Efficiency of Rainfed Wheat Production: A Global Assessment Using Data Envelopment Analysis

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***Abstract*—Rainfed wheat, covering 160 million hectares globally, is critical to food security but faces significant yield gaps due to inefficient resource use and variable climatic conditions. This study evaluates the efficiency of nitrogen (N) and phosphorus (P) fertilizer use in rainfed wheat production worldwide, aiming to identify optimal application rates for achieving 50%, 70%, and 80% of water-limited potential yield (Yw) while minimizing environmental impacts. Building on an expanded Global Yield Gap Atlas (GYGA) dataset previously extended from 49 countries to global coverage using stepwise regression, we applied Data Envelopment Analysis (DEA) to assess production efficiency across 122 countries and their climate zones. Inputs included annual precipitation and N and P applications, with outputs comprising crop yield, production, water productivity, and nutrient use efficiencies under the Constant Returns to Scale (CCR) model. Results reveal stark efficiency disparities: Sweden, Ukraine, Ireland, Finland, and Belgium achieved maximum efficiency (1.0), while India, Iran, and others scored as low as 0.18-0.37 under current conditions. Efficiency improved with higher yield targets, with optimal N and P rates significantly lower than current applications in many regions e.g., Montenegro's N use dropped from 427 kg/ha to 132 kg/ha for actual yield optimization. Climate zone analysis further identified efficient production hotspots, guiding targeted interventions. These findings underscore the potential to enhance global rainfed wheat productivity through optimized fertilizer strategies, offering a pathway to close yield gaps, boost food security, and reduce ecological footprints.**

Keywords-Rainfed wheat; Yield gap; Fertilizer efficiency; Data envelopment analysis; Sustainable agriculture.

I. INTRODUCTION

The global population continues to expand rapidly, driving an escalating demand for food and intensifying pressure on agricultural systems worldwide. Rainfed wheat, cultivated across approximately 160 million hectares, stands as a cornerstone of global food security, particularly for regions reliant on this staple crop to meet nutritional needs [1]. However, its production faces significant challenges due to its dependence on unpredictable rainfall patterns, which exacerbate yield gaps defined as the disparity between actual yields (Ya) and water-limited potential yields (Yw) and threaten sustainable food supply chains. Addressing these challenges requires identifying regions with high production potential and optimizing resource use, particularly for critical inputs like nitrogen (N) and phosphorus (P) fertilizers, to close yield gaps while minimizing environmental impacts [2][3]. Fertilizers, especially N and P, are indispensable for enhancing crop productivity and achieving higher yields. Their use has surged dramatically to support growing food demands, with synthetic fertilizer consumption exceeding safe planetary boundaries [4][5]. This overuse has triggered severe environmental consequences, including air pollution from particulate matter and aerosols [6], climate change and ozone depletion [7][8][10], eutrophication of aquatic ecosystems [9], biodiversity loss [10], and soil acidification [11]. Such inefficiencies not only strain economic returns for farmers but also undermine food security by limiting sustainable productivity [3]. Consequently, optimizing fertilizer application is imperative to balance productivity gains with ecological sustainability, a goal that hinges on determining region-specific, efficient input levels to achieve target yields, such as 50%, 70%, or 80% of Yw. Previous research has laid critical groundwork for understanding fertilizer use and yield relationships. For instance, Smerald et al. [12] demonstrated that redistributing N globally could maintain cereal production with a 32% reduction in fertilizer use or boost output by 15% without increasing N levels, thereby reducing environmental N losses. Similarly, Anderson et al. [2] underscored the need to enhance P Use Efficiency (PUE) to mitigate pollution and conserve finite P reserves. Historical analyses of global N and P fertilizer trends further highlight shifting hotspots and nutrient imbalances, emphasizing the need for spatially explicit strategies [5]. Building on these insights, our prior work expanded the GYGA dataset originally covering 49 countries for rainfed wheat by employing stepwise regression models to extrapolate climate, soil, and management relationships to a global scale [13]. This globally extended dataset provides a robust foundation for assessing production potential and yield gaps worldwide.

Despite these advances, a critical research gap persists: no study has comprehensively evaluated the efficiency of N and P use in rainfed wheat production on a global scale while identifying optimal fertilizer levels to achieve specific yield targets. Access to detailed, spatially variable data is essential for such analyses. While datasets from the International Fertilizer Association (IFA) and Food and Agriculture Organization (FAO) have offered country-level fertilizer use since 1961, they assume uniform application rates, overlooking within-country variations [14]. Efforts to refine these data, such as those by Potter et al. [15] and Mueller et al. [16], incorporated crop-specific patterns but remain temporally limited (circa 2000), restricting their utility for contemporary optimization studies. In contrast, our current study leverages the globally extended GYGA dataset to apply DEA, a nonparametric method, to assess the efficiency of rainfed wheat production across countries and climate zones. By integrating actual and potential yield data with N and P inputs, we aim to identify efficient and inefficient

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production regions and determine optimal fertilizer application rates for achieving 50%, 70%, and 80% of Yw. This approach not only advances our understanding of resource use efficiency but also offers actionable insights for sustainable agricultural intensification, aligning productivity goals with environmental stewardship. The rest of this paper is organized as follows. Section II outlines the data sources and methodology used. Section III presents the results of the efficiency analysis. Section IV discusses the implications of optimal nitrogen and phosphorus application. Section V provides conclusions and future research directions. The acknowledgments and references conclude the article.

II. MATERIALS AND METHODS

A. Data Sources and Conceptual Framework

This study builds on the GYGA database, which aggregates crop modeling outputs for rainfed wheat across 49 countries, providing actual yield (Ya), water-limited potential yield (Yw), yield gaps (Yg), nitrogen (N) and phosphorus (P) application rates, and target nutrient requirements (N50, N70, N80; P50, P70, P80) for 50%, 70%, and 80% of Yw. Water productivity data (for actual yield (WPA), and potential yield (WPP)) are also included, derived from 15-year simulations using validated models (e.g., Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production Systems sIMulator (APSIM)) per GYGA protocols [1]. These targets align with realistic yield potentials under rainfed conditions, informed by nutrient uptake dynamics. The dataset was globally extended by mapping GYGA data to climate zones, using rainfed wheat acreage from the Spatial Production Allocation Model (SPAM2020), soil data from the FAO Harmonized World Soil Database (e.g., organic carbon, pH), and climate variables from GYGA Environmental Data (e.g., growing degree days, aridity index). The extension methodology, including data integration and predictor selection, is fully described in Dadrasi et al. [13].

B. Stepwise Regression Extension and Uncertainty Considerations

The GYGA dataset extension to 122 countries relied on stepwise regression modelling, as outlined in Dadrasi et al. [13], where environmental and management variables were used to predict GYGA parameters (Ya, Yw, N, P needs) across climate zones. This involved analysing approximately 180,000 data points per parameter, averaged by region, with model performance validated ($R^2 = 0.78–0.85$) using the cited study's approach. For this study, the extended dataset supports DEA analysis. Uncertainties include: (1) aggregation of sub-national fertilizer use variability, potentially masking local differences; (2) coarse spatial resolution of global soil and climate data; and (3) assumptions of consistent crop responses across agroecological zones, which may affect DEA accuracy. These were partially mitigated in the original extension through cross-validation with regional data (China, India, USA) and are further addressed here by using relative efficiency scores in DEA, which reduce sensitivity to absolute input errors. Additional details on the regression equations and validation metrics are available in Dadrasi et al. [13].

The GYGA dataset was extrapolated from its original 49-country scope to 122 countries using stepwise regression to extend climate, soil, and management relationships. The validity of this extrapolation was supported by previous studies [13][17], which reported a strong correlation ($r = 0.80$, $p < 0.01$) between modeled and observed yields across 122 countries, thereby confirming the robustness of the approach.

C. Data Envelopment Analysis (DEA)

DEA, introduced by Charnes et al. [18], is a nonparametric linear programming technique employed to estimate production functions and assess the efficiency of multiple Decision-Making Unit (DMUs) [19]. Its primary objective is to optimize efficiency by achieving maximum output with minimum input, either by enhancing output while maintaining input constant or obtaining a specific output with minimal input. The choice between these options depends on the DMUs under consideration. This study adopts an input-oriented approach with multiple inputs and outputs. DEA is utilized to evaluate DMUs' efficiency [20][21].

The DEA was conducted using the deaR package [22] in R (version 4.3.2). To perform DEA, the primary focus was on the countries that account for 98.9% of the rainfed wheat crop area globally. The analysis was based on the annual precipitation, and the application of N and P fertilizers in each climate zone of each country, to achieve the actual yield, as well as 50%, 70%, and 80% of the water-limited potential yield as input and crop yield, crop production, water productivity, N use efficiency, P use efficiency were as output in the CCR model. A specific equation was used in the DEA to estimate the efficiency value in each country and climate zone. The CCR model is a specific variant of DEA used to evaluate the relative efficiency of DMUs in converting inputs into outputs. In the CCR model, the efficiency of each DMU is assessed under the assumption of Variable Returns to Scale (VRS), allowing for scale efficiency to be considered.

Considering j = 1, 2, 3, m DMUs using Xi| i = 1, 2, 3, ., n inputs to produce Yr | r = 1, 2, 3, ., outputs and Ya or Yw (multipliers) Vi and Ur associated with those inputs and outputs, we can also formalize the efficiency expression in (1) as the ratio of weighted outputs to weighted inputs:

$$Efficiency = \frac{\sum_{r=1}^{\delta} \mu r y j r}{\sum_{i=1}^{n} \gamma i x j i} \tag{1}$$

Following the analysis, we obtained efficiency scores ranging from 0 to 1, which reflect the relative efficiency of each DMUs, such as countries or specific climate zones within countries. Using the multiplier (input-oriented) model, we also derived the marginal contributions of each input and output, identified efficiency peers, and calculated their corresponding weights within the envelopment framework. Additionally, the model allowed us to pinpoint areas for improvement, including input excesses and output shortfalls, often referred to as slacks.

An efficiency scores close to 1 indicates that a DMU is performing efficiently, while scores below 1 suggest varying levels of inefficiency. The CCR model further enables us to assess scale efficiency, helping to determine whether a DMU is operating at an optimal scale based on its input-output configuration. These DEA equations are essential tools for evaluating and benchmarking efficiency across different sectors, including agricultural systems. Based on the DEA results, we extracted both the efficiency scores and the target values for each input and output variable included in the model.

III. RESULTS

A. Efficiency

DEA was performed using N and P application rates as input variables under different yield target scenarios. The analysis showed that six countries including Sweden, Ukraine, Ireland, Finland and Belgium, achieved an efficiency score of 1, indicating optimal input use, while all other countries scored below 1 (Figure 1A). The lowest efficiency scores under current conditions were observed in India (0.18), Iran (0.25), Dominican Republic (0.34), Guyana (0.35), Brazil (0.37) and Burundi. These results highlight sub-optimal fertilizer use relative to yield performance. Results from the GYGA were used to determine the optimal level of fertilizer application required to achieve 50% of Yw. As shown in Figure 1B, only seven countries including Ireland, Sweden, Botswana, Cameroon, Guyana, Guernsey and the Netherlands achieved full efficiency (score = 1), while all other rainfed wheat producing countries (out of 122 evaluated) scored lower. The lowest efficiency scores in this scenario were recorded in Mongolia (0.65), the Canary Islands (0.66), South Africa (0.67), Iraq (0.68), Ecuador and Syria. As the yield target increased to 70% and 80% of Yw, efficiencies improved in all countries (Figure 1C, D). The highest efficiencies were observed in Ireland, China, Sweden, Eritrea, Ukraine and the Netherlands, probably due to their high Yw values. Conversely, the lowest efficiencies in these scenarios - ranging from 0.71 to 0.77 - were associated with Portugal, Greece, Afghanistan, Kazakhstan and Syria.

B. Optimal N application

The findings from Figure 2 illustrate nitrogen (N) application rates across various countries, comparing actual or estimated values with optimal values derived from DEA under different scenarios. Under current conditions (Figure 2A), N application reaches its highest levels, averaging 427 kg/ha in Montenegro, 337 kg/ha in Belgium, 314 kg/ha in Ireland, 312 kg/ha in the Netherlands, and 274 kg/ha in China. In contrast, the lowest N fertilizer application rates—averaging 17, 26, 38, 39, 40, 45, and 52 kg/ha—are observed in Tanzania, Tunisia, Ethiopia, Morocco, Kenya, Australia, and Moldova, respectively. These figures, calculated using actual yield (Ya) as the DEA output, have been optimized and reduced, reflecting adjustments in N input based on output. For example, in Montenegro, where the actual yield is 3.09 t/ha with an N application of 427 kg/ha, optimization lowers this to 132.00 kg/ha. In Belgium and Ireland, however, with actual yields of 8.52 t/ha and 8.73 t/ha, respectively, the optimized N application aligns with the actual rates. For the 50%Yw target, the estimated N application is 85 kg/ha, while the optimal value for achieving this target is slightly lower at 81.11 kg/ha. In countries with the lowest N application under current conditions, as depicted in Figures 2B and B1, the estimated N value based on GYGA results is 46.4 kg/ha, with an optimal value of 36.17 kg/ha for 50%Yw. Comparable patterns emerge for the 70%Yw and 80%Yw targets (Figures 2C, C1, D, and D1).

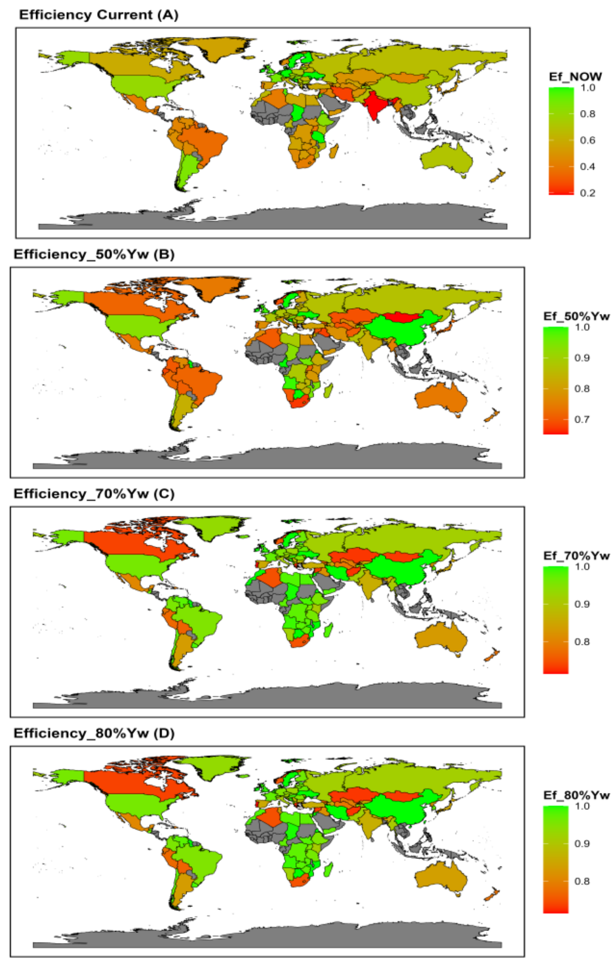

Figure 1. Results of DEA for efficiency values in current conditions (A), Minimum N and P input requirements for achieving target yields of 50% (B), 70% (C), and 80% (D) of Yw based on map and number of efficient and inefficient countries.

Detailed values and further data are provided in the supplementary Excel file across various conditions and scenarios. A key insight from these results is the significant gap between the highest N application under current conditions (427 kg/ha) and the amount required to achieve 80%Yw, which is only 250 kg/ha. This indicates that current N application rates for rainfed wheat production often exceed what is necessary to reach 80%Yw.

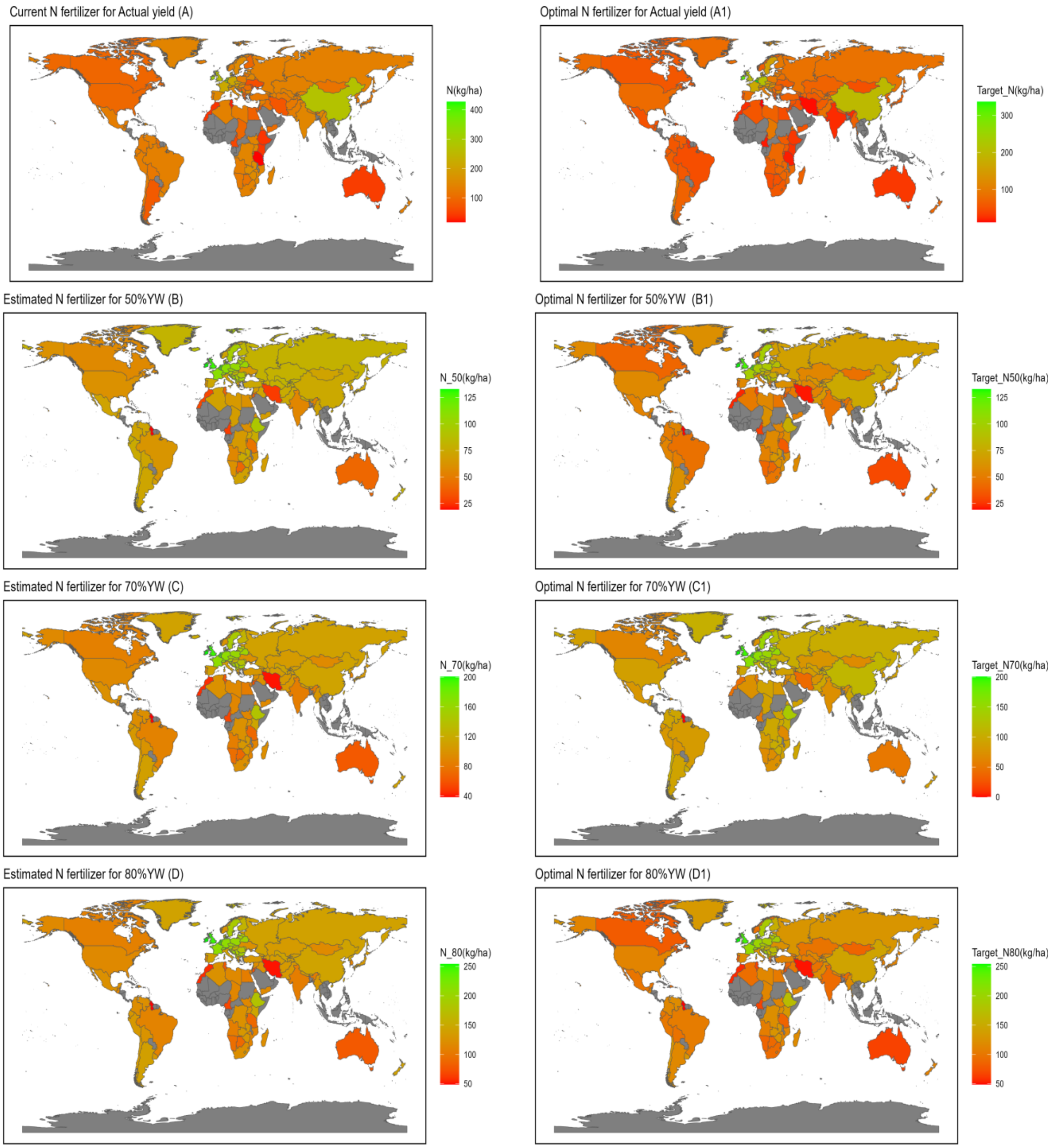

Figure 2. The results of N application levels in both actual and optimal values, derived from DEA analysis across various scenarios. These scenarios encompass current conditions (A and A1), minimum N input requirements, and the optimal necessary to attain target yields of 50%Yw (B and B1), 70%Yw (C and C1), and 80%Yw (D and D1) in rainfed wheat.

C. Optimal P application

The extended GYGA results and DEA for actual or estimated and optimal P fertilizer application in rainfed wheat production are detailed in Figure 3, covering current conditions and scenarios targeting 50%, 70%, and 80% yield water-limited potential (Yw). These findings reveal that P application under current conditions often exceeds the levels needed to achieve 70% and 80%Yw. In the current scenario, the highest P application rates are observed in China at 58 kg/ha, Ireland at 45 kg/ha, Montenegro at 41 kg/ha, and the Netherlands at 31 kg/ha. However, DEA-optimized target values for these countries, identified as having the highest P applications, decrease to 16.8 kg/ha, 45 kg/ha, 15.71 kg/ha, and 30 kg/ha, respectively (Figures 3A and A1). Ireland and the Netherlands show no change in their optimal P values due to their high Ya. Meanwhile, the lowest P inputs averaging 1, 2, 3, 3, and 3 kg/ha are recorded in Tanzania, Tunisia, Ethiopia, Ukraine, and Cameroon, respectively.

In the 50%Yw scenario (Figures 3B and B1), estimated P requirements based on GYGA and DEA range from 3.3 to 25 kg/ha. The highest values averaging 25.5, 25, 24.8, 24.4, and 21.3 kg/ha are linked to Ireland, the Netherlands, the United Kingdom, Belgium, and Liechtenstein, respectively, with optimal P requirements matching these estimates due to their higher Yw compared to other countries. Conversely, the lowest P requirements averaging 3.4, 4.84, 5.1, 5.7, and 7.4 kg/ha are observed in Guyana, Cameroon, Iran, Morocco, and Jordan, respectively. Notably, in China, P application decreases under both estimated and DEA predictions, reflecting its relatively lower Yw. For the 70%Yw scenario (Figures 3C and C1), the highest P requirements averaging 35.7, 34.9, 34.7, 34.1, and 29.19 kg/ha are associated with Ireland, the Netherlands, the United Kingdom, Belgium, and Liechtenstein, respectively, with optimal P values aligning with these estimates due to their superior Yw. The lowest P requirements averaging 7.1, 7.10, 8, 9.53, and 10.4 kg/ha are found in Iran, Guyana, Morocco, Cameroon, and Jordan, respectively, with optimal values remaining unchanged due to their lower Yw. In the 80%Yw scenario (Figures 3D and D1), the highest P requirements averaging 40.8, 39.9, 39.7, 39.1, and 33.40 kg/ha are again linked to Ireland, the Netherlands, the United Kingdom, Belgium, and Liechtenstein, with optimal P values consistent with these estimates due to their high Yw. The lowest P requirements averaging 7.8, 8.2, 9.1, 12.3, 12.5, 10.80, and 11.8 kg/ha are recorded in Guyana, Iran, Morocco, Tunisia, Australia, Cameroon, and Jordan, respectively, with optimal P values unchanged due to their lower Yw. A brief review of the maps highlights that, under current conditions, P fertilizer application frequently surpasses the amounts needed to achieve 70% and 80%Yw, underscoring potential inefficiencies in current practices.

IV. DISCUSSION

A. *Optimum* N and P *application* and efficiency

DEA serves as a methodology for evaluating the efficiency of DMUs undertaking similar tasks within a production framework that utilizes multiple inputs to generate multiple outputs [23]. Over time, several DEA models have emerged, including the Charnes, Cooper, and Rhodes (CCR) model, the Banker, Charnes, and Cooper (BCC) model, and the Free Disposal Hull (FDH) model, which are recognized as fundamental DEA models for evaluating the efficiency of decision-making units [24].

In this study, the CCR model was utilized. The findings from Figures 2 and 3 provide insights into the use of N and P fertilizers in rainfed wheat farming across various countries. It highlights the current (estimated for target Yw) and optimized values obtained from DEA under different scenarios. Optimizing N and P fertilizers based on DEA output (Ya) suggests the adjustment of input levels to achieve target yields more efficiently. As a result, countries like Montenegro, which have excessively high N fertilizer application rates in the current condition, show significant reductions in optimized values to align with yield targets more effectively. Conversely, countries like Belgium and Ireland, with already high actual yields, show optimized N application values that match current practices. As indicated in Figures 2A and 2B, there is a positive and direct correlation between N and P application, which is reported by GYGA and extended for other areas, and Yw at different levels. Also, there are several reports about direct and positive relationships between N and P fertilizer applications with maize yield [25], groundnut [26], barley [27], and wheat [28][29]. The results also highlight the importance of optimizing fertilizer application strategies to maximize crop yield while minimizing input costs and environmental impact. Another output because of DEA is the efficiency value in different DMUs (countries and climate zones in each country). DEA analysis revealed disparities in fertilizer efficiency among different nations. Countries such as Sweden, Ukraine, Ireland, Finland, and Belgium exhibited the highest efficiency, with a value of 1, indicating optimal use of N and P fertilizers to achieve target yields. Conversely, countries like India, Iran, the Dominican Republic, Guyana, Brazil, and Burundi showed lower efficiency, suggesting suboptimal utilization of fertilizers relative to their yield potential. This comparison helps to delineate the optimal N and P fertilizer application rates based on yield values, thereby assisting in refining fertilizer management practices for rainfed wheat production systems.

Furthermore, the evaluation of N and P requirements to achieve target yields of 50%, 70%, and 80% of Yw (actual yield) using GYGA results sheds light on the efficiency of fertilizer utilization across different countries. The analysis revealed varying levels of efficiency, with only a few countries achieving an efficiency of 1, indicating optimal fertilizer use, while others exhibited lower efficiency scores. Moreover, as the target yield percentage increased from 50% to 80% of Yw, the efficiency of fertilizer application generally improved across all countries. Countries with higher actual yields tended to demonstrate higher efficiency in fertilizer utilization compared to those with lower yields. This underscores the importance of considering yield potential when determining optimal fertilizer application rates.

It is possible to increase yield or reduce fertilizer usage by cultivating rainfed wheat in suitable climate zones and limiting cultivation in unsuitable areas [30]. In addition, inside of our results, which defined the suitable climate zone based on efficiency in each country in Figure 1, several fertilizer management techniques have been reported by other studies that can help reduce the amount of fertilizer used while increasing its efficiency. It was reported that optimal nitrogen and phosphorus use efficiency is influenced by a range of management factors beyond fertilizer rates [31]. For example, optimal irrigation scheduling (two irriga-

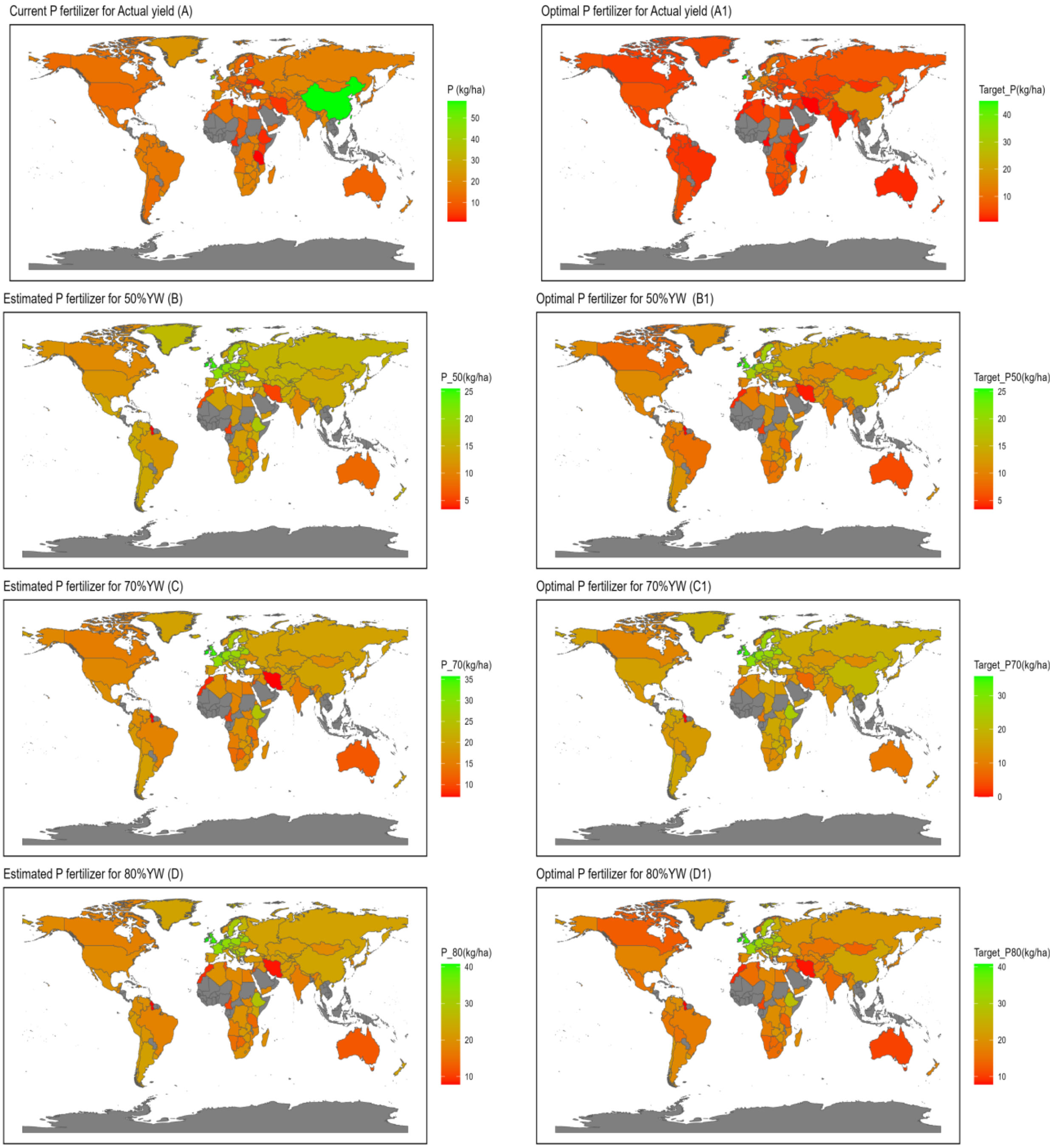

Figure 3. The results of P application levels in both actual and optimal values, derived from DEA analysis across various scenarios. These scenarios encompass current conditions (A and A1), minimum P input requirements, and the optimal necessary to attain target yields of 50% Yw (B and B1), 70% Yw (C and C1), and 80% Yw (D and D1) in rainfed wheat.

tions of 60 mm at stem elongation and flowering) combined with moderate nitrogen rates significantly improves Nitrogen Use Efficiency (NUE) and yield while reducing nitrate accumulation [32]. Long-term manure application, especially when combined with chemical fertilizers, increases soil organic matter and enhances both NUE and crop yields [33]. Retaining crop residues in the field can increase phosphorus use efficiency by over 35%, with additional benefits from factors such as fertilizer type, application method, duration, and climate [34]. Reduced tillage and residue retention further increase soil organic carbon, available phosphorus, and biological activity, supporting better nutrient use [35].

Partial substitution of chemical phosphorus fertilizer with organic manure also significantly increases phosphorus fertilizer efficiency and crop yield [36]. Overall, practices such as optimizing planting date, irrigation, residue retention, increasing soil organic matter, and integrating organic amendments with mineral fertilizers, along with adapting to local climate and soil conditions, are all crucial for improving nitrogen and phosphorus use efficiency. In addition, various fertilizer management approaches, including Enhanced Efficient Fertilizers (EEFs), Integrated Nutrient Management (INM), and split N application, offer potential solutions to enhance NUE and reduce losses [31][37]. It seems that for P fertilizer, the issue lies not in excessive application but rather in the timing of its application, particularly during seed planting. Implementing strategies that involve drawing application during seed planting time appears to be the most effective approach for increasing Phosphorus Use Efficiency (PUE) while minimizing surplus application [38]. By focusing on the timing of P fertilizer application, agricultural practices can optimize the utilization of this essential nutrient, ensuring that it is available to the crop when needed most, particularly during critical growth stages like germination and early seedling establishment [39]. This targeted approach helps enhance PUE by maximizing the uptake and utilization of phosphorus by the crops while minimizing wastage or excess application that may contribute to environmental concerns. Implementing precise application techniques, such as placing P fertilizer directly in the seed zone during planting, allows for more efficient utilization of the nutrient by the emerging seedlings [40].

V. CONCLUSION AND FUTURE WORK

This study aimed to assess the efficiency of N and P fertilizer use in rainfed wheat production across 122 countries, targeting optimal application rates for 50%, 70%, and 80% of Yw while minimizing environmental impacts. We used an expanded GYGA dataset, extended globally via stepwise regression, and applied DEA with the CCR model. Inputs included annual precipitation and N and P applications, with outputs covering crop yield, production, water productivity, and nutrient use efficiencies. Results showed significant efficiency differences, with countries like Sweden, Ukraine, Ireland, Finland, and Belgium achieving full efficiency (1.0), while others, such as India and Iran, scored 0.18–0.37 under current conditions. Optimized N and P rates were often lower, e.g., Montenegro's N use dropped from 427 kg/ha to 132 kg/ha for actual yield optimization. Efficiency improved with higher yield targets, and climate zone analysis identified efficient production regions, providing insights for enhancing global rainfed wheat productivity and sustainability.

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