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Original Article

Can On-Farm Wood Meet the Global Wood Supply and Save Tropical Forests? A Systematic Review

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ABSTRACT

Global wood supply is faced with an annual escalating scarcity threat by population growth and increased wood demand. Natural forests, a chief source of wood, are under pressure from massive deforestation and degradation, whereas plantation forests are faced with challenges of land tenure and competition from other land uses. This systematic review aimed to point out the contribution of on-farm trees to global wood supply and tropical forest conservation. The study adopted the Sample-Phenomenon of Interest-Design-Evaluation-Research type framework to identify relevant literature. Both grey and peer-reviewed publications were considered. Of the 3800 publications identified, 42 substantially met the inclusion criteria and were selected for data extraction. A huge imbalance was evident in the wood supply and demand that forest production could not satisfy alone. On-farm trees were observed to be a significant alternative source of wood supply in South Africa, India, and Kenya, supplying 27, 36, and 70 per cent of total apparent consumption, respectively. Where importation reliance was low and a low forest production rate, on-farm trees contributed more than 50% of the total apparent consumption. China had a high reliance on importation. On-farm trees contributed at least a supply of 8% of total apparent consumption. On-farm trees were the chief source of wood fuel. On-farm trees contribute substantially to the supply chain of industrial roundwood, woodfuel, and sawn wood, reducing the need to infiltrate the forests. Where the full potential of on-farm trees is inadequately exploited, on-farm trees can sustainably contribute to the wood supply chain and save tropical forests.

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INTRODUCTION

Wood is one of the longest-standing building materials in existence and has been prevalent in our everyday lives and the economy. Despite being a renewable resource, the supply is threatened by an escalating scarcity each year (Waswa *et al*., 2020). With the growing world population and growing middle class in emerging economies, the world wood demand is anticipated to triple from 500 in 2018 to 1500 million metric tons (mm^3) by 2050 (Midgley *et al*., 2017; Nawir *et al*., 2007). At the same time, natural forests that have hitherto remained the main source of wood have continued to decline (FAO, 2018). Plantation forests have increasingly provided a supplemental supply of wood and are also facing competition from other profitable land use activities, as well as land tenure challenges that are likely to slow or inhibit expansion (Kanel *et al*., 2012).

Moreover, concerns have been raised regarding the imbalance between supply sustainability and the growing demand for global roundwood, which acts as the main raw material for other wood products (Kanel *et al*., 2012). On average, none of the continents can substantially produce a wood supply that meets the demand of its population. This is evidenced by the constant increase in the global wood importation trends at an annual average rate of 18 mm^3 yr-1 (2354%) since 2010 and the exportation trends of an average increase of 19.3 mm^3 yr-1 (2524%) since 2010 (FAOSTAT, 2021). Thus, there is a looming global shortage of wood for commercial uses, thus critical to increasing the supply of wood from alternative sources, including smallholder on-farm trees (Midgley *et al*., 2017). Indigenous/natural forests are the primary source of wood and regeneration, and trees are diverse on a single stand, whereas plantation forest trees are usually planted of the same species and age.

Zomer *et al*. (2014) evidenced that on-farm trees have the capability to increase at a rate higher than that of forests. On-farm trees provide an opportunity to help close the wood supply gap, deliver better livelihood benefits and save forests from deforestation and forest degradation (Quandt *et al*., 2018). Focusing on alternative wood production, particularly on-farm, to ease the pressure on tropical forests is a viable and sustainable nature-based solution for saving tropical forests. This paper defines on-farm trees as those planted on private land mostly by smallholder producers for subsistence, commercial purposes, or both. On-farm trees are key in producing timber firewood and other products, especially for the rural population. The tree products, particularly wood, form a portfolio of diversified rural livelihoods and impact on households' incomes. However, the amount of wood supplied from on-farm trees remains imprecisely known (Kanel *et al*., 2012).

Several international (UN-FAO, ITTO) and regional (Eurostat, UNECE/FAO Timber Branch) organisations have provided timber market reports and wood market reports, and national organisations have provided wood statistics and information. The data on wood is not only generic but mostly focused on forests alone. Consequently, on-farm wood data is scarce and uncoordinated. The lack of data on wood supply specific to sources is particularly serious, which prevents objectively addressing the forest governance and sustainability issues. The available official sources (UN-FAO, ITTO) are

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usually aggregated (mostly forest data) and exclude on-farm wood sources. Thus, the contribution of on-farm wood to global wood supply and its concomitant role in saving tropical forests remains scantly quantified. It is against this backdrop that this study was undertaken to generate knowledge. Centrally, this study aimed to unravel the contribution of on-farm trees to the global wood supply and its attendant sustainable development co-benefits to tropical forest conservation and restoration. Understanding the contribution of on-farm trees to the global wood supply would be imperative in managing on-farm wood production with inevitable positive consequences on the sustainability of tropical forest resources and concomitant services.

METHODS

We reviewed the contribution of on-farm trees to tropical forest conservation and restoration by analysing in-depth peer-reviewed and grey literature on on-farm trees. The study adopted the SPIDER (Sample, Phenomenon of Interest, Design, Evaluation, Research type) framework to define the critical components of the review question. The framework is focused primarily on defining and guiding search strategy. The SPIDER framework provides an effective alternative to the PICO framework for mixed methods systematic review research (Cooke *et al*., 2012).

We applied the SPIDER framework to determine the review question. Components were defined as on-farm trees as the sample, and tropical forest conservation and restoration was a phenomenon of interest. The design adopted was a mixed methodology. The evaluation component highlighted the contribution of on-farm trees to the phenomenon of interest. The review aimed to analyse literature using qualitative and quantitative methods. The overall objective was to unravel the contribution of on-farm wood supply in tropical forest conservation and restoration. *Table 1* indicates the framework as applied to this study.

Table 1: SPIDER Framework

Framework variable	Context
S-sample	On-farm trees
PI-phenomenon of interest	conservation and restoration of tropical forests
D- Design	Mixed methodology
E- evaluation	Wood supply contribution
R- research type	qualitative, quantitative, and mixed methods

Using e-research database platforms, an in-depth search was conducted on cab abstracts, Scopus, Google Scholar, and Web of Science for peer-reviewed published literature on tropical forests and on-farm trees. In addition, grey literature and relevant regional institutions' reports were reviewed and analysed for data. Additional search was also performed through snowballing for citation tracking of pertinent articles. The citation tracking was used to locate relevant articles not indexed on the selected online databases.

Search terms used were categorically defined to include tropical forests and on-farm trees. The search procedure adopted a single or combination of terms for a better search outcome. This was done in addition to the defined SPIDER framework elements. The search included terms in the title, abstract, and full-text context of relevant literature in the search databases. The search was limited to peer-reviewed literature published in the English language between 2009 and 2020 and with a geographical context limited to a global level and specified countries.

Based on the SPIDER framework highlighted in Table 1, our search yielded 3800 articles, 1500 in Web of Science, 600 in Scopus, 1000 in Google Scholar, 500 in Cab abstracts, and about 200 grey literatures. The search terms used were tropical forest and on-farm trees combined with AND/OR degradation, deforestation, wood supply, and restoration. Specific wood supply terms included roundwood, industrial roundwood, wood fuel, and sawn wood. The primary review entailed screening titles and abstracts, which was

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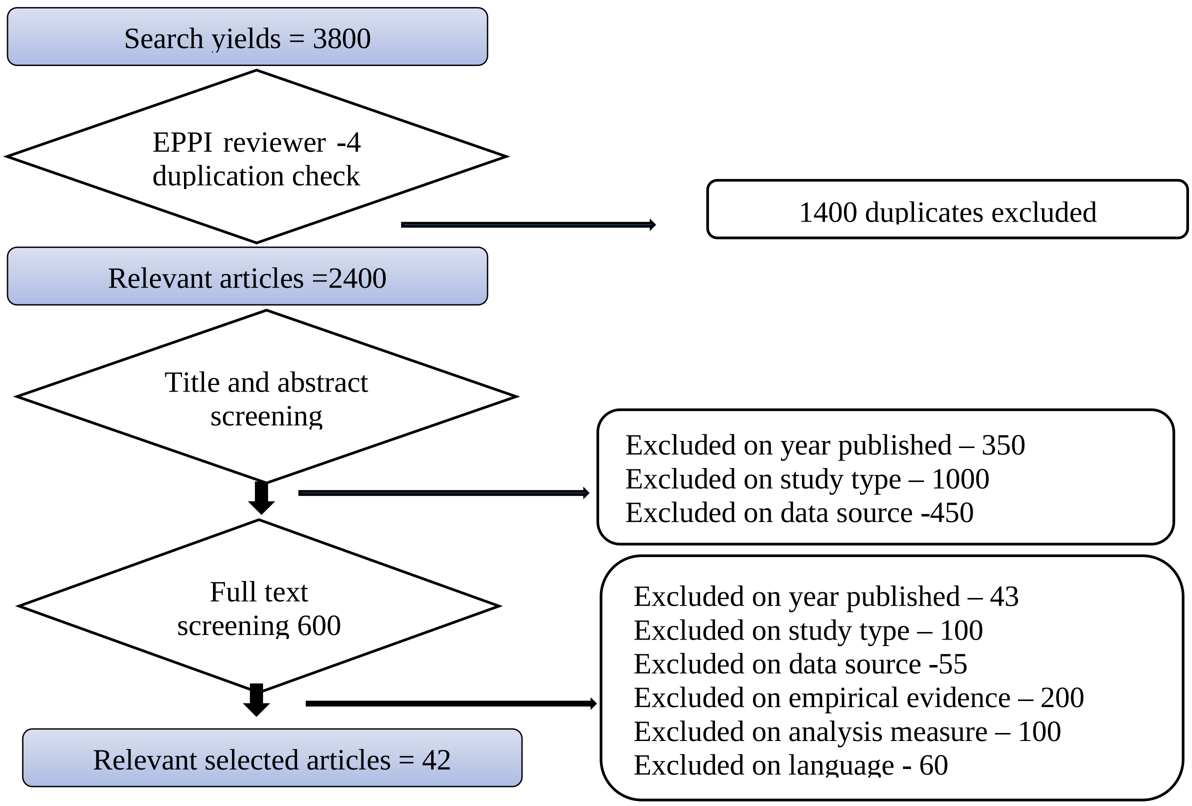
performed using Eppi reviewer-4 software. The screening proceeded to full-text articles, manually conducted in-depth to ensure they met the inclusion criteria and were pertinent to the study.

The search yields were exported to Eppi reviewer-4 software, and 1400 articles were excluded due to duplication. The remaining 2400 publications were screened at title and abstract levels and then further reviewed based on relevance to the SPIDER framework. The selected articles were processed and screened using the inclusion criteria; studies that were peer-reviewed or verifiable grey literature with empirical evidence published between 2010 and 2021 were selected for the next screening stage. Studies with a dependence on secondary data or geospatial data were practically excluded. About 75% of the articles were excluded at the abstract level screening, then a further 90% of the remaining articles were excluded due to the inability to substantially satisfy the inclusion\ exclusion criteria and the SPIDER framework. A total of 42 articles were selected for data extraction. The systematic mapping process of the screening process is illustrated in *Figure 1*.

Figure 1: Systematic mapping process adapted from Rodela et al. (2019)



Data Extraction

Extraction of data from the selected 42 articles was done based on a predefined extraction guide that was tailored to fit the SPIDER framework and relevance to the review question. The extraction focused on the outcome data; however, details on the author, study type and design, publication dates, geographical context of the study, methodology, interventions adopted, and the outcome data type were taken into consideration for enhanced data synthesis. Due to the heterogeneousness of the methodology adopted by the selected publications, our extraction was confined to the empirical evidence narrative synthesis. The quantity of total on-farm trees contribution to wood supply was estimated based on the following formula:

$$ofs = Ac - (fp + I)$$

Where;

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$ofs = On - farm\ trees\ supply$,

$Ac = Apparent\ consumption = (total\ forest\ production + Imports) - Exports$

$fp = forest\ production$

$I = imports$

Wood production/supply trends (for imports and exports) were sourced from FAOSTAT (2020) between 2015 and 2019. Wood supply refers to what is locally produced (from forests and on-farm wood), while apparent is what is locally consumed, including imported wood. On-farm wood supply (*ofs*), see formula 1, was calculated based on forest production ability, apparent consumption, and import and export considerations. A supply of industrial wood, wood fuel, and sawn wood was sourced from FAOSTAT over a period of five years (2015-2019). The regions selected included India, China, and South Africa, based on the availability of tropical and subtropical forest cover, to inform the statistics and information. The average percentage was used to populate the average trend charts per country for comparative purposes (see *Figures* 2,3, and 4). To be comparable with other metrics and improve the interpretation, the trends in mm3 yr-1 are accompanied by percentage change by multiplying the number by 130.8; (Ton/Cubic Yard (Metric) is equivalent to 130.8 Percent- https://hextobinary.com/unit/density/from/tnmetricpcuyd/to/percent.

Quality Analysis and Bias Considerations

All the selected articles were subjected to quality analysis. A two-stage quality analysis was adopted for the quality threshold. The first stage entailed analysing the publications on a defined baseline scale of quality. All the articles that satisfied the baseline threshold were considered for data extraction. During data extraction, all the data were subjected to analysis using stage two specific quality indicators before being considered for synthesis. The two-stage quality analysis indicators used in this review are highlighted in *Table 2*.

Table 2: Two-stage quality indicators

Quality set	Indicator
Baseline	Outcome is practical, backed by data, and standard methodology.
	Consideration and explanation of confounding variables and biases, if applicable
Specific	Key terms, acronyms, and frameworks used are clearly described.
	sampling methods are reliable and clearly described.
	Data collection methods are verifiable and reliable.
	Use of replicable and verifiable data analysis method
	The conclusions and recommendations are logical and backed by the study findings.

RESULTS

Analysis of the Selected Studies

The selected articles presented data on Global, India, China, South Africa, and Kenya trends in the wood supply chain, primarily focusing on industrial roundwood, woodfuel, and sawn wood. The regions were selected based on the availability of tropical and subtropical forest cover to inform the statistics and information. About 40% of the articles adopted a mixed methodology, 45% adopted a quantitative methodology, and 15% employed qualitative methodology in data collection and presentation. 55% focused on the demand and supply trends of wood, and 45% of the articles focused on the role of on-farm trees in tropical forest conservation and restoration. Among the articles presenting data on demand and supply trends, 55% focused on industrial roundwood, 27% focused on woodfuel, and 18% focused on sawn wood demand and supply.

Contribution of On-Farm Trees to Wood Supply

Roundwood Production and Consumption

The FAO (2018) projections estimate that by 2030, global consumption of industrial roundwood will rise by 60% over current levels to

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around 2400 mm^3. Round wood production increased in 2018 but dipped in 2019 in all regions. The highest growth rate was in Oceania (4.4%) and South America (2.8%) from 2014 to 2019 and Asia (2.6%) (FAO, 2018). Import trends also increased at an average 18 mm^3 yr-1 (2354%) from 2010. Global export trends since 2010 have maintained an average increase of 19.3 mm^3 yr-1 (2485%).

Apparent consumption exceeded production at the global level (see Table 3 below). In all regions, the wood supply was marginally higher than the consumption, except in Asia, where wood consumption exceeded the supply. The global wood supply deficit was mostly met through importation and on-farm sources. Further, the potential supply of industrial roundwood (IRW) and wood fuel would increase by 20% and 55% between 2005 and 2030 (FAO, 2017).

China's forest cover is estimated to be about 220 million hectares (mha), equating to about 23% of the total ratio under forests. About 56% of this total is pure natural forest, 5.6% is primary forest, and about 38% is plantation forest (NFI, 2019). The forest cover is 42% state-owned, 37% collective-owned and 20% privately-owned (NFI, 2019). FAO (2009) estimated that China's total wood product consumption was 337.4 mm^3 yr-1 RWE. Of this volume, 245 mm^3 yr-1 RWE was estimated to be consumed in the construction and industry sectors. Domestic consumption amounted to 29 mm^3 yr-1 R.W.E., and exports equalled 63 mm^3 yr-1 (R.W.E.) (F.A.O., 2009). Therefore, domestic self-consumption is assumed to be estimated production from on-farm supply.

China remained the greatest importer of industrial round wood (48 mm^3 yr-1) (FAO, 2018). China experienced 8% annual growth rate in industrial roundwood consumption between 2015 and 2019. Even though almost all harvested wood is destined for China, mostly from tropical countries allegedly illegally harvested (Kleinchmit, 2020), the supply gap was filled by on-farm wood. By application of formula one above, notably, on-farm trees contributed to about 7.7-9.0% of the total industrial roundwood supply, yet on-farm trees are an unexplored sector. Estimates of industrial roundwood supply from on-farm trees showed a constant average annual trend of 8% since 2015. The estimated apparent industrial roundwood consumption exceeded total production, as presented in *Figure 2*.

Total forest cover in India as of 2019 was estimated at 71 mha i.e., about 22% of the total geographical land in India (FAO & UNEP, 2020). Between the years 2015 and 2020, industrial roundwood production was reduced at an annual rate of 1.3%. This was attributed to reduced reliance on forest resources and increased dependence on on-farm wood occasioned by a supportive agroforestry policy (Midgley *et al.*, 2017). Trends in quantities of industrial roundwood consumption exceeded supply in India. On-farm trees are alternative sources of industrial roundwood in India. On-farm trees contribute an annual average of 39%. This indicates a significant contribution of more than one-third from on-farm trees. Supply estimates of industrial roundwood from on-farm were estimated to be constant across the five-year period since 2015.

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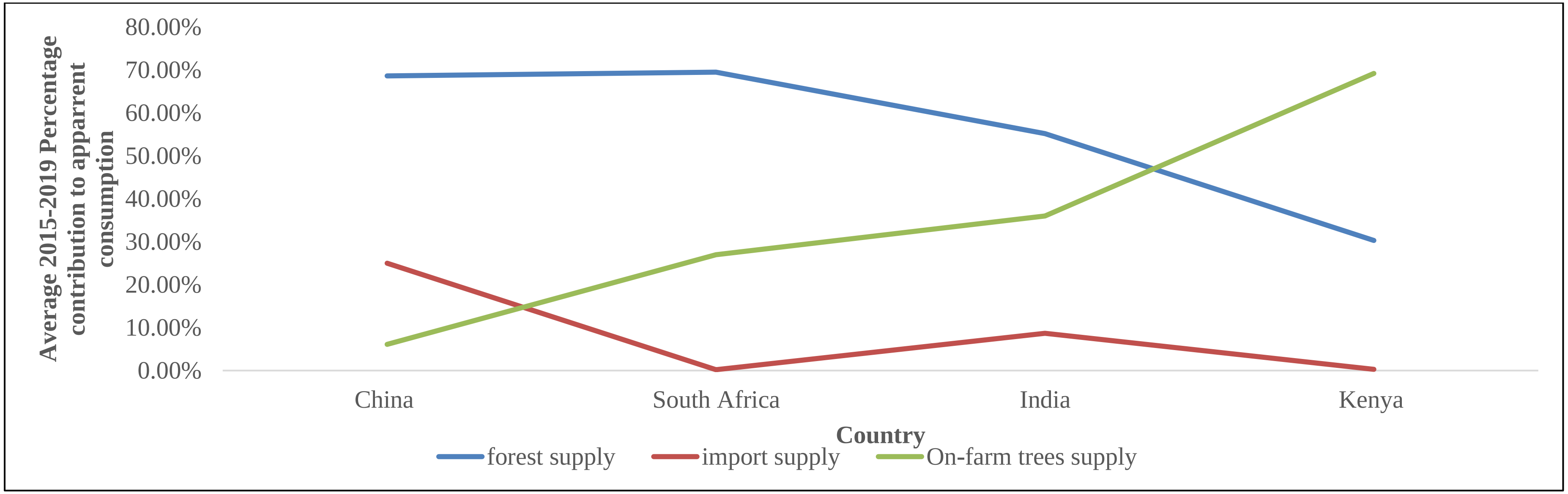
Table 3: Wood products demand and supply in 2019

Country	Forest production ability in %	Apparent consumption mm³			Import mm³			Export mm³			On-farm wood supply in percentage		
		Industrial roundwood	Sawn wood	Woodfuel	Industrial roundwood	Sawn wood	Woodfuel	Industrial roundwood	Sawn wood	Woodfuel	Industrial roundwood	Sawn wood	Woodfuel
China	91.2%	244	128	0.15	64	39	0.007	0.08	0.20	0.0001	6.1%	5.4%	8.8%
South Africa	70.8%	15.5	2.1	12.6	0.025	0.15	0.9	0.45	0.21	0.26	27 %	23.8%	26.1%
India	60.6%	53.1	8.0	302	4.2	1.3	0.015	0.006	0.01	0.0003	36.3%	32.5%	39.4%
Kenya	30.3%	1.0	0.29	26	0.01	0.001	0.29^{-4}	0.006	0.003	0	68.7%	68.9%	69.2%

Figure 2: Average Industrial Roundwood supply 2015-2019



Source- FAOSTAT 2020.

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The total forested land in South Africa is estimated to be about 40 mha. Of this proportion, 1.4 mha is commercial plantation forest, translating to about 1.1% of the total land coverage, 0.5 mha is covered by natural forest, and the majority is covered by woodland region (FAO, 2015). Proportionally, commercial plantations are the chief supplier of timber in South Africa and are owned 82% by private entities and about 18% by the state and public. The DAFF (2019) estimated that the total forest production of roundwood in 2017 was estimated to be about 17 m^{m3} yr-1. The total country production of roundwood in 2017 in South Africa was 2 mm^3 yr-1 (FAOSTAT, 2021). Therefore, forest production contributed an average of about 71% of the total production in South Africa. On-farm industrial roundwood supply contributed an average of 4 mm^3 yr-1 of wood between the years 2015- 2019. By use of formulae 1 above, of the total wood supply, on-farm trees have contributed an annual average of 25% consistently since 2015.

In Kenya, total forest cover is approximated to be 7.2% of the total land cover. Natural forest covers an area of about 4.7 mha, whereas plantations constitute 0.2 mha. For the natural forest cover, gazette natural forests cover an area of 905,357 ha, and natural forests in community lands cover an area of 3,252,922 ha. The current total forest cover gazetted as public forests stands at about 2.5 mha (GoK, 2011). Farmlands distribution in Kenya is estimated to cover an area of 9,939,255 ha with a current potential of sustaining an average wood biomass of about 17.58 m^3 per ha. The national wood supply potential is estimated to be about 31 mm^3 yr-1 against a demand of 45 mm^3 yr-1. In these estimates, public forests supply an average of about 9% of the total supply, whereas private forests supply 21%, and on-farm trees supply the majority, 70% of the total supply (GoK, 2013). The on-farm supply of round wood has shown a declining trend since 2015. Of the total supply of industrial roundwood in Kenya, on-farm trees contributed a significant average of 68%, implying that on-farm trees are a pathway of alternative wood supply. This would ease pressure on forest resources.

Woodfuel Production and Consumption

Global woodfuel production and consumption has been observed to have an upward trend since 2015. Woodfuel production is noted to be marginally higher than consumption. An increase in population predisposes wood consumption to exceed the supply, particularly in developing countries where households primarily rely on woodfuel for cooking and lighting. In 2019, global wood fuel production amounted to 1944 mm^3 yr-1, an increase of 2% from 2015 (FAOSTAT, 2020). Most regions experienced a slow increase in wood fuel production save for Asia and Oceania, which had decreased annual growth rates. Asia was the largest producer in the same period, accounting for 38% (718 mm^3 yr-1), whereas Africa ranked second, with 36% (700 mm^3 yr-1) of global wood fuel production.

Woodfuel accounts for about 50% of the total fuel consumption in India (FSI, 2002, as cited in FAO, 2020). It is India's rural population's mainstay for cooking food and other household and non-agricultural work such as rural crafts. The annual consumption is estimated to be about 250-300 mm^3 yr-1. However, there is a huge gap in production supply from forests and consumption, with on-farm trees filling this gap. Much of the wood fuel is collected from forests in an unsystematic way, impacting the growing stock and ecological imbalances. About 5.6% comes from natural forests through illegal collection. Woodfuel collection for home use, especially in communities living within forest vicinity, is traditionally uncontrolled and unmonitored. 75% of all forest production is estimated to be fuelwood, factoring in the unaccounted-for quantities. The total accounted for total roundwood forest production in India, which is equivalent to about 61%. On average, since 2015, on-farm trees contributed about 39% annually as alternative sources of woodfuel. The supply estimates of woodfuel from on-farm observed a slight gradual decline in production over the 5 years period since 2015.

In South Africa, about 60% of the total energy consumed comes from woodfuel, including

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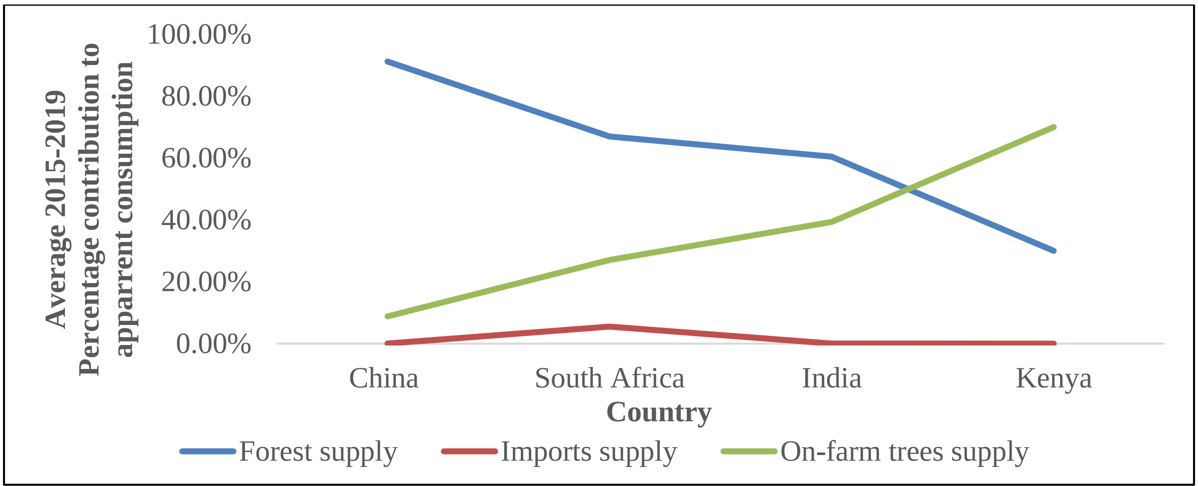
charcoal (Uhunamure *et al.*, 2017). More than nine million people, roughly 80% of the rural population, depend exclusively on firewood for daily domestic use. Charcoal use is confined to middle-income earners in the urban centres (Uhunamure *et al.*, 2017). The estimated forest supply is 71%, and on-farm trees have contributed an average of 27% in supply since 2015, presented in *Figure 3*.

Figure 3: Average woodfuel supply 2015-2019;



Source- FAOSTAT 2020

In Kenya, according to Kenya National Bureau Statistics [KNBS] (2019), over 80% of Kenyans use woodfuel as the main type of cooking fuel, 84% of them being households in rural setups. About 11.6% of the total Kenyan population was found to use charcoal as the main source of cooking fuel (KNBS, 2019). Further, the supply and demand of cooking solutions at the household level established that the average mean usage of firewood per household (averaged at 3.9 members) per week was 24 kg and 7 kg per week for charcoal (GoK, 2019). This translates to 158,284 m^3 of weekly firewood and 9350 m3 of charcoal consumption. This equates the consumption at the household level only; consumption for schools, hotels and restaurants, ceremonies, and other consumers may escalate the figure by two to three-fold value. Woodfuel over-dependence and over-extraction from the natural forest is a major cause of declining tree cover and loss of biodiversity. Using Formulae 1 above, in total, national woodfuel production supply has been 30% and 69% from forests and on-farm trees, respectively, since 2015.

Sawn Wood Production and Consumption

Global sawn wood production trends have recorded an average increase of 71 mm^3 yr-1(9286%) since 2010. Imports trends also increased at an average rate of 26 mm^3 yr-1 from 2010 (3401%). Global export trends since 2010 have maintained an average increase of 26.7 mm^3 yr-1 (3492%), FAOSTAT, 2021. Europe and Asia displayed the highest production, with an annual growth rate of 3.2% and 3.4%, respectively. The annual growth rate was attributed to the increase in industrial roundwood production in the region. North America experienced the least sawn wood production, with an annual growth rate of 0.8% between 2010 and 2019. Sawn wood consumption was observed to exceed production (FAOSTAT, 2020).

China is the largest producer and importer of sawn wood. Its production escalated by 32%, from 68 mm^3 yr-1 (2014) to 90 mm^3 yr-1 (2018), making it the largest producer since 2017 (F.A.O., 2020). Its consumption rate grew by 34% between 2015 and 2019 (FAO, 2020). Where China's forest production for sawn wood was 91.2%, and the apparent consumption was 117 mm^3 yr-1, on-farm

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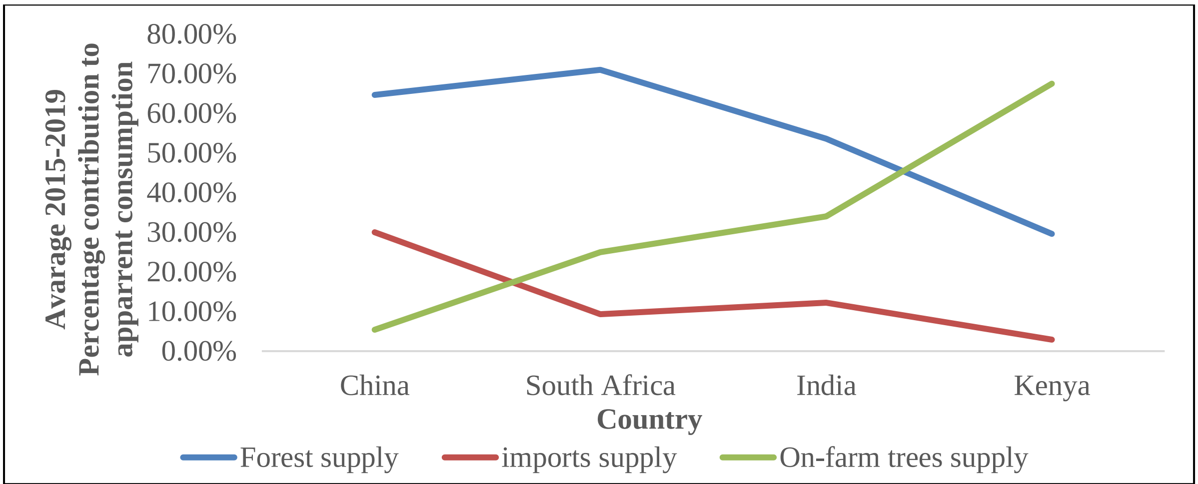
trees contributed an average of 7.5% (981%) since 2015.

In India, sawn wood production capacity has plateaued at 6.8 mm^{3}yr-1 (889%) since 2007. The import trend has increased since 2010 from 0.23 mm3 yr-1 to 1.3 mm^3 yr-1 in 2019 (i.e., 30 to 170%). Exports declined from 2014 value of 0.032 mm^3 yr-1 to 001 mm^3 yr-1 (i.e., 4 to 0.13%) in 2019 (FAOSTAT, 2021). This trend in the increase in imports and decrease in exports explains an attempt to satisfy the growing demand for domestic consumption. However, with an annual combined consumption of about 33.6 mm^3 yr-1 for wood used in housing construction, furniture, and agricultural implements, forest production and imports cannot meet the demand alone (Shrivastava & Saxena, 2017). Therefore, where the apparent consumption of sawn wood was estimated to be 7.5 mm^{3}yr-1 since 2015, imports contributed an average of 11%, and on-farm trees contributed an average of 39% in the sawn wood supply chain. A comparison of sawn wood trends to apparent wood consumption (*Ac*) is presented in *Figure 4*.

Figure 4: Average sawn wood supply 2015-2019



Source- FAOSTAT 2020

Sawn wood domestic consumption in South Africa continues to experience an outstanding expansion. This is indicated by their production capacity, which peaked after recording the lowest volume of 1.4 mm^3 yr-1 in 2012, a drop of 33% from the previous peak volume of 2.1 mm^3 yr-1 (in 2003). In 2018 saw, South Africa recorded the highest volume of 2.2 mm^3 yr-1 of sawn wood production. The production peak placed it as one of the largest sawn wood producers in Africa by accounting for volume (FAOSTAT, 2021). The building sector is the biggest market for sawn wood in South Africa, absorbing around 75% of the total production (DAFF, 2020). This shows almost complete consumption of the domestic production of sawn wood. The country's forest production capacity is 71%, and the remaining volume is primarily estimated to be produced from on-farm trees. Cumulatively, on-farm trees are estimated to contribute an average of 26% to the sawn wood supply in South Africa.

Sawn wood production in Kenya has always shown an intermittent stagnation in supply from 1993 to 2000. The production was constant at 0.18 mm^3 yr-1 (23%). It then dropped to the lowest levels between 2001 and 2004 at 0.078 mm^3 yr-1 (10%); between 2005 and 2011, the production volume increased at a constant rate of 0.13 mm^3 yr-1 (17%). Production trends show a constant of 0.29 mm^3 yr-1 (38%) since 2015 (FAOSTAT, 2020). Approximately the major source of sawn wood supply is derived from on-farm trees at an average of 70% in the supply chain.

In summary, on-farm trees were observed to be a significant producer of industrial roundwood, sawn wood, and woodfuel in developing countries like Kenya, India, and South Africa as of 2019.

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While big economies like China have focused on the importation, on-farm trees contributed a substantial volume in the supply of both roundwood, sawn wood and wood fuel. The on-farm wood supply (*ofs*), see Formula 1, was calculated based on forest production ability, apparent consumption, and import and export considerations. On average, on-farm wood contributed 69% of industrial roundwood, sawn wood, and woodfuel supply in Kenya, 25.5% in South Africa, 36% in India, and 6.7% in China. On-farm trees (*of*) significantly bridge the wood supply deficits and can save tropical forests when sustainably explored.

Role of on-farm trees in tropical forest conservation and restoration

The high deforestation rate leads to forest cover loss estimated at ten mha annually (FAO & UNEP, 2020), indicating a significantly high wood demand that forests are struggling to meet. Deforestation grossly impacts the overall health of the forest, pointing to an unrecoverable, devastated forest state in the future (FAO & UNEP, 2020). With the high global demand, different countries' total forest production ability has been observed to be unable to satisfy the domestic wood demand. This is evidenced by the overall annual global increase in the importation trends of industrial roundwood at the average rate of 18 mm^3 yr-1 (2354%) since 2010 and export trends average annual global increase of 19.3 mm^3 yr-1 (2524%) since 2010 (FAOSTAT, 2020). Besides, illegal logging is evidently a leading cause of extensive tropical forest deforestation and degradation.

Of the reviewed articles, 20% featured research on illegal logging and its relation to tropical forest degradation. Illegal logging has been largely documented to generate a devastating impact on tropical forests. Driven by a high growing wood demand that exceeds the supply ability, more so an increased industrial appetite for tropical hardwood such as mahogany, teak and rosewood owing to their high market prices, illegal logging has led to extensive and uncontrolled tropical forest deforestation degradation, loss of biodiversity and subsequently climate change (FAO, 2020). Wit *et al*. (2010), from their analysis, highlight a constituting percentage of 30-40% contribution to the total timber production from unregulated chainsaw logging in tropical forest countries that including Guyana, Republic of Congo, Democratic Republic of the Congo (DRC) and Uganda. The percentage contribution was noted to be higher in Cameroon, Ghana, and Peru. The source of the wood used is mostly unverified and may predominantly be illegally logged. Quantitatively, going by an average estimation of 20-40% of the total roundwood production, this can be translated to 775 – 1551 mm^3 of Roundwood equivalent in 2017, 803- 1606 mm^3 of Roundwood equivalent in 2018, and 793- 1587 mm^3 of Roundwood equivalent in 2019 going by FAO (2021) statistics of total global roundwood production values (FAOSTAT, 2020).

The high volume of wood from illegal sources that degrades the tropical forest at an alarming rate is driven by inadequate charcoal supply, the need for fuelwood for domestic consumption due to poverty, and commercial wood production due to high wood demand (Sereyrotha *et al*., 2020). Meanwhile, Sibale *et al*. (2012) observed that smallholder farmers who planted trees on their farms recorded increased production of charcoal, firewood, and other wood products not only for home consumption but also for sale to the community. A comparative analysis (Hagos, 2020) showed that the availability of an enhanced number of trees on-farm reduced the number of hours taken to go to the forest and collect firewood by half. This significant time saved by the availability of firewood on the farm can be otherwise spent on other income-generating activities and considerably reduce illegal firewood and other wood products from the nearby forests. Besides positive, sustainable household income, on-farm trees considerably impacted deforestation (Sibale *et al*., 2012). The availability of sufficient trees on the farm supplemented the households with necessary wood resources, limiting the need to infiltrate and harvest the same products from the nearby forests.

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In addition, households could sell part of their on-farm supply to the community, balancing the supply and allowing the nearby degraded forest to regenerate. The sale of wood generated an average income of about 66,000 Malawian Kwacha per household (Sibale *et al*., 2012).

On-farm tree species such as *Paraserianthes falcataria*, *Grevillea robusta*, and *Albizia falcataria* provide a source of a fast-growing wood supply for use in light construction, woodfuel, production of veneers and pallets as well as furniture. The amount of volume produced can considerably supply the market with a substantial amount of wood, thereby reducing the supply-demand gap and minimising demand pressure and, subsequently, the overall deforestation through reduced wood harvest pressure in the nearby tropical forest (Liyama et al., 2014). Evidently, on-farm trees have significantly shown the ability to mitigate these profound negative impacts of illegal logging by increasing the availability of wood and related products from the forest. On-farm trees create a substantially increased supply of wood and related products for household consumption and commercial sale and significantly reduce the wood harvest pressure of nearby tropical forests. Additionally, the surplus yields from the harvest can be sold to the community around and beyond, creating a sustainable income generation through an observed household income increase of up to 182% in involvement in on-farm tree farming.

Inadequate forest production ability is conspicuous in the wood supply chain. Forest production varies among countries, and an attempt to increase wood supply still presents a significant supply gap in the global demand for wood. On-farm wood supply has been observed as a sustainable option in topping up the shortage, especially in rural areas where there is a high consumption rate of woodfuel and timber for repairs and maintenance (Howard & Liang, 2019; USDA, 2019; BMEL, 2021; FAO, 2009; DAFF, 2019; FAO, 2020). For instance, thousands of small-scale tree farmers in Linyi, China, have joined forces to benefit from the growing demand for certified sustainable timber (WWF, 2016). In Guangxi, smallholder and informal forests amount to about 800,000 ha of eucalyptus and produce more than 12 mm^3 yr-1 of wood annually. The eucalyptus generates considerable employment and raw materials for industry worth over US$2.4 billion after local primary processing (Midgley *et al*., 2017).

Furthermore, the Nepal Government has recognised the important role of on-farm trees in offsetting the wood supply deficit through the enactment of the agroforestry policy (Government of Nepal, 2019). More than 30% of the total timber and fuel wood in Nepal (Kanel *et al*., 2012) is supplied on farms. On-farm trees were projected to surpass the supply from Nepal government forest in the year 2020 and beyond (Kanel *et al*., 2012). Similarly, India's National Agroforestry Policy supports over 80% of smallholder on-farm tree producers (Government of India, 2014). As of 2020, the total forest cover in India was 21.71 per cent of the total geographical area, with 1,540 sq. km increase in forest cover over 2019 (ISFR). The increase in forest cover could be attributed to supportive agroforestry policy (ISFR, 2021).

In summary, on-farm trees were demonstrated to have a substantial potential to save the tropical forest from deforestation and degradation in three ways (Jose & Dollinger, 2019; Midgley *et al*., 2017; Sears *et al*., 2018; Zomer *et al*., 2014). Foremost, on-farm trees within altered landscapes where tropical forests are distributed can act as habitats for preserving biodiversity. Secondly, on-farm trees support conservation in situ by acting as the best alternative to forest product sources, thereby reducing forest extractions. Lastly, on-farm trees act as ex-situ conservation by including seed collections, field trials, and field' gene banks' (Zomer *et al*., 2016). A considerable supply of industrial round wood and woodfuel production was observed in China. Sawn wood supply from on-farm trees was considerably low in the two countries. The on-farm wood supply was calculated based on forest production ability, apparent consumption, and import and export

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considerations. Table 4 summarises the wood supply and demand for industrial roundwood, sawn wood, and woodfuel in six countries.

DISCUSSION

Our review aimed to unravel the contribution of on-farm trees to the conservation and restoration of tropical forests. This objective was achieved by interrogating the role of on-farm trees in global wood supply. The findings largely demonstrate the evidence of the role of on-farm trees in the sustainability of global wood supply. The findings indicate an outright inability of forest resources to fully satisfy the wood supply. Among the analysed countries, South Africa had the highest share of roundwood supply from domestic forest production at 73%. China, despite having a high forest production index of 91%, the forest supply could only meet 68% of the total apparent consumption. On-farm trees are observed to be a significant alternative source of wood supply in South Africa, India, and Kenya, supplying 27%, 36%, and 70% of the total apparent consumption, respectively.

Objectively, China's slightly less than two-thirds forest supply to the apparent consumption and a low on-farm tree supply is attributed to the high reliance on importation. The high index supply from on-farm trees and a significantly low production supply from forests in Kenya can be attributed to the imposed moratorium on timber harvesting in all public and community forests. This drives supply focus to other alternative sources, particularly on-farm trees (Dongmo, 2022; Reitano & Kristen, 2018). Available data on importation highlights negligible supply quantities. However, due to Kenya's lack of a reliable wood inventory, the quantities may be higher than the quoted values. This can be observed especially in the setting of escalating illegal logging activities in the neighbouring countries (Lawson, 2014).

Significantly, the above findings in Kenya's setup indicate the ability of on-farm trees to sustainably contribute to the wood supply chain. The findings correlate with the conclusion of Flanagan et al. (2017) on the substantial contribution of smallholder tree farmers to the commercial wood supply. The study, however, highlights a critical need to promote and increase smallholder tree farmers' productivity to ensure long-term wood sustainability from on-farm sources (Flanagan *et al*., 2017).

Woodfuel supply from on-farm trees was slightly higher in China and India than industrial roundwood. Notably, the importation of woodfuel was observed to significantly decrease quantity compared to industrial Roundwood. Most of the supplies were from forest production at the rates of 91%, 60%, 66%, and 30% for China, India, South Africa, and Kenya, respectively. The rest of the supply deficit was primarily from on-farm trees. The findings align with FAO's (2018) observation that the major sources of woodfuel include natural forests, plantation forests, and on-farm trees. Non-forested areas such as farms contribute substantially to the woodfuel supply chain. The report also notes that most woodfuel harvested in most supply chains is a by-product of various types of forest and tree-based agricultural land-use systems (FAO, 2018).

Furthermore, the FAO report on agroforestry wood productivity indicates an average continuous woodfuel production of about 736-997 mm^3 yr-1 annually in humid tropical regions in Southeast Asia alone. While this volume may seemingly appear high, comparably, FAOSTAT quantified volume is based on reported data, whereas woodfuel consumed at the household level and harvested from farms is rarely reported, contributing to the scanty literature on actual wood production from trees on farms. The Tigray region quantified farmland woodfuel volume of 98 mm^3/ 0.53 ha of farmland, which sums up the immense empirical ability of on-farm trees to relieve the menace of tropical forest deforestation and allow its regeneration considerably. However, these values present a scenario where the productivity of on-farm trees has not been fully harnessed to achieve maximum yields. Implementing policies and promoting on-farm tree cultivation can significantly increase supply

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quantities, hence a substantial, reliable supply. The findings agree with Anyonge and Roshetko (2003) that farm-level wood production has potential that is not limited only to the farmers' needs and household consumption but also enhances local and regional wood supply and ecosystem and biodiversity conservation.

The synthesis indicates a significant average increase in the importation of sawn wood among all the analysed countries. This increase in importation quantities was coupled with a decrease in on-farm tree supply and a slightly lower forest production supply among all countries. China had a 15% increase in importation of sawn wood compared to industrial roundwood. India had a 50% increase, while South Africa had a 99% average increase in the importation of sawn wood compared to industrial roundwood and woodfuel. Importation of sawn wood in Kenya elicited no significant change. FIM (2017) highlights that the increasing trend in the consumption and demand for sawn wood globally is driven by the increase in construction in most developed and developing countries.

Hitherto, policies and legislation have affected future on-farm wood supply. Midgley *et al*. (2017) resound that the future prospect of a sustainably on-farm wood supply depends on a supportive policy environment that encourages enterprise-oriented organisations at a local level to establish well-informed private and individualised out-grower schemes. Policies may stimulate production while others discourage some forms of consumption, simultaneously affecting future on-farm wood supply and demand levels. Generally, the forest sector, including smallholder on-farm tree producers, is faced with weak forest governance and enforcement/rule-of-law, legal pluralism, i.e. unclear and overlapping mandates of different government organisations; undemocratic practices and corruption; power imbalances and paternalistic attitudes of governments and donors towards smallholders (FAO, 2017b). Most countries do not have policies that govern these trees on farmland nor specify how to deal with products from on-farm tree plantations (Foundjem-Tita., 2013). Overly, in developing countries, government policies restrict smallholders' involvement in timber production because regulations designed for large-scale timber production (e.g. cutting and transportation permits, registration procedures) are applied to smallholders (Arvola et al., 2019; FAO, 2017b).

Perdana *et al.* (2012) research identified government policies (timber trade regulations) that increased transaction costs for Indonesian smallholders and traders and served as a disincentive for smallholders' investment in teak plantations. Similarly, in Indonesia, the timber transport policies applied by the government created a disincentive for farmers to engage in better teak marketing practices in Indonesia (Barr *et al*., 2010; Feliciano *et al*., 2018; Nawir *et al*., 2007; Pearce & Davis, 2015; Perdana *et al*., 2012). Equally, Maryudi *et al* . (2015) revealed that growers in Indonesia were 'constrained by the existing regulatory framework' and that 'substantial, prohibitive costs of mandatory legality verification' are seen as the principal constraint discouraging smallholder engagement with commercial markets.

In Nepal, forest regulations on the sale and transport of wood, even from private forests, are very strict (Government of Nepal, 2019; Kanel *et al*., 2012). In Nepal, the permit regimes from forest product harvesting to transport to sales are significantly higher than in other sectors. Even in private forests, the permit regime is full-blown. These permit regimes have increased the rent-seeking behaviour of staff and hooligans, thus dampening efficiency, equity, and sustainability. Similarly, in Ghana, smallholder producers faced excessive bureaucracy and unfavourable policies and legislation (Hajjar, 2015; Osei-Tutu *et al*., 2012). The lack of policy and legal structures for small-scale forestry has resulted in a lack of incentives to conserve and re-plant trees (Osei-Tutu *et al*., 2012). Moreover, the legislation does not protect farmers' rights over on-farm trees. Hansen's, 2011) study in Ghana revealed a low level of compliance with laws on farm timber

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extraction. Regulations require timber operators to obtain prior and informed consent from farmers besides timely compensation for crop damage (Hansen, 2011), but this was the reverse with timber operators (Hansen, 2011).

Supportive regulations would provide significant incentives for smallholder farmers to invest in trees on their land. A study by Nawir *et al* . (2007) in Ethiopia, Vietnam, South Africa, and Indonesia documented the role of supportive policies in farm-based forestry. Supportive policies have led to increased productive forest plantation areas in Vietnam, which increased 7 per cent per year from 1990 to 2005, mainly through farm-based initiatives (Duguma, 2013; FAO, 2009). Also, in Ethiopia, the forest policy provides farmers with tax incentives that are proportionate to the number of trees they plant (Duguma, 2013; Nawir *et al*., 2007). Moreover, the government lifted controls on the pricing and marketing of forest products, paving the way for an open and competitive market for wood. Thus, farmers face little restriction in selling tree products (Nawir *et al*., 2007).

Equally, the recently endorsed National Agroforestry Policy of Nepal has one of its goals as the development, expansion and commercialisation of agroforestry systems to contribute to national prosperity (Government of Nepal, 2019). The policy envisages eliminating the hurdles and regulations on planting, felling, and transporting trees on non-forest lands. India was the first country to develop a policy on agroforestry with the objectives of enhancing landscape and livelihoods (Government of India, 2014). In Ethiopia, policymakers are keen on policies that allow the issuance of land ownership certificates to land owners (Maryudi *et al*., 2015; Nawir *et al*., 2007). The Vision 2030 also gives attention to efficient wood-based industrial development (Government of Kenya, 2013). Also, in Vietnam, promotional policies and land allocation created a 'push effect' and induced tree growth before the demand and markets were developed (Arvola *et al*., 2020; Clement & Amezaga, 2013).

In regard to wood markets, smallholder farmers have little access to market information concerning timber demand and price, little knowledge of market specifications, and geographically scattered and weak linkages with market agents (Anyonge & Roshetko, 2003; Government of Nepal, 2019; Kanel *et al* ., 2012; Scherr, 2004). As a result, they have little knowledge of how to assess the value of their trees and how and where to market them. The market constraint is compounded because farmers often plant and manage trees without a specific market or product in mind (Amare *et al*., 2019; Anyonge & Roshetko, 2003; Maryudi *et al*., 2015). In developing countries, smallholders sell their products to middlemen in the absence of sufficient marketing information about current prices and are often not in a position to negotiate higher rates, which lowers prices even more (Anyonge & Roshetko, 2003; Nawir *et al*., 2007; Perdana *et al*., 2012). Yet in Asia and Africa, well-functioning wood markets were identified as sufficient conditions to trigger smallholder tree growth (Arvola *et al*., 2020). Most wood product markets and market institutions are structured to serve large-scale natural forest and plantation producers (Hajjar, 2015; Kanel *et al*., 2012; Maryudi *et al*., 2015; Midgley *et al*., 2017; Nawir *et al*., 2007). Thus, mostly in developing countries, smallholder planters are challenged with efficient markets (Scherr, 2004).

Also, risks and high transaction costs incurred by the intermediaries were cascaded to the growers to tree growers in terms of low prices. The risks and transaction costs included low prices for low-quality wood; prices uncontrolled (intermediaries have to negotiate prices with many buyers and sellers), intermediaries deal with authorities and bear the cost of government restrictions on postharvest processes, including wood transport, which is often smoothed through bribes (Nawir *et al*., 2007).

Positive economic growth enables higher resource allocation to on-farm tree management, including growing, protecting, and applying improved technologies, all of which will improve or raise

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on-farm wood supply quantities over time. On-farm tree growing is a climate-smart practice that is being bolstered by organisations to adapt to and mitigate the effects of climate change. On-farm trees considerably ward off the need to infiltrate the forest to acquire forest products for sale due to poverty. Furthermore, adequate on-farm trees provide households with a continuous supply of woodfuel and, in turn, reduce the time taken to collect the same products from the nearby forest by half and even more depending on the distance of the forest and the depth required to collect enough firewood. This significantly discourages forest harvest as the time saved can be used to engage in other income-generating activities. The findings correlate with Kiyani *et al*. (2017) conclusions that enhanced adoption of agroforestry can considerably reduce the intense wood products harvest from natural forests due to increased fringe population increase and uncontrolled forest product harvest activities through increasing the supply of wood products.

Notably, on-farm tree production, if well utilised and implemented, can effectively save a tropical forest from gross deforestation through an adequate supply of forest resources and as an income source to the communities who depend on the forest. This subjectively can also be harnessed to curb illegal logging. While aiming to achieve deforested and degraded land restoration within a short time interval. Initiatives such as the Convention on Biodiversity through the Aichi Targets, the UNFCCC's REDD+ goals, the Rio+20 goals, the Bonn challenge, and the AFR100 can refocus their approach to significantly include on-farm trees in their activities through the participation of smallholder wood producers. This will catapult the restoration goals that are already lagging target timelines.

CONCLUSIONS

The study established that there was a huge imbalance between wood demand and supply at the global and national levels. The wood imbalance could be attributed to the unexplored on-farm trees sector to satisfy the escalating demand. Despite scant data, on-farm trees were evidenced to be a key pathway to sustainable wood production. The wood supply from on-farm trees' contribution to the apparent consumption is crucial in closing the wood supply gap. On-farm trees mitigate the profound negative impact of illegal logging by providing wood products. On-farm tree growing is a climate-smart practice which has a positive spill-over on increased wood supply and forest restoration. On-farm trees contribute substantially to the supply chain of industrial roundwood, woodfuel and sawn wood, among other wood products. Therefore, where the full potential of on-farm trees is adequately exploited, on-farm trees can sustainably contribute to the wood supply chain, save the tropical forest, and enhance forest ecosystem services. Supportive policies and good governance, including efficient markets, are critical to embolden on-farm wood supply.

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