesel pumps (CSTEP, 2025). It has hence been assumed that diesel pumps are used in 5% of the irrigated areas under paddy in the state. While solar pumps are making gradual headway in the state, they were not considered in this analysis.

The impact assessment showed that the emissions from surface irrigation powered by an electric pump were one-eighth or 12% of those of an electric pump used for borewell irrigation. Further, emissions from a diesel pump set for surface irrigation were 38% of those from an electric pump set for borewell irrigation (refer to the Appendix).

For the scope defined in this study, the total emissions from paddy cultivation in the state were 16.6 MMT of CO_{2eq}, with on-field emissions contributing 8.2 MMT of CO_{2eq}. A recent study by the GHG Platform India in Odisha estimated emissions from rice cultivation to be 7.15 MMT of CO_{2eq}, which is 13% less than the on-field emissions estimated in this study (GHGPI, 2022). However, off-field emissions must also be included in this estimate to provide a clearer picture of the energy and material inputs required for paddy cultivation.

4.2. Target setting

The Odisha Climate Change Action Plan (2021–2030) identifies several technical and policy gaps, including limited access to climate and sectoral data in agriculture and the absence of quantified evidence on the long-term impacts and sustainability of existing policies (Government of Odisha, 2018). This report addresses these gaps by generating actionable evidence and scenario-based insights to guide data-driven decision-making. The scenarios analysed could provide a scientific basis for setting measurable targets under the 'Key Activities' outlined in the Action Plan, which focus on both climate change adaptation and mitigation.

In this context, Scenario 1 (75% conventional cultivation, 12.5% natural farming, 12.5% DSR) can serve as a feasible target for achieving emission reductions with minimal yield loss, enabling a

6% reduction in emissions from paddy cultivation across the state, with only a 7% reduction in net yields compared to the base scenario. However, if a reduction in net yield is an acceptable trade-off, Scenario 3 (25% conventional cultivation, 37.5% natural farming, 37.5% DSR) could be adopted, as it would enable a 19% reduction in emissions from paddy cultivation across the state. While initial yields may fall by 22%, improved productivity from natural farming practices (post-maturity) could limit long-term yield decline to just 5%.

By combining life cycle assessment (LCA) and scenario modelling, this analysis equips the government with a forward-looking approach to measure and enhance policy impact, ensuring that Odisha's climate strategies are both evidence-based and outcome-oriented.

4.3. Study limitations

The following are the limitations of the study:

- The DAP used in the simulations comprises 57% phosphorus nutrient (DAP [22-57-0]) instead of 46% (DAP [18-46-0]), which is commonly used in India. Hence, the quantity of DAP used in the simulations is slightly lower than the levels commonly used in India.
- SO_2 and PO_4^{3-} emissions from DAP and FYM were not modelled owing to the lack of data.
- The use of seed-treatment chemicals, micronutrients, and herbicides in conventional and DSR cultivation was not modelled owing to a lack of data.
- It was assumed that weeding and chemical application were done by hand and were, thus, not modelled.
- Concoctions for natural farming that require pulse flour were modelled with maize flour instead owing to the lack of data.
- Concoctions for natural farming that require jaggery were modelled with sugarcane instead owing to the lack of data.
- Cow urine, ghee, tender coconut water, grape juice, neem leaves, and bund soil were not modelled owing to lack of data.
- The average grid emission factor of India is 0.76 kg CO_2/kWh, but the value shown in SimaPro (1.41 kg CO_2/kWh) was considered in this study.
- The potency of GHGs is measured in kg CO_2 equivalents (CO_{2eq}). As per the Biennial Update Report to the United Nations Framework Convention on Climate Change (MoEFCC, 2024), the defined values for CH_4 is 21 kg CO_{2eq} and N_2O is 310 kg CO_{2eq}, but the values shown in SimaPro (CH_4 = 33 kg CO_{2eq} and N_2O = 298 kg CO_{2eq}) were considered.

5. Conclusion

Paddy is a crop of paramount importance in Odisha. Not only does it provide subsistence to several farmers but also supports many livelihoods. Paddy cultivation is, however, among the top-most emitters in the agricultural sector and is also a resource guzzler, given its extensive water and fertiliser requirements. Given these environmental and resource challenges, it is imperative to adopt climate-smart agricultural practices for rice cultivation to ensure sustainable farming. In this report, LCA was performed for two important climate-smart practices (natural farming and DSR cultivation), in comparison with conventional (flooded) cultivation. The GWP and water consumption per acre of both CSA practices were found to be significantly lower than those of conventional cultivation (14%–36% and 27%–30%, respectively). However, because their yield is also lower than that of conventional cultivation (40% and 20%, respectively), the GWP and water consumption per tonne of yield were the highest for DSR and natural farming, respectively, among the three cultivation techniques.

The projected impact of adopting these CSA practices in areas under lift irrigation was also estimated in this study. The scenario wherein conventional cultivation was completely replaced with natural farming and DSR cultivation (50% each) showed a 25% drop in GWP and a 30% drop in yield from the Base Scenario. A 100% natural farming scenario showed a 36% drop in GWP and 40% drop in yield from the Base Scenario. Similarly, a 100% DSR cultivation scenario showed a 14% drop in GWP and 20% drop in yield from the Base Scenario. These aspects need to be considered closely while strategising how much area must come under climate-smart solutions in the state.

While these CSA practices offer substantial benefit to the plots they are performed on, the reduction in yields is a factor to consider while pushing for their adoption. Further, their GWP and water consumption per tonne of yield must also be considered. This would allow more reasonable and achievable targets for GHG emission reduction and improved water management.

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7. Appendices

7.1. Appendix A: Components of concoctions used in natural farming

The following tables list the components of various concoctions used in natural farming.

Table A1: *Components of Beejamrutham*

Component	Quantity per 100 kg seeds
Cow dung	5 kg
Cow urine	5 litres
Lime	50 g
Water	20 litres
Bund soil	1 kg

Table A2: *Components of Ghana Jeevamrutham (Type 1)*

Component	Quantity per unit
Cow dung	100 kg
Jaggery	1 kg
Gram flour (Besan)	1 kg

Table A3: *Components of Dravajeevamrutham*

Component	Quantity per unit
Cow dung	10 kg
Cow urine	5–10 litres
Jaggery	2 kg
Pulse flour	2 kg
Water	200 litres
Bund soil	A handful

Table A4: *Components of Brahmastra*

Component	Quantity per unit
Cow urine	10 litres
Neem leaves	5 kg
Custard apple leaves	2 kg
Papaya leaves	2 kg
Pomegranate leaves	2 kg
Lantana camera leaves	2 kg
White Datura leaves	2 kg

Table A5: *Components of Neemastra*

Component	Quantity per unit
Cow urine	10 litres
Green chilli	500 g
Neem leaves	5 kg

Table A6: *Components of Agniastra*

Component	Quantity per unit
Water	100 litres
Cow urine	5 litres
Cow dung	5 kg
Neem leaves	5 kg

Table A7: *Components of Sapthadhanyankura Kashayam*

Component	Quantity per unit
Sesame seeds	100 g
Green moong dal	100 g
Black urad dal	100 g
Lobiya	100 g
Horse gram	100 g
Chickpea (Chana)	100 g
Wheat	100 g
Water	200 litres
Cow urine	10 litres

Table A8: *Components of egg amino acid*

Component	Quantity per unit
Eggs	5
Lemons	10–15
Jaggery	250 g
Water	100 litres

Table A9: *Components of Panchagavya*

Component	Quantity per unit
Fresh cow dung	5 kg
Cow urine	3 litres
Boiled milk	2 litres
Cow ghee	500 g
Ripe bananas	12
Black organic jaggery	500 g
Water	3 litres
Tender coconut water	3 litres
Grape juice	2 litres

7.2. Appendix B: Estimation of inventory quantities and emissions

7.2.1. Fertilisers

7.2.1.1. Fertiliser quantity

Data on nutrient application to the soil in conventional and direct-seeded rice (DSR) cultivation are given below:

- Nitrogen nutrient = 80 kg N/ha
- Phosphorus nutrient = 40 kg P/ha
- Potassium nutrient = 40 kg K/ha

In this study, it was assumed that nutrients are supplied to the soil through a mix of urea, diammonium phosphate (DAP), and muriate of potash (MOP). According to data from the Tamil Nadu Agricultural University (TNAU, 2014),

- Urea contains 46% N
- DAP contains 22% N and 57% P, and
- MOP contains 60% K.

Hence, the amounts of fertilisers applied to the soil were calculated as follows:

- *MOP (kg) = (K nutrient requirement)/60%*
- *DAP (kg) = (P nutrient requirement)/57%*
- *Urea (kg) = (N nutrient requirement – DAP × 22%)/46%*

7.2.1.2. Emissions following fertiliser application

As mentioned in Section 2.3.2, N_2O (from fertiliser leaching and volatilisation) and CO_2 (from urea) are the main contributors to the emissions after fertiliser application. The methodology followed by Klein et al. (2006) and country-specific emission factors (EFs) provided by MoEFCC (2024) and Hergoualc'h et al. (2019) were used in this study.

N_2O emissions from fertiliser application:

Emissions (kg N_2O) = EF_{1fr} × (N input per year) × (Crop duration in annum) × 44/28,

where EF_{1fr} = 0.003 kg N_2O – N/kg N input.

N_2O emissions from fertiliser volatilisation:

Emissions (kg N_2O) = (N input per year) × $Frac_{GASF}$ × EF_4 × (Crop duration in annum) × 44/28,

where EF_4 = 0.5% and $Frac_{GASF}$ (the fraction of fertiliser volatilised into NH_3 and NO_x) = 20%.

N_2O emissions from leaching:

Emissions (kg N_2O) = (N input per year) × $Frac_{LEACH}$ × EF_5 × (Crop duration in annum) × 44/28,

where EF_5 = 0.5% and $Frac_{LEACH}$ (the fraction of fertiliser lost to leaching) = 10%.

CO_2 emissions from urea:

Urea, in the presence of water and urease enzymes, is converted to ammonium ion (NH_4^+), hydroxyl ion (OH^-), and bicarbonate ion (HCO_3^-).

Emissions (kg CO_2)=EF × (Amount of urea applied) × (Crop duration in annum) × 44/12,

where EF = 0.2.

Other emissions:

Emissions contributing to the acidification potential (AP) and eutrophication potential (EP) from urea and MOP were calculated using the EFs provided by Selvaraj et al. (2021).

EF of AP-related emissions from urea = 5.3 g SO_2/kg urea

EF of EP-related emissions from urea = 0.54 g PO_4^{3-}/kg urea

EF of AP-related emissions from MOP = 7.2 g SO_2/kg MOP

EF of EP-related emissions from MOP = 0.3 g PO_4^{3-}/kg MOP

7.2.2. Farmyard manure (FYM)

7.2.2.1. FYM preparation

FYM preparation was based on the constituents given in (Indian Council of Agricultural Research, n.d.):

Table A10: *Constituents for farmyard manure preparation*

Component	Proportion
Cow dung	67%
Cattle shed waste	20%
Ash	10%
Household waste	2%
Vegetable waste	1%

Given that cow dung had the highest proportion among the components of FYM, emissions from its production were modelled. Enteric fermentation (a digestion process in ruminant animals producing methane) and manure management are two major processes during cow dung production that result in emissions and were modelled based on India-specific EFs (Samal et al., 2024). The amount of cow dung produced per day was obtained from a report by the NITI Aayog (2023). It was assumed that all cow dung was gathered from one cow.

Days to produce the required amount of cow dung = Required amount /Cow dung produced per day,

where cow dung produced per day = 11 kg/cow.

Emissions from enteric fermentation (kg CH_4 *) = EF× (Days to produce required amount of cow dung),*

where EF = 37 kg CH_4 /cow/y.

Emissions from manure management (kg CH_4 *) = EF× (Days to produce required amount of cow dung),*

where EF = 4 kg CH_4 /cow/y.

7.2.2.2. Emissions following FYM application

Emissions after FYM application were obtained using a process similar to that used for fertiliser application. CO_2-, AP-, and EP-related emissions were not calculated in this study.

Emissions from FYM application:

$Emissions\ (kg\ N_2O) = EF_{1fr} \times (N\ input) \times (Crop\ duration\ in\ annum) \times 44/28$,

where $EF_{1fr} = 0.003$ kg $N_2O - N$/kg N input

Emissions from FYM volatilisation:

$Emissions\ (kg\ N_2O) = (N\ input) \times Frac_{GASM-AM} \times EF_4 \times (Crop\ duration\ in\ annum) \times 44/28$,

where EF_4 = 0.5% and $Frac_{GASF-AM}$ (the fraction of FYM volatilised into NH_3 and NO_x) = 20%.

Emissions from leaching:

$Emissions\ (kg\ N_2O) = (N\ input) \times Frac_{LEACH} \times EF_5 \times (Crop\ duration\ in\ annum) \times 44/28$,

where EF_5 = 0.5% and $Frac_{LEACH}$ (the fraction of FYM lost to leaching) = 10%.

7.2.3. Irrigation

7.2.3.1. Amount of water required for irrigation

According to the National Rice Research Institute (2021), rice requires an average of 2,500 litres of water per kg of produce. Considering the expected yields from each cultivation technique, water requirement was calculated as follows:

Water requirement=2,500 litres × (Expected yield)

In the case of natural farming, where alternate wetting and drying (AWD) is performed, it was assumed that the water requirement was 27.5% less than that for conventional farming on an average (Carrijo et al., 2017). Further, DSR cultivation was assumed to utilise 30% less water than conventional cultivation (Kumar et al., 2024).

7.2.3.2. Emissions from energy use for irrigation

Lift irrigation (a method of raising water from a lower to a higher elevation for irrigation) was assumed to be powered by a 12 Horsepower (hp) electric pump of 85% efficiency (Arun Shankar et al., 2016). The water source was assumed to be a borewell of 400-feet depth (Central Ground Water Board, 2013). Based on these assumptions, the average flow rate was calculated as follows:

$Flow\ rate\ (m^3/s) = ((Total\ water\ requirement))/((Work\ done)) \times (Power\ of\ pump),$

where

$Work\ done\ (kWh) = (Density\ of\ water) \times (Acceleration\ due\ to\ gravity) \times (Height\ of\ lift)$

The time required to pump this amount of water was calculated as follows:

$$Time\ required\ (h) = (Water\ requirement)\ /\ (Flow\ rate)$$

Hence, the electricity requirement was calculated as follows:

$$Electricity\ requirement\ (kWh) = (Power\ of\ pump) \times (Time\ required)$$

In the case of surface irrigation, the depth of the water resource was considered to be 49 ft. All other parameters for an electric pump under surface irrigation were considered to be the same as above. A diesel pump was modelled with a power output of 7 hp with an efficiency of 25%. The EF for diesel was assumed to be 2.68 kg CO_2/litre diesel.

7.2.3.3. Post-irrigation emissions

Post-irrigation emissions include CH_4 emissions from flooding and N_2O emissions from soil drainage. EFs provided by Dhingra et al. (2019) and Evans et al. (2013) were used in this study.

$Emissions\ from\ flooding\ (kg\ CH_4) = EF \times (Crop\ duration\ in\ annum),$

where EF = 159.74 kg CH_4/ha/y in the case of flooded irrigation and EF = 19.3 kg CH_4/ha/y in the case of multiple aeration (AWD).

$Emissions\ from\ soil\ drainage\ (kg\ N_2O) = EF_2 \times (Crop\ duration\ in\ annum) \times 44/28,$

where EF_2 = 0.4 kg $N_2O - N$/ha/y in the case of flooded irrigation and EF_2 = 5 kg $N_2O - N$/ha/y in the case of AWD. Since AWD is followed in both natural farming and DSR cultivation, this value was assumed for EF_2 for both.

7.2.4. Machinery usage

As per the Odisha University of Agriculture and Technology (2023), the only machinery used in conventional and DSR cultivation within the scope of this study was tractors for ploughing and carrying. It was assumed that no machinery was used in natural farming. Data from the Odisha University of Agriculture and Technology (2023) were used to determine the total duration of tractor use and information from the Government e Marketplace (2023) was referenced for the fuel requirement per hour.

$Total\ fuel\ usage\ by\ tractor = (Total\ duration\ of\ use) \times (Fuel\ requirement\ per\ hour),$

where the total duration of tractor use = 8 h/ha and fuel requirement of tractor = 4.74 litre/h.

7.3. Appendix C: Estimation of paddy cultivation emissions in Odisha

Areas under paddy cultivation in Odisha are disaggregated, as shown in Table A11 (CSTEP, 2025).

Table A11: *Disaggregation of land classes under paddy in Odisha*

Land class	Proportion of paddy cultivated area
Upland	25.3%
Medium land	38.8%
Lowland	35.9%

The distribution of rainfed areas in Odisha is shown in Table A12. Because the non-irrigated lowlands comprise deep-water rice, they have not been included in this table.

Table A12: *Disaggregation of rainfed areas under upland and medium land in Odisha*

Total rainfed area	Flood prone	Drought prone	Upland
Upland	--	--	100%
Medium land	27.1%	72.9%	--

Further, irrigated areas are disaggregated into areas under lift irrigation using electric pumps, surface irrigation using diesel pumps, and surface irrigation using electric pumps, as shown in Table A13.

Table A13: *Disaggregation of irrigated areas in Odisha*

Total irrigated area (upland, medium land, and lowland)	Lift irrigation (electric pumps)	Surface irrigation (diesel pumps)	Surface irrigation (electric pumps)
	12.8%	5%	82.2%

Hence, the land allotment under each category is calculated as shown in Table A14.

Table A14: *Land allotment under each category*

Land class	Rainfed (lakh hectare)	Deep water (lakh hectare)	Irrigated (lakh hectare)
Upland	7.81	0	1.95
Medium land	4.94	0	10.03
Lowland	0	12.05	1.8

To estimate emissions from deep-water rice, rainfed upland, and rainfed drought- and flood-prone areas, the emission values from all sources under conventional paddy cultivation, except flooding and irrigation, are taken as they are because all conditions, except for the two, are the same in all cases. To estimate the emissions from flooding, the methane emission factor for each case was considered, as shown in Table A15 (Dhingra et al., 2019).

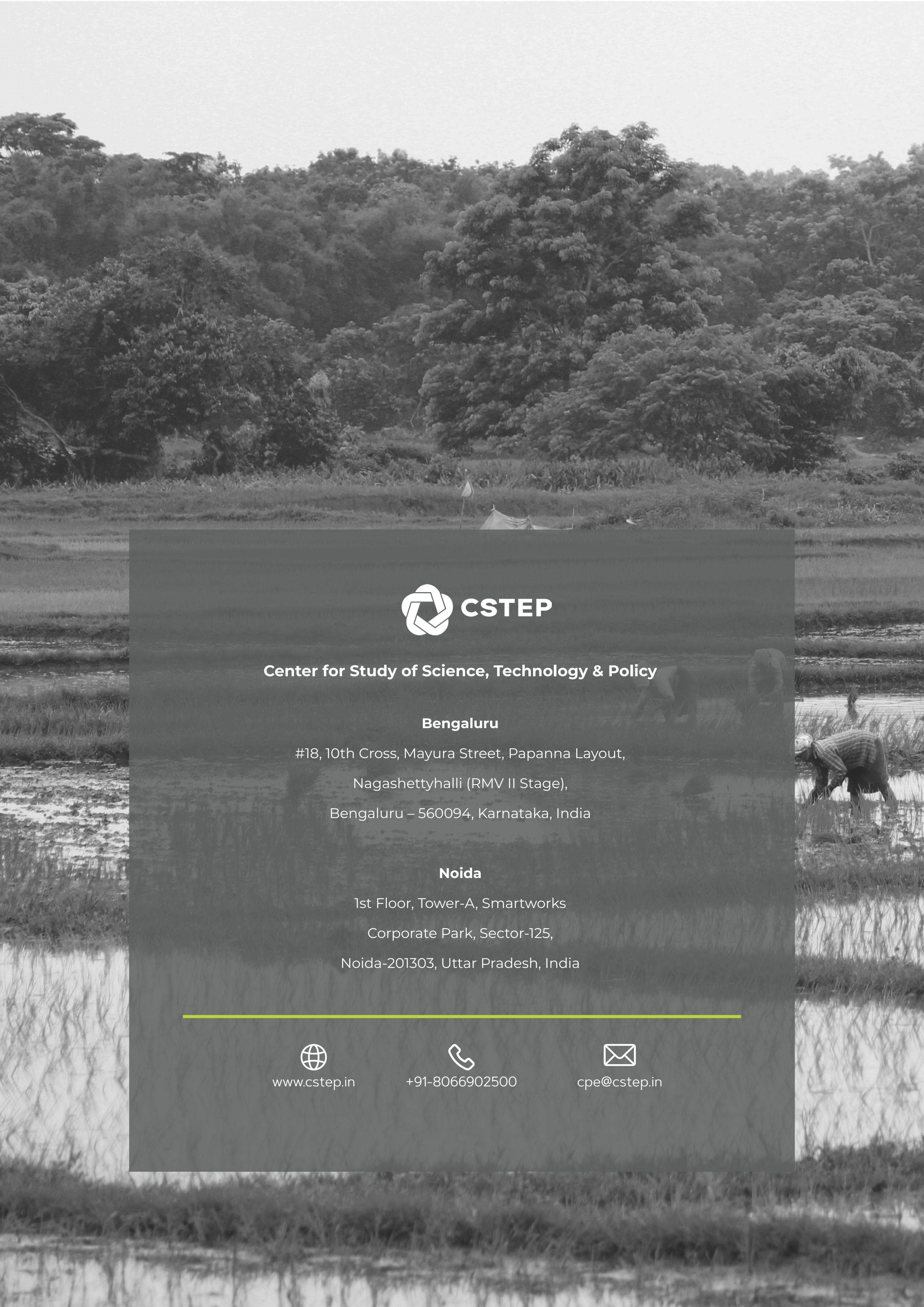
Table A15: *Methane emission factors of various paddy systems*

Paddy system	Methane emission factor (kg CH_4/ha/annum)
Continuous flooding (conventional)	159.74
Deep water	190
Flood prone	189
Drought prone	66.84

Further, emissions from irrigation in these areas were taken as zero as they are rainfed. Table A16 summarises the GWP per acre of each paddy cultivation category, along with the area under each in Odisha. These data were used to estimate paddy cultivation emissions in the state.

Table A16: *GWP per acre of each category with land allotment*

System		GWP per acre (kg CO_{2eq})	Area (lakh hectare)
Irrigated	Lift irrigated (electric pump)	4,460	1.76
	Surface irrigated (electric pump)	2,009	11.33
	Surface irrigated (diesel pump)	2,723	0.69
Rainfed	Upland	783	7.81
	Flood prone	1,821	1.34
	Drought prone	1,150	3.6
Deep water	Deep water	1,826	12.05



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