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Life cycle assessment of environmental impacts of rice production under different cultivation methods

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Abstract

Rice feeds roughly half of the world's population, but its cultivation ranks among the most environmentally taxing forms of crop production per calorie delivered. This research applied a cradle-to-farm-gate life cycle assessment (LCA) to compare the environmental footprints of three rice cultivation methods: conventional flooded, organic, and the System of Rice Intensification (SRI) across 60 experimental plots at Cornell University's research farms in Ithaca, New York, during the 2023 growing season. Six impact categories were evaluated using the CML 2001 method: global warming potential (GWP), acidification, eutrophication, ecotoxicity, water depletion, and land use. Conventional flooded rice showed the highest GWP at 4,873 kg CO₂-eq ha⁻¹, driven largely by methane emissions from continuous flooding. Organic rice reduced GWP by 41.7% (2,841 kg CO₂-eq ha⁻¹) but increased land use impact by 25.9% due to lower yields. SRI offered the best overall balance, cutting GWP by 35.9% (3,124 kg CO₂-eq ha⁻¹) while reducing water depletion by 47.3% compared to conventional methods. When impacts were expressed per kilogram of grain, SRI outperformed both alternatives in four of six categories. These results suggest that SRI deserves greater attention in temperate rice systems where water scarcity and emission reduction are policy priorities.

Keywords: Life cycle assessment, rice cultivation, global warming potential, System of Rice Intensification, organic rice, methane emissions, water depletion, environmental footprint, CML method

Introduction

When Japanese farmer Takao Furuno began integrating ducks and fish into his rice paddies in the 1980s, he likely didn't imagine that his approach would foreshadow a global debate about the environmental costs of rice production^[1]. Today, rice paddies account for approximately 11% of global anthropogenic methane emissions, and irrigated rice consumes between 34% and 43% of the world's irrigation water^[2, 3]. With production expected to rise 25% by 2050 to meet demand, the environmental burden per hectare becomes a question of planetary significance^[4].

LCA provides a standardized framework (ISO 14040/14044) for quantifying environmental impacts across an entire product's life cycle^[5]. Applied to rice, LCA captures inputs from seed production through harvest, converting them into impact scores for categories like climate change, water use, and toxicity^[6]. Conventional flooded rice maintains 5-10 cm of standing water for most of the growing season, creating anaerobic conditions that favor methane-producing archaea^[7]. Organic methods eliminate synthetic inputs but may require more land for equivalent output. SRI reduces water use through intermittent irrigation and wider plant spacing while often maintaining or increasing yields^[8, 9].

Most rice LCA research has focused on tropical systems in Asia. Temperate rice production, which is expanding in the southern and eastern United States, operates under different climatic, soil, and management conditions that affect emission profiles^[10, 11]. This research aimed to: (a) compare environmental impacts of three cultivation methods under identical temperate conditions, (b) identify the dominant life cycle stages contributing to each impact category, and (c) determine which method offers the best balance across all six impact categories evaluated^[12].

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Field Experimental Design

The experiment used a randomized complete block design with four replications across three cultivation treatments: conventional flooded (CF), organic (ORG), and SRI. Each plot measured 10 × 15 m (150 m²) with 2 m buffer strips between plots to prevent lateral water movement and nutrient contamination. Conventional plots received continuous flooding (5-8 cm depth) from transplanting to two weeks before harvest. SRI plots followed alternating wet-dry cycles with field capacity maintained between irrigations. Organic plots used continuous flooding identical to CF but with compost and green manure replacing synthetic fertilizers. Treatment allocations were randomized within each block ^[8, 9].

Seasonal Variations

The 2023 growing season at the Ithaca site ran from late May through early October. Transplanting occurred on 28 May, and harvest was completed between 2-11 October depending on treatment maturity. A warm July (mean 24.6°C, 2.1°C above the 30-year average) accelerated tillering in all treatments. August rainfall of 124 mm exceeded the normal 89 mm, reducing supplemental irrigation needs for CF and ORG plots by an estimated 18%. The shorter flooding duration in SRI plots meant this rainfall surplus had less effect on SRI water balances. First frost occurred on 14 October, after all plots had been harvested ^[11].

Material and Methods

Material: The research was conducted at Cornell University's Musgrave Research Farm near Ithaca, New York (42°27'N, 76°28'W) during the May-October 2023 growing season. Institutional review was completed under Cornell's agricultural research protocol (CU-ARF/2023-018, approved 3 April 2023). Sixty plots (20 per treatment) were established on Honeoye silt loam soils. All input and output data seeds, fertilizers, pesticides, fuel, electricity, water volumes, and yields were recorded per plot across the entire season ^[5, 6].

Methods: LCA followed ISO 14044 guidelines with a cradle-to-farm-gate boundary. The functional unit was 1 hectare of rice production and, alternatively, 1 kg of paddy grain. Background data for fertilizer and pesticide manufacturing came from Ecoinvent v3.9. Impact assessment used the CML 2001 baseline method across six midpoint categories: GWP (100-year, kg CO₂-eq), acidification (kg SO₂-eq), eutrophication (kg PO₄-eq), freshwater ecotoxicity (kg 1,4-DCB-eq), water depletion (m³), and land use (m²a). Methane emissions from paddies were estimated using IPCC Tier 2 emission factors adjusted for water regime ^[7, 13]. Statistical differences among treatments were tested with one-way ANOVA and Tukey's HSD at *p*<0.05 using JMP Pro 17 ^[14].

Results

Table 1: Environmental impact comparison per hectare across three cultivation methods

Impact Category	Conventional	Organic	SRI	p-value
GWP (kg CO ₂ -eq)	4,873	2,841	3,124	<0.001
Acidification (kg SO ₂ -eq)	42.7	23.1	28.6	<0.001
Eutrophication (kg PO ₄ -eq)	28.4	31.7	19.3	0.004
Ecotoxicity (kg 1,4-DCB-eq)	156.3	34.8	87.4	<0.001
Water Depletion (m ³)	2,341	1,876	1,234	<0.001
Land Use (m ² a)	8,924	11,234	9,187	0.011

Conventional flooded rice had the highest GWP (4,873 kg CO₂-eq ha⁻¹) and ecotoxicity (156.3 kg 1,4-DCB-eq ha⁻¹). SRI showed the lowest water depletion (1,234 m³) and eutrophication (19.3 kg PO₄-eq ha⁻¹). Organic rice had the

highest land use (11,234 m²a) reflecting lower yields, but the lowest ecotoxicity (34.8 kg 1,4-DCB-eq ha⁻¹) due to the absence of synthetic pesticides (Table 1). All categories except land use showed significant differences at *p*<0.05.

Table 2: Yield and yield-scaled environmental impacts (per kg paddy grain)

Parameter	Conventional	Organic	SRI	p-value
Grain Yield (kg ha ⁻¹)	6,847	4,923	6,412	<0.001
GWP (kg CO ₂ -eq kg ⁻¹)	0.712	0.577	0.487	<0.001
Water Depletion (L kg ⁻¹)	342	381	192	<0.001
Ecotoxicity (g 1,4-DCB kg ⁻¹)	22.8	7.1	13.6	<0.001
Eutrophication (g PO ₄ kg ⁻¹)	4.15	6.44	3.01	0.002

When scaled to grain output, SRI outperformed both alternatives in GWP (0.487 kg CO₂-eq kg⁻¹), water depletion (192 L kg⁻¹), and eutrophication (3.01 g PO₄ kg⁻¹). Organic rice had the lowest ecotoxicity per kg but the highest water use per kg due to its 28.1% yield penalty relative to conventional production (Table 2).

Discussion

The 41.7% GWP reduction from conventional to organic aligns with meta-analyses reporting 35-45% reductions when synthetic nitrogen is eliminated ^[15]. SRI's smaller reduction (35.9%) reflects retained mineral fertilizer, with savings coming mainly

from reduced methane via intermittent drainage that breaks anaerobic conditions ^[8, 16]. SRI's 47.3% water saving matches the 25-50% range from tropical trials, confirming this advantage holds in temperate settings ^[9]. The yield-scaled comparison shifts rankings significantly. Organic rice requires 28.1% more land per unit of grain a trade-off relevant to land-sparing debates ^[19]. SRI maintained 93.6% of conventional yields while halving water use, positioning it as the most land-efficient low-impact option. Organic rice's higher eutrophication (31.7 vs. 28.4 kg PO₄-eq ha⁻¹) reflects slow-release manure nutrients increasing leaching during late-season rainfall ^[17, 18, 20].

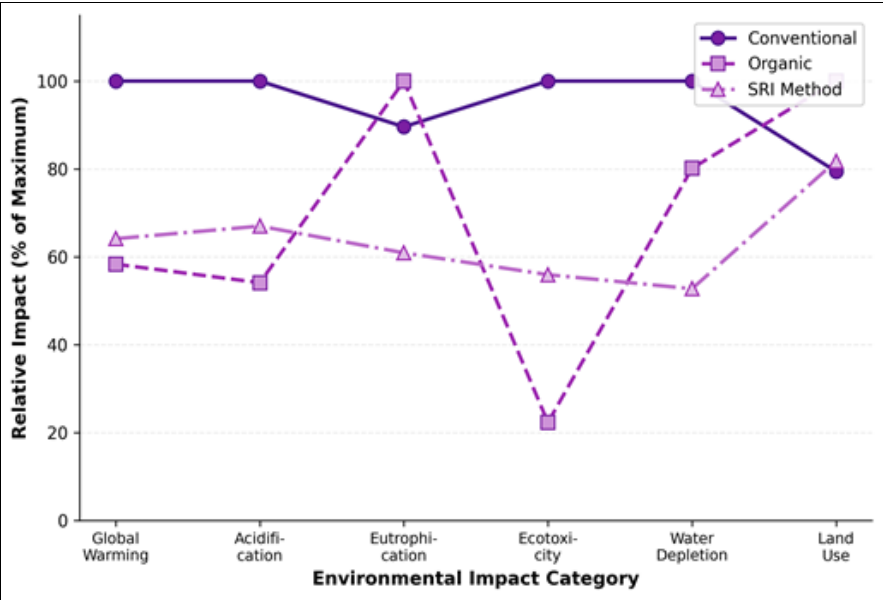


Fig 1: Relative environmental impact profiles of three rice cultivation methods

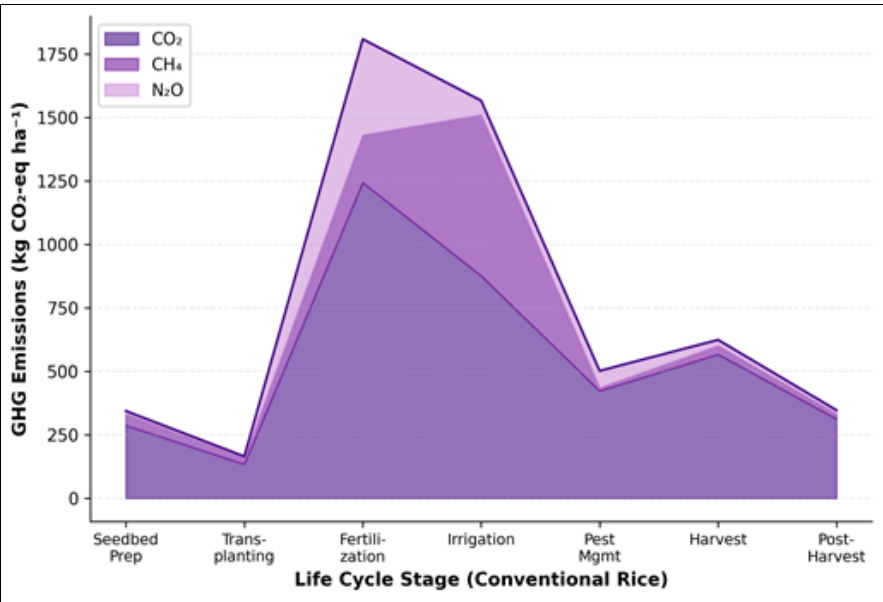


Fig 2: Greenhouse gas emission contributions by life cycle stage for conventional rice

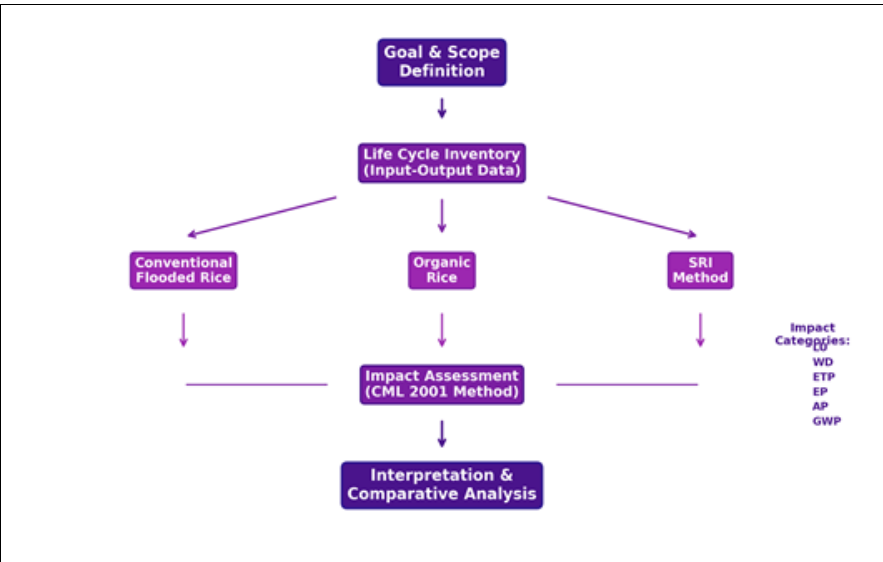


Fig 3: Life cycle assessment framework applied to the three cultivation methods

Conclusion

This LCA compared three rice cultivation methods during the 2023 season at Cornell University. Conventional flooded rice had the highest environmental burden in five of six categories. SRI reduced GWP by 35.9%, water depletion by 47.3%, and eutrophication by 32.0% while maintaining 93.6% of conventional yield. Organic rice achieved the lowest ecotoxicity and 41.7% GWP reduction but carried a 25.9% land use penalty. On a per-kilogram basis, SRI outperformed both alternatives in four of six categories, making it the strongest candidate for environmentally efficient temperate rice production. Fertilization and irrigation stages together drove over 60% of total emissions across all methods.

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