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WATER FOOTPRINT ASSESSMENT OF SOYBEAN UNDER AGROFORESTRY-BASED LAND USE SYSTEMS

Yogesh Kumar[1], Sandeep Chouhan[1]*, Tarun Kumar Thakur[2], Anita Thakur[1], Suneel Rathore[3] and S.R.K Singh[3]

[1]Krishi Vigyan Kendra (Indira Gandhi National Tribal University, Amarkantak) Anuppur, M.P., India
[2]Department of Environmental Science, Indira Gandhi National Tribal University, Amarkantak, M.P., India
[3]ICAR-ATARI Zone IX, Jabalpur, M.P., India
*Corresponding author E-mail: chouhankvk@igntu.ac.in

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ABSTRACT

Water footprint assessment offers a holistic framework to quantify freshwater consumption associated with crop production, encompassing green (rainwater), blue (irrigation), and grey (pollution dilution) water components. The present investigation was conducted at the KVK Research Farm, Indira Gandhi National Tribal University, Amarkantak (M.P.) during 2017–18 and 2018–19 to evaluate the grain yield, above-ground biomass, harvest index and water footprint of soyabean (var. NRC-86) under five *Dalbergia sissoo–Emblica officinalis* based agroforestry land-use systems arranged in a Randomized Block Design (RBD) with four replications. The results revealed that the 100% *E. officinalis* system (T5) recorded significantly the highest grain yield (1108 and 982.25 kg/ha/yr in 2017–18 and 2018–19, respectively) and the lowest total water footprint (1.64 and 1.70 m^3/kg), while the 100% *D. sissoo* system (T1) recorded the lowest grain yield (851.5 and 831.75 kg/ha/yr) and the highest total water footprint (2.03 and 1.88 m^3/kg) across both years. A clear negative relationship ($R^2 > 0.85$) was established between total water footprint and grain yield, confirming that progressive substitution of *D. sissoo* with *E. officinalis* enhances water-use efficiency and crop productivity simultaneously. The pooled mean total WFP of soyabean across treatments (1.84 m^3/kg; equivalent to 1841.58 m^3/t) was comparable to global estimates, validating the methodology. The study underscores the potential of *E. officinalis*-based agroforestry as a water-smart and ecologically sustainable land-use strategy for soyabean production in semi-arid tropical regions.

***Keywords* :** Agroforestry; Water footprint; Green water; Blue water; Grey water; Soyabean; *Emblica officinalis*; *Dalbergia sissoo*; Water-use efficiency; Amarkantak.

Introduction

Agroforestry is a land-use system which integrates trees, crops and animals in a way that is scientifically sound, practically feasible, ecologically desirable, and socially acceptable by the farmers (Nair, 1979). It can play a major role in bringing along sustainability to the desired level of diversification. As the size of land holdings is shrinking and sole crop yields are reducing, integrating tree farming with agriculture remains the most viable strategy to increase farm productivity (Bijalwan *et al*., 2020; Verma *et al*., 2019).

Approximately 85 percent of worldwide freshwater is currently consumed by agriculture (Shiklomanov, 2000; Hoekstra and Chapagain, 2007). The concept of "water footprint" was introduced by Hoekstra (2002) as a consumer-based indicator that maps the impact of agricultural production on universal water sources. The overall water footprint (WF) of farmed crops is the sum of green, blue, and grey components (Mizutani, 2010). Agroforestry offers an effective and sustainable land and water utilization option, with water conservation and productive water use being among its key advantages.

Despite growing global interest in agroforestry water dynamics, empirical data on water footprint under species-specific agroforestry combinations from semi-arid tropical India remain sparse. The present study was therefore undertaken to quantify and compare grain yield, biomass and water footprint of soyabean under different *Dalbergia sissoo–Emblica officinalis* based agroforestry systems.

Materials and Methods

Study Site

The field experiment was conducted at KVK Research Farm, Indira Gandhi National Tribal University (IGNTU), Amarkantak, Madhya Pradesh, India (22°48•22.9″ N; 81°45•03.2″ E) during 2017–18 and 2018–19. The study area represents a dry tropical habitat. Annual rainfall ranged from 1269 mm to 1770 mm. Maximum temperature recorded in May was 42°C and minimum in December was 2.3°C. The soil was slightly acidic with good macro-nutrient (NPK) content, providing favorable conditions for soyabean production under agroforestry.

Experimental Design and Treatments

A Randomized Block Design (RBD) with five treatments and four replications was employed. The treatments comprised: T1–100% *Dalbergia sissoo*; T2–75% *D. sissoo* + 25% *E. officinalis*; T3–25% *D. sissoo* + 75% *E. officinalis*; T4 –50% *D. sissoo* + 50% *E. officinalis*; and T5 –100% *E. officinalis*. Soyabean variety NRC-86, an early-maturing variety (90–95 days) resistant to girdle beetle, stem fly and charcoal rot, was grown in all plots. Grain yield, straw yield, above-ground biomass and harvest index were recorded at physiological maturity.

Water Footprint Estimation

The water footprint (WF) of soyabean under different treatments was estimated using the Water Footprint Assessment (WFA) framework of Hoekstra *et al*. (2011). Soil moisture at different depths was monitored throughout the crop season to estimate seasonal evapotranspiration and total crop water use. The WF was expressed in cubic metres of water per kilogram of grain yield (m^3/kg). Green WFP represents rainwater consumed, blue WFP represents irrigation water, and grey WFP represents the volume of water required to dilute pollutants to acceptable levels.

Statistical Analysis

Data were statistically analyzed following the method described by Panse and Sukhatme (1967) for a completely Randomized Block Design. Analysis of Variance (ANOVA) tables were prepared separately for each year and for pooled data. Statistical computations were performed using SPSS software. Correlation and linear regression analyses were used to examine the relationship between grain yield and water footprint.

Result and Discussion

Yield–Water Footprint Interaction in Soyabean Under Agroforestry

Data collected during the course of the inquiry was correctly collated and statistically evaluated to determine the impact of various treatments. The performance of soyabean production showed significant differences among treatments (Table 1, Fig. 1). The significantly highest grain yield was recorded in agroforestry (AF) with 100% *E. officinalis* (1108 and 982.25 kg/ha/yr during 2017–18 and 2018–19, respectively), while the lowest was recorded under 100% *D. sissoo* (851.5 and 831.75 kg/ha/yr, respectively).

Above-ground biomass reflected a similar trend; highest biomass was recorded with 100% *E. officinalis* (1758.25 and 1519.5 kg/ha/yr in 2017–18 and 2018–19) and lowest with 75% *E. officinalis* + 25% *D. sissoo* (1661 and 1477 kg/ha/yr). The highest harvest index was observed under T5 (38.97%) and the lowest under T1 (36.73%) during 2018–19. During 2017–18, differences in harvest index were least significant, possibly because trees were at an early growth stage and exerted minimal competitive influence on the underlying crop. Similar observations were reported by Odhiambo *et al*. (2001) and Thakur *et al*. (2008). The significant impact of microclimate on crop yield was also documented by Shankaran *et al*. (1987), Righi *et al*. (2007), Reynolds *et al*. (2007), Wang *et al*. (2016), and Sahoo *et al*. (2021). The present investigation confirmed that age, type, morphology and spatial arrangement of tree species profoundly influence the yield attributes of agricultural crops grown in agroforestry systems.

Table 1 : Mean performance of soyabean yield, above-ground biomass and harvest index under different agroforestry land-use systems over the years

Land-Use System	Grain Yield (kg/ha/yr)			Straw Yield (kg/ha/yr)			Above-Ground Biomass (kg/ha/yr)			Harvest Index (%)		
Land-Use System	2017 -18	2018 -19	Mean	2017 -18	2018 -19	Mean	2017 -18	2018 -19	Mean	2017 -18	2018 -19	Mean
T1: 100% D. sissoo	851.50	831.75	841.63	1473.00	1426.00	1449.50	2324.50	2257.75	2291.13	36.64	36.83	36.73
T2: 75% E.off+25% D.sis	1037.00	896.50	966.75	1661.00	1471.00	1566.00	2698.00	2367.50	2532.75	38.41	37.87	38.14
T3: 25% E.off+75% D.sis	954.25	803.75	879.00	1458.50	1413.75	1436.13	2412.75	2217.50	2315.13	39.58	36.24	37.91
T4: 50% E.off+50% D.sis	978.75	817.00	897.88	1593.50	1419.00	1506.25	2572.25	2236.00	2404.13	38.01	36.54	37.27
T5: 100% E. officinalis	1108.50	982.25	1045.38	1758.25	1519.50	1638.88	2866.75	2501.75	2684.25	38.70	39.23	38.97

SEm±	41.57	25.62	14.82	63.00	22.20	22.70	96.30	33.75	32.50	0.74	0.72	0.40
CD (5%)	124.00	76.40	43.40	188.00	66.30	66.80	287.40	100.70	95.30	2.22	2.15	1.17

Note: *Values are means of four replications; SEm± = Standard Error of Mean; CD = Critical Difference at 5% level.*

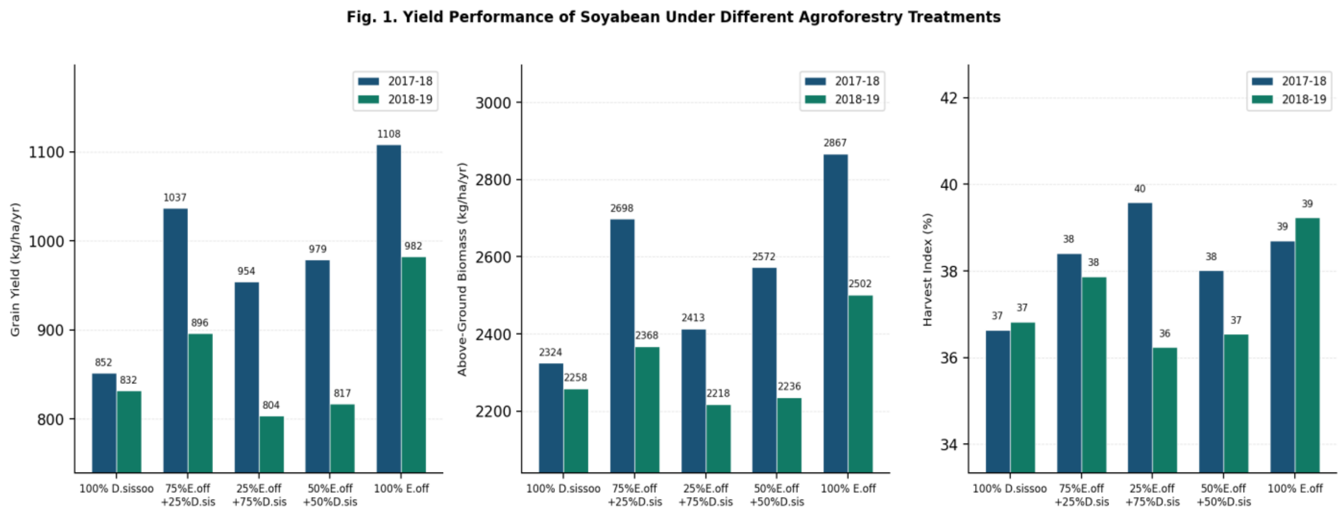

Fig. 1 : Yield performance of soyabean under different agroforestry land-use systems over the years.

Water Footprint Dynamics of Soyabean Under Different Agroforestry Treatments

The water footprint of soyabean showed significant differences among treatments (Table 2, Fig. 2). The green water footprint was highest under 100% *D. sissoo* (T1: 0.57 and 0.92 m^3/kg in 2017–18 and 2018–19) and lowest under 100% *E. officinalis* (T5: 0.46 and 0.83 m^3/kg). The blue water footprint followed the same trend, with T1 recording the highest (1.07 and 0.57 m^3/kg) and T5 the lowest (0.87 and 0.51 m^3/kg) values. The blue WFP is influenced by crop water requirement, time of sowing, plant nutrition, and inherent crop properties such as root depth, leaf area and canopy architecture (Allen *et al*., 2006; Costa *et al*., 2021).

The total water footprint was highest under T1 (2.03 m^3/kg) in 2017–18 and under T3 (1.91 m^3/kg) in 2018–19, while the lowest was consistently recorded under T5 across both years (1.64 and 1.70 m^3/kg). Overall, 100% *E. officinalis* system recorded the lowest total WFP, confirming it as the most water-efficient agroforestry land-use system for soyabean. The pooled mean total WFP (1841.58 m^3/t) was comparable to global estimates: Mekonnen and Hoekstra (2014) reported 2107 m^3/t; Huang *et al.* (2012) obtained 1816 m^3/t for Beijing; and Bleninger and Kotsuka (2015) found 2210 m^3/t in Brazil, validating the present findings.

Table 2 : Green, blue, grey and total water footprint (m^3/kg) of soyabean crop under different agroforestry land-use systems over the years

Land-Use System	Green WFP (m^3/kg)			Blue WFP (m^3/kg)			Grey WFP (m^3/kg)			Total WFP (m^3/kg)		
Land-Use System	2017-18	2018-19	Mean	2017-18	2018-19	Mean	2017-18	2018-19	Mean	2017-18	2018-19	Mean
T1: 100% D. sissoo	0.57	0.92	0.74	1.07	0.57	0.82	0.39	0.40	0.39	2.03	1.88	1.95
T2: 75% E.off+25% D.sis	0.49	0.87	0.68	0.92	0.54	0.73	0.33	0.38	0.36	1.75	1.79	1.77
T3: 25% E.off+75% D.sis	0.56	0.93	0.74	1.04	0.58	0.81	0.38	0.41	0.39	1.97	1.91	1.94
T4: 50% E.off+50% D.sis	0.52	0.92	0.72	0.97	0.57	0.77	0.35	0.40	0.38	1.84	1.90	1.87
T5: 100% E. officinalis	0.46	0.83	0.65	0.87	0.51	0.69	0.31	0.36	0.34	1.64	1.70	1.67
SEm±	0.02	0.01	0.01	0.04	0.01	0.02	0.01	0.006	0.004	0.07	0.03	0.02
CD (5%)	0.06	0.04	0.02	0.11	0.02	0.05	0.04	0.02	0.01	0.21	0.08	0.07

Note: *WFP = Water Footprint; SEm± = Standard Error of Mean; CD = Critical Difference at 5% level.*

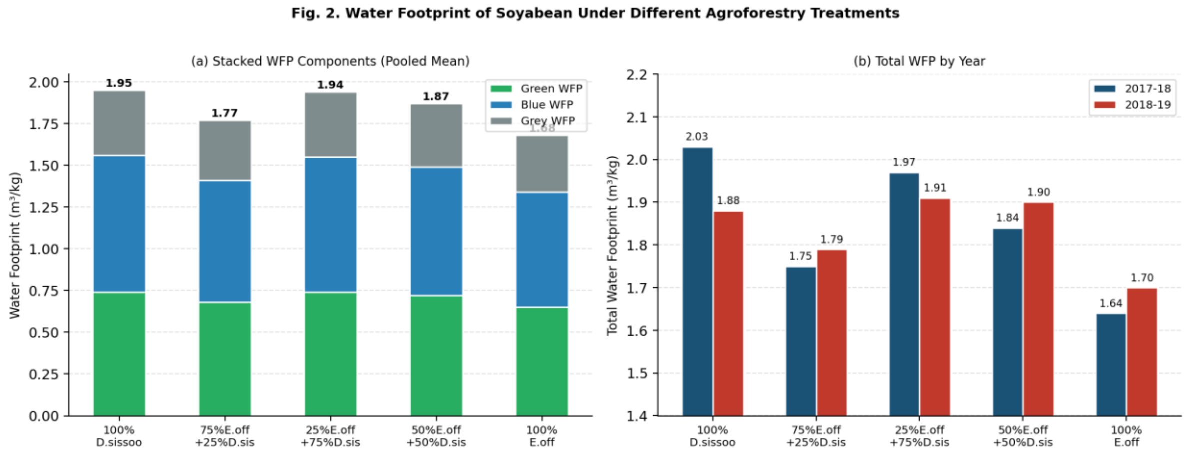

Fig. 2 : Water footprint components of soyabean under different agroforestry treatments.

Relationship Between Grain Yield and Water Footprint

Regression analysis revealed a significant negative linear relationship between grain yield and total water footprint across all years and treatments (Fig. 3). The coefficient of determination (R^2) exceeded 0.85 for all three datasets (2017–18, 2018–19 and pooled mean), confirming a strong inverse association. As total WFP increased from T5 to T1, grain yield declined systematically. T5 (100% *E. officinalis*) consistently achieved the highest yield with the lowest water footprint, making it the most water-productive system. This negative relationship held across seasons, confirming its robustness and the ecological advantages of *E. officinalis*-dominant agroforestry systems for sustainable water management in soyabean production.

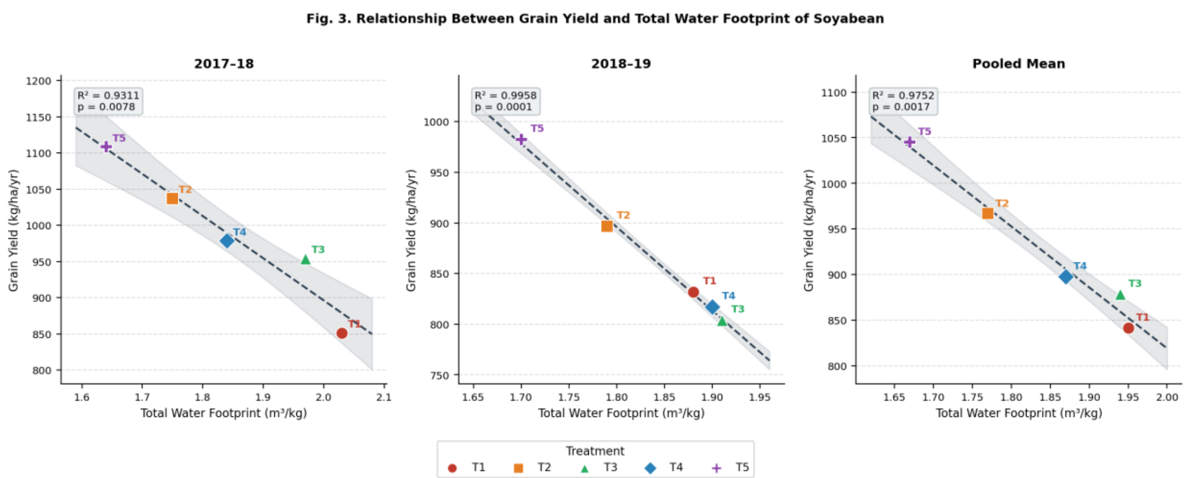

Fig. 3 : Relationship between grain yield (kg/ha/yr) and total water footprint (m³/kg) of soyabean under different agroforestry land-use systems.

Conclusion

The present investigation demonstrated that the type and proportion of tree species in agroforestry systems significantly influence both crop productivity and water footprint. The 100% *Emblica officinalis* system consistently recorded the highest grain yield, above-ground biomass and harvest index, while simultaneously exhibiting the lowest green, blue, grey and total water footprint. A strong inverse relationship ($R^2 > 0.85$) between grain yield and total WFP confirms that enhancing crop productivity and reducing water footprint are complementary objectives achievable through appropriate species selection in agroforestry. The total WFP of soyabean (mean: 1841.58 m³/t) was consistent with global benchmarks, validating the WFA methodology under Indian agroforestry conditions. Adoption of *E. officinalis*-based agrisilviculture systems is strongly recommended for semi-arid tropical regions to achieve water-smart, economically viable and ecologically sustainable soyabean production.

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