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Assessing the Water Footprint of Winter Wheat Cultivation for Ethanol Production in Uttar Pradesh, India

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Abstract

Water is a vital resource that underpins agricultural productivity, ecosystem health, and socio-economic growth. Its significance is particularly pronounced in meeting food and energy demands, especially in regions where water scarcity poses challenges. This study aims to evaluate the water footprint of ethanol production from wheat, focusing on six districts of Uttar Pradesh, India: Agra, Aligarh, Fatehpur, Gorakhpur, Kanpur, and Varanasi. The analysis examines water use across three stages: wheat cultivation, wheat straw production, and ethanol production, to identify regional variations in water consumption. The findings reveal notable disparities in water usage across the districts. Varanasi exhibited the highest water footprint for wheat cultivation at 932.7 m^3/ton and wheat straw production 289.1 m^3/ton. In contrast, Gorakhpur had the largest green water contribution during straw production 85.0 m^3/ton. For ethanol production, Varanasi again recorded the highest water footprint (349.1 m^3/ton), while Gorakhpur reported the lowest (282.3 m^3/ton). These results underscore the importance of developing localized water management practices to improve resource efficiency and promote sustainable biofuel production systems.

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Introduction

Global population growth and evolving lifestyles have significantly increased the demand for freshwater resources,[1] making their sustainable management a critical global challenge. Asia, which hosts the majority of the world's population at 63%,[2] is projected to experience a 44% increase in its population between 2000 and 2050.[3] Within Asia, India accounts for 37% of the population, highlighting its significant role in regional water resource dynamics.[4] As freshwater demand grows, especially in agriculture and energy sectors, the need for precise assessments of water use efficiency has become increasingly urgent.[5]

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The interplay between water and energy further emphasizes this urgency, as energy is required for water extraction, purification, and transportation, while water is a key input in energy generation.[6] Addressing this nexus is essential, given the competing demands for water from various sectors and the strain on limited resources.[7] Among renewable energy sources, biofuels such as ethanol have gained prominence for their ability to reduce greenhouse gas emissions and provide a sustainable alternative to fossil fuels.[8] However, the long-term viability of ethanol production depends on evaluating its resource use, particularly water, at each stage of production.[9]

The water footprint (WF) framework offers a systematic approach to assessing water use in production processes by dividing it into three components[10]: green water (rainwater stored in soil),[11] blue water (surface and groundwater),[12] and grey water (water needed to assimilate pollutants).[13] This classification allows for a comprehensive understanding of freshwater use and its environmental implications. While WF studies on agricultural crops are relatively well-documented,[14] the application of this methodology to biofuel production—especially ethanol derived from wheat remains limited.

Wheat is a staple crop in India and a major contributor to the country's food and bioenergy sectors.[15] Uttar Pradesh, as the leading wheat-producing state, accounts for 32% of India's wheat production.[16] Advances in agricultural practices following the green revolution have boosted wheat yields in this region from 14.1 quintals per hectare to 25.8 quintals per hectare,[17] making it a critical area for exploring the resource efficiency of wheat-based ethanol production. Despite this importance, studies specifically focusing on the WF of ethanol derived from wheat in Uttar Pradesh are scarce, with existing research primarily centered on other crops like sugarcane and maize. Analysis of water footprint of different biomass for energy production will lead us towards a path with reduced water consumption[18] in energy production and in turn will help in sustainable development.[19] Energy crops are by far the most diverse in terms of potentials, with estimations ranging from extremely modest to exceeding the present global primary energy supply.[20]

This study aims to bridge this gap by evaluating the WF of ethanol production from winter wheat in six districts of Uttar Pradesh. By analyzing the green, blue and grey WF components and identifying regional differences in water use efficiency this research provides actionable insights for enhancing sustainability in biofuel production. The results are intended to guide policymakers and stakeholders in implementing strategies that optimize water management and promote resource-efficient energy solutions.

Materials and Methods

Data Source

Meteorological data, including monthly averages for maximum and minimum temperatures, relative humidity, wind speed, hours of sunlight and precipitation, were collected from meteorological stations located within six districts in Uttar Pradesh. In addition, long-term climate data were obtained from the CLIMWATS climate database, published collaboratively by the FAO's Water Development and Management Unit and the Climate Change and Bioenergy Unit.[21] Information specific to the crop, such as the timing of various growth stages, sowing and harvesting dates, and soil characteristics was sourced from the Department of Agronomy at SHUATS in Prayagraj and was assumed to be uniform across all districts. Crop coefficient (Kc) values for wheat were taken from a prior study in Harrai village, Prayagraj.[22] Data on average crop yield, necessary for calculating the water footprint over the 2017–2022 period, were sourced from the Statistical Abstract of Uttar Pradesh (Government of India, http://updes.up.nic.in).

Study Area

The study was conducted in the state of Uttar Pradesh, located between 23°52'N to 31°28'N latitude and 77°3'E to 84°39'E longitude. Uttar Pradesh is the fourth largest state in India by area and the most populous. Due to its varied terrain, climate, and topography, the state is divided into nine agro-climatic zones: the Terai region, Western Plain, Central Western, South-Western, Central Plain, Bundelkhand, North-Eastern Plain, Eastern Plain and Vindhyan regions.[23] Figure 1 illustrates the study area selected for estimating the water footprint.

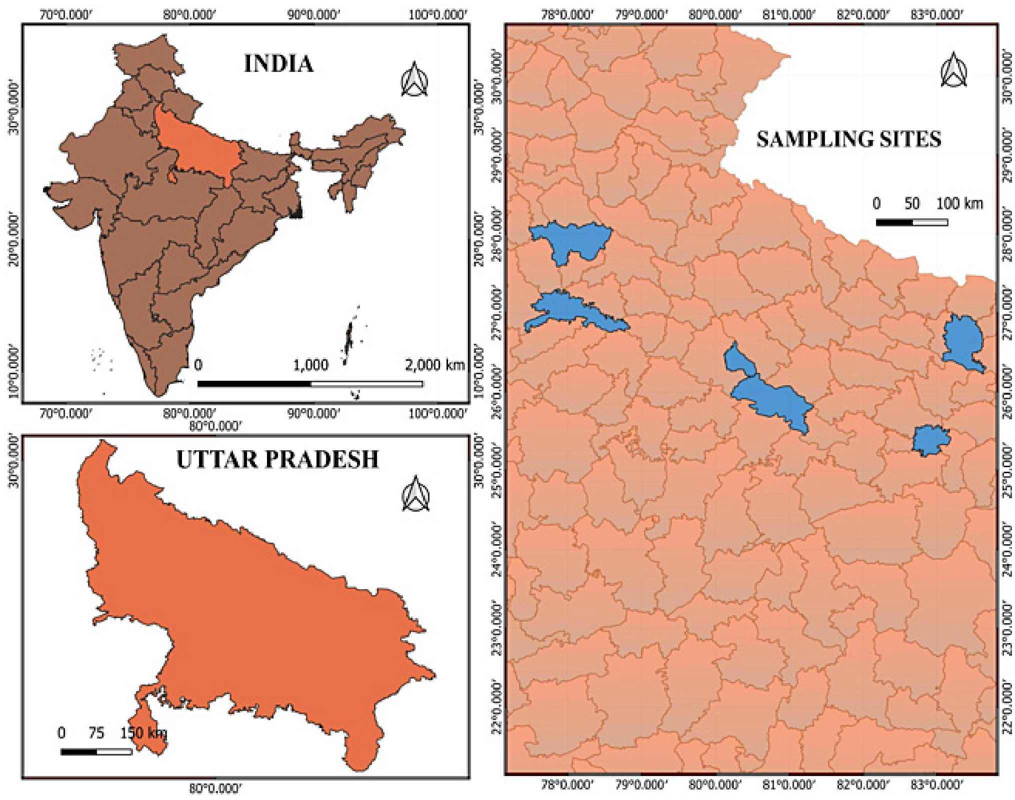

Fig.1: Study region considered for estimation of water footprint

Methodology

This study adopts the methodology outlined by Hoekstra (2002), to evaluate the water footprint associated with ethanol production from wheat in six districts of Uttar Pradesh: Agra, Aligarh, Fatehpur, Gorakhpur, Kanpur, and Varanasi. The assessment proceeds through three primary stages: first, estimating the water footprint of wheat as the foundational input for calculating the water footprint of its byproduct, wheat straw. Subsequently, the wheat straw serves as the input for determining the water footprint of ethanol.[24]

The water footprint of wheat is analyzed in terms of its green, blue, and grey water components. The green and blue water footprints are calculated following the guidelines provided in the Water Footprint Assessment Manual.[25] To estimate crop water use (CWU, m³/ha), the CROPWAT 8.0 model is utilized to compute crop evapotranspiration (ETc, mm/day). The water footprint of wheat is then determined by dividing CWU by the crop yield (Y, ton/ha), as illustrated in equation 1 below.

This approach provides a comprehensive framework for quantifying the water inputs across the production chain, from wheat cultivation to ethanol generation.

$$WF_{blue,\ green} = \frac{CWU_{blue,green}}{Y} = \frac{10 \times \sum_{d=1}^{lgp} ET_{blue,green}}{Y} \quad ...(1)$$

The grey water footprint of the crop (WF_{grey}, m³/ton) is calculated by taking the chemical application rate per hectare (AR, kg/ha) and multiplying it by the leaching factor (α). This product is then divided by the difference between the maximum acceptable concentration (Cmax, kg/m³) and the natural concentration of the pollutant in question (Cnat, kg/m³), and subsequently divided by the crop yield (Y, ton/ha), as illustrated in equation 2.[26] This study specifically quantifies the grey water footprint associated with nitrogen, operating under the assumption that approximately 10% of the nitrogen fertilizer applied is subject to loss through leaching.[27] The United States Environmental Protection Agency (US-EPA) recommends a maximum permissible concentration of 10 mg of nitrate per liter, measured as nitrate-nitrogen (NO_3-N). In addition, the World Health Organization (WHO) and the European Union establish a threshold of 50 mg of nitrate (NO_3) per liter. Adhering to the WHO guidelines from 2007, this study employs the limit of 50 mg/L of nitrate-nitrogen (NO_3-N) for its assessments.

$$WF_{grey} = \frac{(\propto \times AR)/(Cmax - Cnat)}{Y} \quad ...(2)$$

The water footprint of products is determined using the stepwise accumulation method outlined in the Water Footprint Manual.[28] Following the assessment of the water footprint for the primary crop, the next step involves calculating the water footprint of the byproduct, specifically wheat straw. This byproduct serves as an input for estimating the water footprint associated with ethanol production. The water footprint of the input product can be categorized into its green and blue components. The water footprint of products can be calculated using the formula provided in equation 3 below.

$$WF_{prod}[p] = (WF_{proc}[p] + \sum_{i}^{y} \frac{WFprod[i]}{fp[p,i]}) \times fv[p] \quad ...(3)$$

In this context, $WF_{prod}[p]$ represents the water footprint (volume/mass) of the output product (p), while $WF_{prod}[i]$ denotes the water footprint of the input product. Additionally, $WF_{proc}[p]$ indicates the water footprint associated with the processing step, expressed as water use per unit of the processed product (p) (volume/mass). The term fp[i] refers to the product fraction, and the parameter fv[p] signifies a value fraction.

Results and Discussion

The water footprint associated with ethanol production from wheat is determined through a three-step process. The first step involves estimating the water footprint of wheat cultivation, followed by assessing the water footprint of wheat straw production. The final step evaluates the water footprint for converting wheat straw into ethanol.

Table 1: Calculated water footprint of wheat crop in six districts

District	WF_{blue}(m^3/ton)	WF_{green}(m^3/ton)	WF_{grey}(m^3/ton)	WF_{total}(m^3/ton)
Agra	643.4	57.1	19.5	720
Aligarh	630.0	126.5	19.4	775.9
Fatehpur	515.9	221.9	20.8	758.6
Gorakhpur	468.6	267.7	21	757.5
Kanpur	579.4	231.7	18.6	829.7
Varanasi	693.1	216.9	22.7	932.7

The initial step focuses on calculating the water footprint of wheat cultivation across six districts in Uttar Pradesh. The findings from this stage are outlined in table 1, highlighting regional differences in water use for wheat production within the study area.

The results indicated that, among the stations analysed, Varanasi had the largest overall water footprint for wheat production, amounting to 932.7 m^3/ton. This footprint was divided into 22.7 m^3/ton for grey water, which represents the water required to dilute pollutants generated during agricultural activities, 693.1 m^3/ton for blue water, which refers to irrigation water drawn from surface and groundwater sources, and 216.9 m^3/ton for green water, which comes from rainwater that is retained in the soil and available for plant use. These values are detailed in table 1 and illustrated in figures 2 and 3.

Following Varanasi, Kanpur recorded the second-highest water footprint during the crop growth stage, amounting to 829.7 m^3/ton. In contrast to Varanasi, the majority of Kanpur's water footprint, 70% was attributed to blue water, reflecting the area's significant dependence on irrigation. Green water contributed 28% of the total footprint, while grey water accounted for only 2%, indicating lower pollution levels compared to other regions. These variations emphasize the differing dependence on water resources among regions and highlight the necessity for tailored water management strategies to promote sustainable agricultural practices.

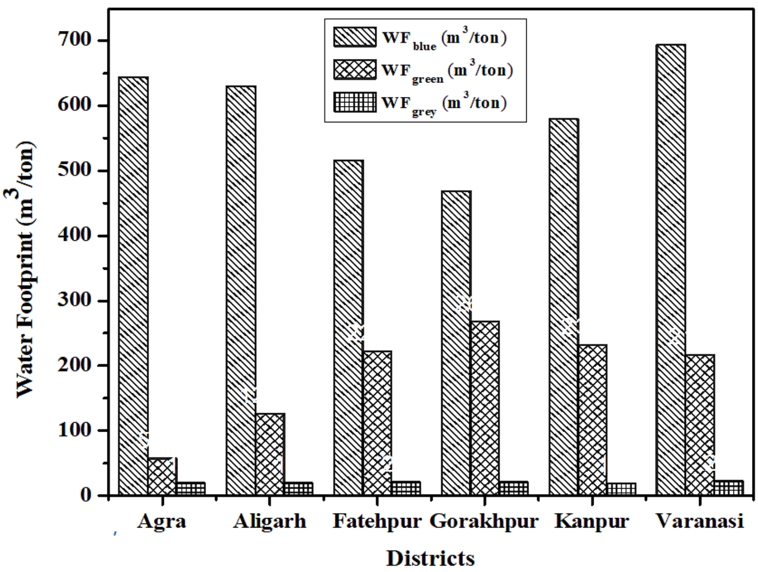

Fig.2: Bar plot showing variation in water footprintduring the crop growth stage in the selected stations

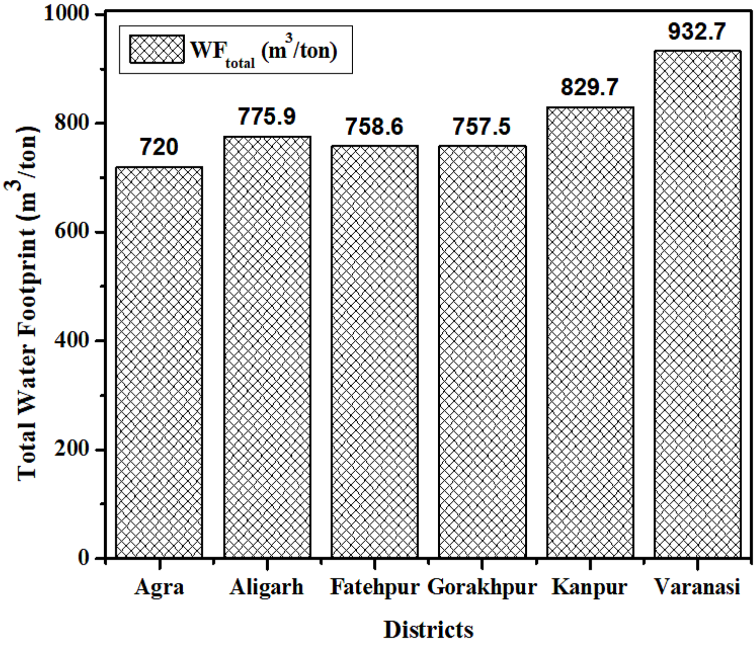

Fig. 3: Variation in total water footprint of wheat crop during the growth stage

In the second step, the water footprint associated with straw production, a byproduct of wheat processing, is calculated and subsequently utilized to evaluate the water footprint of ethanol production. The variations in both the blue and green water footprints for straw production, along with the overall water footprint from the crop across the six districts, have been analyzed. These findings are illustrated in table 2 and figure 4.

Table 2: Calculated water footprint of wheat straw

District	WF_{blue}(m^3/ton)	WF_{green}(m^3/ton)	WF_{total}(m^3/ton)
Agra	204.4	18.1	222.5
Aligarh	200.1	40.2	240.3
Fatehpur	163.9	70.5	234.4
Gorakhpur	148.8	85.0	233.8
Kanpur	184.0	73.6	257.6
Varanasi	220.2	68.9	289.1

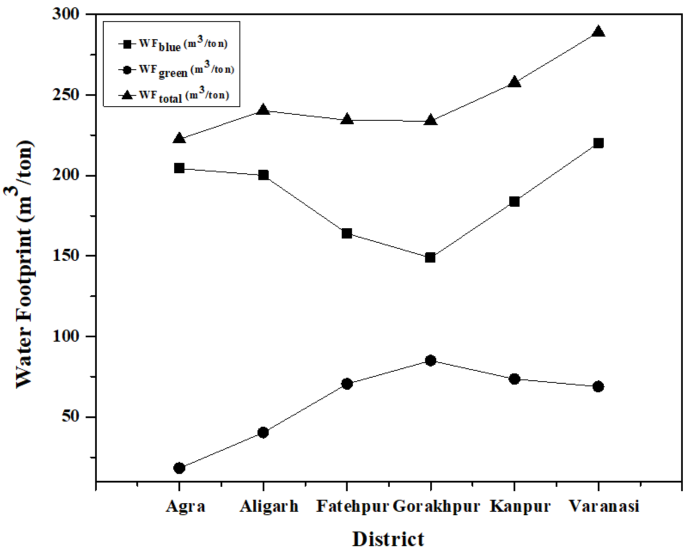

Fig.4: Plot displaying variations in the wheat straw's blue, green, and overall water footprints in selected stations

Table 3: Calculated water footprint in ethanol production

District	WF_{blue}(m^3/ton)	WF_{green}(m^3/ton)	WF_{total}(m^3/ton)
Agra	246.8	21.8	268.6
Aligarh	241.6	48.5	290.1
Fatehpur	197.9	85.1	283
Gorakhpur	179.7	102.6	282.3
Kanpur	222.2	88.9	311.1
Varanasi	265.9	83.2	349.1

The concluding phase of this research involved evaluating the water footprint of ethanol production in six districts of Uttar Pradesh, with wheat straw serving as the primary feedstock. The value fraction and product fraction for wheat straw and ethanol were calculated following established methodologies referenced in prior research (e.g., Gerbens-Leenes & Hoekstra, 2012). The grey water footprint for both wheat straw and ethanol was assumed to be negligible in all districts, as wastewater generated during production was effectively recycled within the processing facilities. This recycled water was utilized for purposes such as cleaning and equipment washing, thereby eliminating the need for additional external water resources for these activities.

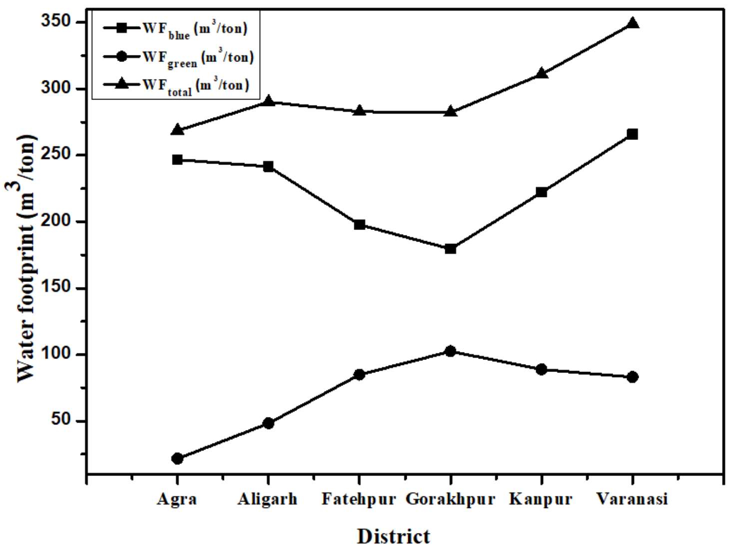

Fig.5: Plot displaying variations in the blue, green, and overall water footprint in ethanol production in selected station

The results of the assessment, presented in table 3 and figure 5, provide a detailed understanding of the water requirements for ethanol production in the region. These findings emphasize the critical importance of efficient water use and recycling in the biofuel production process, especially in areas where water resources are limited. The study demonstrates how integrating wastewater recycling into production workflows can reduce water demand, contributing to more sustainable practices within the biofuel sector. This approach also offers a framework for improving resource management in water-scarce regions, supporting the broader goal of sustainable biofuel production.

Conclusion

According to the study's findings, Varanasi had the highest blue and grey water footprints for wheat production, measuring 693.1 and 22.7 m^3/ton, respectively, whereas Gorakhpur has the highest green water footprint, estimated to be 267.7m^3/ton. The reason for Varanasi's high water demand for irrigation and low yield per hectare may be due to inefficient irrigation techniques that result in significant water loss. For the sake of future water security, measures to considerably lower Varanasi's water footprint must be investigated. Farmers and officials should also encourage sustainable agricultural practices to minimize the water footprint of wheat growing in other places as well. Education and incentives for farmers can play a crucial role in adopting such practices.

Secondly the water footprint of wheat straw, an essential input for ethanol production, was also examined. The findings revealed that Varanasi once again had the greatest blue water footprint 220.2 m^3/ton, and Gorakhpur had the highest green water footprint 85.0 m^3/ton. It's interesting that the manufacturing of ethanol and wheat straw is assumed to have little impact on grey water. It may reflect current method however it is crucial to promote ethical wastewater treatment. Wastewater treatment and reuse can both lessen its negative effects on the environment and help conserve resources. The study concluded that the total blue water footprint of ethanol production was highest in Varanasi at 1179.2 m^3/ton, followed by Agra, at 1094.6 m^3/ton. The lowest blue water footprint for ethanol production from wheat was observed in Gorakhpur, at 797.1 m^3/ton which is significantly lower than that of Varanasi and Agra. These findings suggest the need for interventions to enhance ethanol yield in Gorakhpur and implement effective strategies for improving water use efficiency and quality in districts like Agra, Aligarh, and Varanasi, which exhibited the largest blue water footprints.

However, Gorakhpur recorded the highest green water footprint for ethanol production, at 455.3 m^3/ton followed by Fatehpur and Kanpur at 394.2 and 377.5 m^3/ton, respectively. This indicates that districts such as Gorakhpur, Kanpur, and Fatehpur rely less on groundwater resources, as most of their water requirements are met by rainfall. Consequently, these districts are more favourable for establishing ethanol production facilities, given their reduced dependence on blue water resources.

Unlike previous studies conducted in Uttar Pradesh, such as the work by Mohammad Suhail (2020), which focused solely on the water footprint of crops, this study extends the analysis to include the water footprint of ethanol production. This comprehensive approach provides deeper insights into the environmental sustainability of biofuel production processes.

Overall, these findings emphasize the critical need to adopt sustainable water management practices in ethanol production to ensure the conservation of water resources for future generations. The water footprint of wheat production serves as a key metric for both producers and consumers, underscoring the environmental impact of agricultural and industrial processes and the need for sustainable development in the biofuel sector.

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Conflict of Interest
The authors do not have any conflict of interest.

Data Availability Statement
All information related to the manuscript is available in hard copy from Government of India Publications, and it is also accessible online by using the reference provided.

Ethics Statement
This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Author Contributions
- **Afreen Fatima:** Formal analysis, Writing – original draft, Reviewing and editing.
- **Sadanand Yadav:** Data curation, Visualization.
- **Deepa Srivastava:** Supervision Writing – review & editing

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