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FERTILISER USE IN MALAYSIAN FOREST PLANTATIONS–TRENDS OF THE PAST AND STRATEGIES FOR THE FUTURE

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This paper summarises the historical perspective on the birth of planted forests in Malaysia and the various fertiliser use studies which have been carried out from 1977 to 2019 on Malaysian forest soils. It also aims to recommend a guideline on forest fertilisation based on past research and explores the possibilities of alternatives to fertilisers such as organic soil amendments and agroforestry systems that may advocate a sustainable solution in the long run to complement a circular bio-economy. It further highlights the requirement for smart silvicultural practices, in line with current trends and a changing climate, to boost forest plantation to meet the global demand for wood supply. Past researches and current needs will assist the development of a suitable framework on tree nutrient management for the future of planted forests.

Keywords: Tropical, planted forests, regenerative agriculture, soil fertility, sustainable, circular bioeconomy

INTRODUCTION

The global demand for wood products has continuously increased for decades and this has highlighted Malaysia as the largest exporter of tropical hardwood logs, sawn timber, tropical plywood, veneer and mouldings. Malaysia's export of timber and timber products jumped to US$4.65 billion in 2000 from US$3.57 billion in 1990 (OECD/FAO 2020). After 12 years, Malaysia accounted for a whopping figure of US$4.83 billion of wood exports in 2012 mainly to Japan, USA and India (MTC 2020). This has drastically taken its toll on natural forest resources, mainly in the tropics.

The relentless pursuits of economic progress, urbanisation, land use change and agricultural crops expansion, has taken its toll on the architecture of natural forests. The insatiable appetite for development has seen natural landscapes transform into agricultural plantations, housing development and industrial plants. Manokaran (1992) reported that a total of 1.64 million ha of lowland forests, representing up to 20% of the forested area in the Peninsula, were cleared to provide settlements for land development schemes such as Federal Land Development Authority (FELDA) and Federal Land Consolidation and Rehabilitation Authority (FELCRA). From 1970 to 1989, forests were reduced by 31% in Peninsular Malaysia whereas 29.9 and 10.5% respectively in Sabah and Sarawak (Manokaran 1992). Realising the severe impact on these resources, the government initiated the Compensatory Forest Plantation Programme (CFPP) in the 4th Malaysia Plan (1981–1985) to establish 188,000 ha of planted forests (Abd-Latif et al. 2018). This was mainly to regulate and reduce the logging pressure on natural forests whilst sustaining an economic level of timber production. Similar programmes were conducted in East Malaysia to generate a continuous supply of timber through forest plantations. Fast-growing exotic species such as *Acacia mangium, Gmelina arborea* and *Paraserianthes falcataria* were planted. By the end of 1996, a total of 56 248 ha of fast-growing forest plantations had been established in Peninsular Malaysia (Thai et al. 1998). Strategies were needed as the global demand for wood products simultaneously increased for decades as aforementioned.

Past scenarios on planted forests

Historical backgrounds on forest plantation trials were established by Wyatt-Smith (1963) and Appanah & Weinland (1993) where earliest work cites planting of nyatoh taban (*Palaquium gutta*) in the 1880s due to its dwindling supplies (Hill 1900). *Palaquium gutta* was heavily sought after for building railway sleepers. Pockets of plantations emerged in Ayer Kroh, Malacca and

Sungai Buloh Forest Reserves. Rubber (*Hevea brasiliensis*) also took centerstage besides *P. gutta*, and was introduced in the early 1900s. With the new found excitement and government support, research and development increased in afforestation and replanting programs on relatively infertile soils such as in Kepong, where the Forest Research Institute (FRI) was set up (1927–1941). The area was chosen deliberately knowing that heterogeneous properties of soil (poor to fertile) will eventually provide an assortment of ecological conditions for tree plantings and reflect the potential or the weakness of tree species for timber (Ng 2010, Jeyanny et al. 2019). The plantation trials in 1926 started off with 25,000 seedlings of 100 indigenous and exotic species such as *Agathis, Calophyllum, Dipterocarpus, Drybalanops, Dyera, Shorea, Eucalyptus, Cassia* and many others (Ng 2010). Mitchell (1957) focussed on afforestation of infertile ex-tin tailings and reported promising results of species such as *Acacia auriculiformis*, *Eucalyptus deglupta*, *Fagraea fragrans* and *Pinus merkusii* in the 1960's. Working on harsh and degraded areas, it was common knowledge that nutrient inputs were a prerequisite for tree planting and sustenance, besides selection of suitable timber species. Parallel to these developments, the need for increased productivity of timber trees required utilisation of soil amendments, fertilisers and water management. Selection of suitable tropical timber species were also important as the outcome of timber products durability, strength and marketability depends on the availability of planting stocks, current market needs and recent requirements for sustainably managed and legally sourced timber (World Bank and International Finance Corporation 2019). Under the flagship of Forest Stewardship Council, several programmes on forest certification, chain of custody certification or other third party voluntary partnership agreements on timber legality has taken precedence in recent years for European exports.

Selection of potential tropical species

The Forest Research Institute of Malaysia initially came forward with 12 species of timber for plantation purposes which outlined the procurement of seeds up to forest plantation establishment techniques (Krishnapillay 2002). This manual was completed in the interest of plantation forestry and to serve as a complete guide for investors. Later, a similar concise reference material was initiated with 16 species for forest plantations, which were mainly *A. mangium*, *Swietenia macrophylla, Khaya ivorensis*, *Hevea brasiliensis* and *Acacia* hybrids of exotics. Some other native species which were also earmarked were *Shorea leprosula*, *Shorea roxburghii*, *Dryobalanops aromatica*, *Hopea odorata*, *Dyera costulata* and *Endospermum malaccense* (Ab-Rasip et al. 2004, Jeyanny et al. 2010). Another recommendation followed suit by the Malaysian Timber Board narrowing to 8 species, with the inclusion of *Neolamarckia cadamba*, *Paraserianthes falcatria* and *Octomeles sumatrana* (MTIB 2007). Besides the given species, other information which were provided were silvicultural practices, economics, utilisation, technical properties, pests and diseases management, to serve as a handbook. Despite the given species and information, some of the shortfalls which were encountered were the scarcity of good planting stocks, the change of preferred species within a short period of time and the concrete knowledge of tried and tested full-fledged research and development initiatives on selected species. Furthermore, results were somewhat scarcely available to investors in plantation forests who were in dire need for practical and management recommendations (Abd-Latif et al. 2018). Both guides on species are still used to date although it is important to note that additions such as bamboo were made later on. Some of the species lack lustre, due to price fluctuations, inflation rates and current market trends and needs.

As the distribution of natural forests were influenced by several factors, mainly elevation, soil temperature and moisture regimes, it is vital to look at the natural vegetation distribution before potential species are even selected to be planted in forest plantations (Abd-Latif et al. 2019). Although Krishnapillay (2002) and Ab-Rasip et al. (2004) mentioned on soil requirements, they did not clearly state the soil types and properties associated with the species. Furthermore, the ecophysiological traits related to environmental properties and timber characteristics were not fully consolidated to prescribe a suitable regime.

As the Malaysian landscape is fairly diverse, species of trees are also distributed heterogeneously; for instance, highland soils at elevations above 1,200 masl which are fairly moist with high organic material support montane ericaceous vegetation such as *Podocarpus*, *Dacyrodes* and *Araucaria*, and lower montane vegetations such as *Agathis*, *Knema* and *Castanopsis* (Kumaran et al. 2010, Saw 2010). Hilly areas > 300 masl boasts *Shoreas*, *Calophyllum* and *Dipterocarpus* sp. on sedentary soils which are moderately well to somewhat excessively drained deep soils with variable texture. Lowlands (< 300 masl) hosts similar group of Dipterocarpaceae family (*Anisoptera*, *Dipterocarpus*, *Drybalanops*, *Hopea*, *Parashorea* and *Shorea*) but on highly leached conditions with low exchangeable bases and cation exchange capacity (Abd-Latif et al. 2019). Different sets of vegetation thrive on other soil types such as coastal sandy beaches, mangroves, peat swamp forests and limestone karsts but these species are usually not chosen for planted forests, except for *Gonystylus* sp. which grows well in peatlands (Abd-Latif et al. 2019).

Looking back at previous literature, the disparity between timber species selection, either exotics or native, with its site suitability was paramount. Especially when choices of natives were not methodically experimented despite the fact that they suit different ecological landscapes. Current researches are skewed to several species such as *Shorea roxburghii*, *Aquilaria malacensis*, *Endospermum malaccense* and *Eucalyptus* hybrids. This include non-timber species such as bamboo and rattan which takes precedence to satiate the current trends and demand. Bamboo has its share of limelight as it is highlighted as biocomposite products which can be used as materials for furniture, packaging, decoration, vehicle and construction and has more than 1,000 uses (Liese & Kohl 2015, Chaowana & Barbu 2017). Thus, exploring soil fertility needs of plantations may serve as a better insurance for productive tree/plant growth.

Tropical forest soils characteristics

The soils in Malaysia are highly weathered and categorised as ultisols and oxisols, known to be acidic, poor in nutrient content and with varying degrees of limitation (Shamshuddin 2006). This was true for most lowland soils due to leaching and run off processes, which was facilitated by increased precipitation, seasonal variations, soil water table, soil texture, organic matter and interaction factors (Miao et al. 2007, Schulte & Ruhiyat 1998, Jeyanny et al. 2019). Tropical forest soils were fairly acidic with low soil pH (3.5 to 4.5) and had a tendency for low phosphorus (P) due to fixation with aluminium and iron oxides (Dabin 1980). Thus, it is believed that phosphorus acquisition by tropical trees was controlled by the turnover of organic phosphorus compounds and the rapid recycling of phosphorus from organic debris such as litterfall (Johnson et al. 2003, Condron & Tiessen 2005, Tiessen 1998). Another characteristic of tropical soils is that it is low in nitrogen (N) availability due to leaching, erosion and denitrification processes (Bruinjzeel 1998, Nottingham et al. 2012). Other nutrients such as potassium, calcium and magnesium are all part of the suite of nutrients which requires further understanding (Bruinjzeel 1998, Wright et al. 2011).

Most tropical timber species have gradually adapted to the restrictions and low nutrient availability thorough mechanisms such as (i) synchronised low growth rates with a high photosynthetic capacity, coupled with low nutrient absorption, (ii) abundant biomass production of roots associated with mycorrhizae, (iii) minimal response to fluxes or nutrient additions, (iv) minimal nutrient requirement along the year to produce new tissue and (v) low throughfall nutrient loss from old leaves (Chapin 1980, Chapin et al. 1986). Various researchers have explained in detail on the mechanisms of adaptations to soil physical constraints, low or high soil fertility, nutrient constraints such as soil acidity, phosphorus deficiencies, high salinity, waterlogging and light interception (Dabin 1980, Vitousek 1984, Kauffman et al. 1998, Poschenrieder et al. 2008, Soethe et al. 2008, Turner & Engelbrecht 2011, van Breugel et al. 2011, Jeyanny et al. 2019). Exemplary sites on tree species adaptability to soil constraints stand tall in Kepong, Bidor, Hulu Perak, Setiu and many other sites within Peninsular Malaysia (Mitchell 1957, Arifin et al. 2012, Ahmad-Zuhaidi et al. 2018, Jeyanny et al. 2019).

Forest plantation nutrition

The earlier dogma on forest nutrition was based on the concept that trees should grow on soils other than those earmarked for planting crops. Planting forests are usually carried out on infertile soils, thus foresters hardly considered the nutrient requirement for forest trees. Many parts of the tropics accepted that forest trees can grow without inputs but in order to maximise the productivity of trees with heterogeneous species adaptability capacity, fertilisers or soil amendments need to be introduced to promote healthy and favourable growth. This needs to be complemented with irrigation, weed management and other silvicultural practices. Mustanoja and Leaf (1965) reported that fertilising forests in the tropics was initiated in the mid twentieth century, starting off with forest plantations in 1950s (Evans 1992). Early works were reported in Cuba, Brazil and the Central Americas from 1970s to 1980s (Alvarado 2015).

The past and current researches on plant nutrition in Malaysia are scarce as only handfuls of researchers have reported results for timber species. In Malaysia, forest fertilisation started in the 1970s with the encouraging results on *Pinus* sp. One of the very first pioneering experiments by Platteborze (1971) involved fertilising *Pinus caribaea* with P and NPK fertilisers in Batu Arang, Selangor which resulted in significant growth in heights (66%) for P fertilised seedlings. Following suit, further researches on *Pinus* sp., *Drybalanops*, *Shoreas* and *Araucaria* were conducted (Sundralingam & Carmean 1974, Sundralingam & Ang 1975, Sundralingam, 1970, 1983, Sundralingam et.al. 1985). Sundralingam & Carmean (1974) reported fertilisation of *Pinus* for two years increased heights to 26–43% as compared to unfertilised soils of Bahau Forest Reserve. The latter work showed that a significant increment of 27–30% for height and basal area growth after 38 months for *Pinus* sp. (Sundralingam & Ang 1975). These researchers mentioned the use of straight fertilisers such as urea, superphosphate, ammonium phosphate, kieserite, ammonium sulphate as well as compound fertilisers of Nitrophoska (12:12:19). Sundralingam (1970) reported the very first experiment which measured soil properties with regards to fertilisation (Table 1). Earlier planting in the CFPP utilised Christmas Island rock phosphate (CIRP), ammonium sulphate and triple super phosphate (TSP) for *A. mangium*, *E. camaldunensis* and *P. falcatria* (Wan-Rasidah et al. 1988). These timber prospects were planted on Durian soil series and fertilised every 6 months in the field, from initial planting up to 18 months. The study points out the importance of P in improving tree growth but not N fertilisation. In *P. falcataria*, N fertilisers seem to increase wood specific gravity after 21 months and indicated that fertilisation may lead to short merchantable logs, a plus point for timber products (Wan-Rasidah & Sulaiman 1992). Research in the 1990's took a paradigm shift where initiatives on different soil ecological conditions and species diversity complemented with foliar nutrient levels were explored (Table 1). The common goals in rejuvenating degraded soils such as beach ridges interspersed with swales (BRIS) and ex-tin tailings witnessed pioneering work by Amir and Wan-Rasidah (1994), Ang et al. (2006) and Ghazali et al. (2007) for *Acacias* and other exotics. Similar correlations between soil fertility and foliar analysis studies were explored by Amir-Husni & Mona (1991) in natural forests, exhibiting the contrast between fertile and infertile soils and the differing nutrient retention capacity of *Kompassia* and *Shoreas*. The most recent study by Jeyanny et al. (2019) captured the soil fertility levels in planted forests after almost a century. The heterogenous land in FRIM, both containing hilly slopes and parts of an ex-mining land were reforested in the 1920s. Based on the reports, moderate levels for soil pH, CEC and C:N were recommended at 4.5–5.5, 5–10 cmol kg^{-1} and 10.9–12.8 respectively for suitable tree growth. Despite the given facts, one needs to look at the physical and biological properties of soil besides tree physiology, reproductive status, survival and growth characteristics that may warrant well-developed plantation forests.

Current researchers should avoid some of the common pitfalls in fertilisation trials done by their predecessors where most of the experiments were confined to glasshouse trials. Even if it further continued to out–planting trials fertilisation was carried out up to initial years (2–3 years only) and field measurements are scanty due to funding constraints, site specific variations, natural microbial inoculation, climatic variations, throughfall/stemflow and plant genetic adaptability (Zulkifli et al. 1989, Manokaran 1980, Wan-Juliana et al. 2009, Camenzind et al. 2018).

Common fertilisation practices for forestry in Malaysia, in plantation establishment, involves utilisation of phosphate rock in planting holes with organic composts, followed by compound fertiliser application every 3 months for the first 12 months (Krishnapillay 2002). Although forest fertilisation is prominent in temperate forests, the need for fertilisers in plantation in Malaysia is not priority due to several factors. Mainly unlike

Table 1 Selected forest timber species and their soil properties on forest soil nutrition

		Soil						Foliar			
No	Species	Soil pH	C	N	Av.P	K	CEC	N	P	K	References
			%	%	mg kg^{-1}	cmol kg^{-1}		%	%	%	
1	*Araucaria hunsteinii*	5.5	1.1	0.09	1.5	0.15	nd	nd			Sundralingam 1970
2	*Leucaena leucophala*	4.3–4.8	2.0–3.2	0.11–0.22	2.4–5.85	0.08–0.14		3.0–4.1	0.13–0.22	0.88–1.47	Norani & Ng 1981
3	*Acacia mangium,*	nd	nd	0.06–0.10	0.75–4.00	0.15–0.25					Wan-Rasidah et al. 1988
	Eucalyptus camaldunensis	nd	nd	0.12–0.15	1.85–2.80	0.19–0.25	nd	nd			
	Paraserianthes falcatria			0.12	2.60–5.10	0.24–0.25					
4	*Shorea* sp.	4.2–4.4	nd	0.07–0.10	5.29–6.73	0.10–0.18	nd	1.3–1.7	0.07–0.08	0.6–0.7	Amir-Husni & Mona 1990
	Kompassia sp.							2.1–2.7	0.08–0.1	0.7–1.2	
5	*Acacia mangium*	3.7–4.1	3–8.2	0.20–0.43	0.80–2.49	0.32–0.53	3.05–3.27	2.14–2.35	0.08–0.11	0.10–0.65	Amir-Husni & Wan-Rasidah 1994
6	*Hevea brasiliensis*	nd	0.5–2.6	0.11–0.20	11.0–20.0	0.51–2.0	nd	3.21–3.5	0.20–0.25	1.25–1.50	Pushparajah 2009
7	*Acacia mangium*	4.5–4.6	0.22–0.73	0.1–0.07	1.25–1.84	0.10–0.16	2.28–4.75	2.18	0.06	1.02	Wan-Rasidah et al. 1998
	Khaya ivorensis							1.14	0.04	0.28	
8	*Acacia mangium*	4.4–4.6	0.22–0.73	0.07–0.10	nd	nd	2.28–4.75	nd			Wan-Rasidah et al. 1999
9	*Acacia hybrid* *Shorea macrophylla,* *Khaya ivorensis*	4.6–6.5	0.1–0.3	0.01–0.05	1.0–17.0	0.02–0.15	1.0–15.0	nd			Ang et al. 2006
10	*Acacia hybrid*	nd	1.71–6.3	0.27	0.81	0.02	nd	2.12	0.18	0.33	Ghazali et al. 2007
11	*Khaya ivorensis*	7.0	nd	0.02	0.31	trace	nd	2.23	0.26	3.32	Jeyanny et al. 2009
12	*Dyera costulata*	3.9–5.0	0.9–1.2	0.1–0.2	2.9–3.6	0.04–0.05	nd	nd			Jeyanny et al. 2010
13	*Acacia mangium*	4.61–4.91	0.4–1.5	0.06–0.12	1.5–2.9	0.06–0.16	nd	nd			Jeyanny et al. 2011
14	*Shorea leprosula*	4.36–4.42	1.0–3.29	0.08–0.25	6.49–7.22	0.03–0.13	nd	nd			Arifin et al. 2012
15	*Pinus* sp.	3.71–4.06	2.94–3.36	0.07–0.26	2.99–5.81	0.03–0.07	5.5–10.27	nd			Jeyanny et al., (2019)
16	Mixed species of Dipterocarps & Non Dipterocarps	4.0–4.37	0.13–1.15	0.11–0.18	1.81–5.73	0.01–0.11	4.57–8.67	nd			Jeyanny et al., (2019)

C: carbon, N: nitrogen, Av. P: available phosphorus, K: potassium, CEC: cation exchange capacity agricultural crops, the return on investment (ROI) is late usually after 15–20 years, the escalating fertiliser costs, shortage of manpower and mechanisation strategies in plantations as well as difficulty of accessibility on rough terrains and marginal land (Ahmad-Zuhaidy & Ab-Rasip 2021). One of the promising species, agarwood, was estimated to produce an investment return of 55% when planted with banana (Mamat et al. 2010). There are many other species which needs thorough financial analysis which is required to understand the cost benefit ratio of applying fertilisers for merchantable quality of timber products. With the global phosphate rock supply projected to grow from 235 Mt in 2018 to 255 Mt in 2023, mainly for agricultural crops and the ever increasing price of rock phosphates reaching 27% in 2013 within a span of 30 years, reduced input of phosphate is forecasted in planted forests (Mew 2016, Heffer & Prude 2019). Furtherment, the current Ukraine-Russia crisis has escalated fertiliser prices, for instance, urea costs USD 1000 $tonne^{-1}$ in 2022 compared to USD 500 $tonne^{-1}$ in 2011 (Crespi et al. 2022).

Besides phosphorus (P), imperatively, other elements such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) are also considered as macronutrients that provide for plant growth. Trace elements such as manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), boron (B), chlorine (Cl) and molybdenum (Mo) are equally fundamental for tree growth (Table 2). At this juncture, the current study did not dwell extensively on the nutrient uptake mechanisms and the role of mineral nutrition in controlling metabolic functions but rather looked at previous studies on soil fertility in planted forests of Malaysia and made an attempt to provide a simple guideline on the nutrient requirement of trees.

Based on the current and past knowledge on soil fertility in plantation forests, a broad guide on suitable levels of nutrient contents in forest soils is being proposed mainly to assist forest managers in determining the health of the trees in relation to selected nutrients (Table 3). The values are a summary of recordings taken from past publications, field observations and unpublished reports for planted forests in Malaysia. This table is not exhaustive as other factors such as optimum foliar nutrients status, tree age, physiological properties and soil types have not been extensively explored. The other confounding limitations, such as nutrients

Table 2 Mineral elements required by plants

Element	Absorbed form	Major functions
Macronutrients		
Nitrogen (N)	NO_3^- and NH_4^+	In proteins, nucleic acids, etc.
Phosphorus (P)	$H_2PO_4^-$ and HPO_4^{2-}	In nucleic acids, ATP, phospholipids, etc.
Potassium (K)	K^+	Enzyme activation, water balance, ion balance, stomatal opening
Sulfur (S)	SO_4^{2-}	In proteins and co-enzymes
Calcium (Ca)	Ca^{2+}	Affects the cytoskeleton, membranes, and many enzymes; second messenger
Magnesium (Mg)	Mg^{2+}	In chlorophyll, required by many enzymes, stabilizes ribosomes
Micronutrients		
Iron (Fe)	Fe^{2+} and Fe^{3+}	In active site of many redox enzymes and electron carries; chlorophyll synthesis
Chlorine (Cl)	Cl^-	Photosynthesis; ion balance
Manganese (Mn)	Mn^{2+}	Activation of many enzymes
Boron (B)	$B(OH)_3$	Possibly carbohydrate transport (poorly understood)
Zinc (Zn)	Zn^{2+}	Enzyme activation; auxin synthesis
Copper (Cu)	Cu^{2+}	In active site of many redox enzymes and electron carriers
Nickel (Ni)	Ni^{2+}	Activation of one enzyme
Molybdenum (Mo)	MoO_4^{2-}	Nitrate reduction

Table 3 Recommended levels of soil properties for tropical forest plantations in Malaysia

Soil properties	Range	References based on Table 1
pH	3.5 – 6.5	1–2, 4–5, 7–9, 11–16
CEC	> 3 cmol kg^{-1}	5, 7–9, 15–16
Nitrogen	> 0.1%	1–8, 10, 12–16
Available P	> 5 mg kg^{-1}	2–5, 6, 9, 12–16
K	> 0.25 cmol kg^{-1}	3, 5–6
Carbon	> 1%	1–2, 5–6, 10, 12–16
C:N	10–15	1–2, 5–6, 10, 12–16

(Ca, Mg, Na) antagonism and their interactions in their ionic form, thus forming complexes in the soil which renders them unavailable for uptake by the growing plants, have not been studied at depth.

Alternative strategies for nutrient management

The increasing prices of fertilisers are projected to change its demand in the next decade. Phosphate rock production recorded based on a global range, showed an increase of 13 to 94 USD tonne^{-1} in 2013 as compared to 16 to 55 USD tonne^{-1} in 1983 (Mew 2016). Furthermore, the global phosphate rock supply was projected to grow from 239 Mt in 2019 to 261 Mt in 2024, an increase of 9% over the period, which will eventually surge fertiliser prices. The new world advocates sustainable development goals (SDGs) as outlined by the UN convention that emphasises the need to recalibrate farming and plantation systems to suit the current environment. The SDGs advocate land degradation neutrality and circular economy whereby Keestra et al. (2018) earmarked several key goals in relation to sustainable land development which is interconnected with forest plantations. In relation to soil processes and utilisation, they are no poverty, zero hunger, clean water and sanitisation, affordable clean energy, responsible consumption and productions, sustainable economic growth, resilient infrastructure, climate action and life on land. These goals advocate minimal inorganic fertilisation, utilisation of organic by-products, minimising eutrophication, conservation of biodiversity (i.e. microbes), reducing greenhouse gas emission from fertilisers (i.e methane emission and nitrous oxide), replenishment with organic matter and many others. Thus, utilisation of inorganic fertilisers needs to discover its niche amidst concurring with SDGs. Thus the below discussion emulates what is needed in providing nutrients for planted forests and how sustainability can be achieved in the current scenario.

Soil amendments

Researches spanning on fortified soil amendments such as composts, mulching, biofertilisers with microbes and biochars are not replete. For instance, composts and biochars were tested on *Shorea roxburghii, S. materialis* and *Dipterocarpus grandiflorus* in degraded soils, and positive effects of combination of biochar and composts were seen for *S. roxburghii* height increments (Jeyanny et al. 2017, Mohamad-Fakhri et al. 2020). *Khaya senegalensis* responded positively to raw and composted biosludge (papermill) applications, outperforming the widely used inorganic fertiliser with increments of height, diameter and plant biomass compared to control (Rosazlin et al. 2015). Enhancement of *Bambusa vulgaris* with composts and biochar were tested by Amir et al. (2017) whereas Wan-Asma et al. (2011) showed positive results in mulch mats from empty fruit bunches (EFB) reducing leaching of nutrients for Acacias planted on sandy soils. Other studies have tested microbes such as *Rhizobium* on *Leuceana leucophela*, and mycorrhizas on Acacias (Norani & Ng 1981, Jeyanny et al. 2011, Lee & Alexander 1994, Lee et al. 2006). However the visualisation of a long term investment in mono species microbes for forest plantation sustainability is sceptical due to assorted soil ecological conditions, microbes' adaptability and the interactions with other abiotic and biotic factors.

Regenerative agriculture/agroforestry

Historical timelines report that the rapid increase in human population from 1.6 billion in 1900 to 7.4 billion in 2016 is owed to the infamous production of synthetic N fertilisers, promoting monocrop dominance in depleting land areas to feed humankind (Smil 1999). The importance of food production, or rather food security, was of greater priority and intensification was eminent with the introduction of irrigation, selection of cultivars for planting, mechanisation and the application of fertilisers, pesticides and herbicides since the beginning of the 20th century (Rhodes 2017).

The early 1980's witnessed an increase of intercropping systems in the Asian region, mainly incorporating timber species with agricultural crops. Agroforestry was seen as a multifunctional approach for food systems, with intentional combination of trees and shrubs with crops or livestock. Despite its revival in the 1980's in Malaysia, it was recognised as traditional farming practices for half a century, which can be seen in its inceptions in Europe, Asia and in Africa. The 'taungya system' which started off in Burma as early as 1800s was a classic example (King 1987). In 'taungya system', trees were planted among crops so the trees will be able to benefit from fertilisers applied for crops. Agroforestry promoted biodiversity, organic matter replenishment, reduced nutrient and pesticide run offs, increased soil health, prevented erosion, hosted wildlife habitats and was seen as a holistic approach to farming (Dixon et al. 1994, Steppler & Nair 1987, Wilson & Lowell 2016). Agroforestry in Malaysia started off with the introduction of teak (*Tectona grandis*) in Mata Ayer Forest Reserve in Perlis in the 1950s where hill paddy and tobacco were planted between the teak seedlings (Dahlan 1979). This was followed by planting of Yemane trees intercropped with tobacco in Perak between 1954–1960 (Shaharuddin et al. 1992). Some preliminary studies on 'taungya system' were done in Negeri Sembilan in Kenaboi, Gallah, Setul and Bahau Forest Reserves. In 1969, 100 acres of *P. cariibaea* were integrated with black twig variety tapioca in Gallah Forest Reserve (Cheah 1971). Other species of indigenous origin include *Shoreas* and *Dryobalanops* (Shaharuddin et al. 1992). However the significance of agroforestry was only emphasised between 1981 to 1985 due to the importance of agriculture and forestry (Nor-Aini 1995). Other crop and tree systems were introduced gradually such as *Shoreas* with coconut, and *Fragrea* species. Some early research on soil nutrients by Chintu & Zaharah (2003) suggests the ability of *Paraserianthes falcatria* and *Gliricidia sepium* litterfall in enriching maize planted in alley cropping system with N close to 30–40%. Improvements on soil pH, organic matter and nutrients were also recorded. Other researchers tested fertilisers on agroforestry systems in Malaysia but did not explore the possibilities of nutrient removal/inputs, organic matter recycling or symbiotic/antagonistic relationships between agroforestry species (Vimala et al. 2004, Hassan et al. 2004, Ho et al. 2006). Thus despite establishment of agroforestry models, data on these areas are still limited.

The aforementioned possibilities might have catalysed defining research in spearheading agroforestry practices towards the contemporary SDGs. However, the fact that agroforestry embeds three crucial parts, people, planet and profits via providing cultural, ecological and economic benefits is an important land use strategy at present time. Sustainable agro-ecosystems in the humid tropics such as in Malaysia is called for to mimic a closed nutrient cycle with multiple benefits. Agroforestry is also coined as regenerative agriculture due to its capacity to bring into existence again. Regenerative agriculture advocates 5 principles that replicates nature and agroforestry practices such as minimizing tillage, keeping the soil covered, maintaining living roots, maximizing crop diversity and integration of livestocks (Lal 2020). A timeless model that advocates regeneration is a self-sufficient forest. In light of soil fertility, the improved conditions include soil cover, diverse biology and enhancement of nitrogen-carbon fixing processes, water storage and nutrient retention (Sherwood & Uphoff 2000). Common rotational exercises with fruit trees-leafy greens-tubers-leguminous trees are able to improve soil fertility and reduce incidence of pest and diseases (Mohler & Johnson 2009). The renewed dependence on resources such as soil, plants, animals and forests maybe another way for regenerative agriculture, and it will be worthwhile to see how new systems of dual/polyculture may benefit the soil health in Malaysia particularly in plantation settings.

Native timber species

Based on literature review, one of the possible setbacks on the exploration of native timber trees were the mindset of the colonial masters, testing trees more common to their homegrown environments such as *Pinus, Araucarias, Acacias, Eucalyptus and Khayas* in the early 1920s. Carle et al. (2020) reported similarly where there was a predominance to introduce exotic species in the southern hemisphere countries. Although the CFPP included some native species, the current and future market for timber calls for the exploration of other species from *Shorea, Hopea, Dipterocarpus, Drybalanops, Neobalonocarpus* and others to be researched for upstream products, furniture, constructions and many more (Abd-Latif et al. 2019, Ahmad-Zuhaidi 2021). This will hopefully reduce the dependency on rubberwood (*Hevea*) which leads the current timber market in Malaysia.

Smart silvicultural practices

A contextualisation on smart silvicultural practices is needed in the aim of SDGs. Fertilisers, if applied, needs to be well timed, less toxic, well-spaced and applied moderately which will lead to increase in biomass rather that loss in leaching or harvesting residues. For example, P and C removals can be reduced if on site pruning and thinning in plantations are reapplied in forms of wood chips and leaf litter to conserve organic matter, improve rooting and fertility conditions (Jeyanny et al. 2011, Nykvist & Sim 2009). The current trend foresees planted forests in mitigating climate change by acting as a carbon sink. The recent problem on *Ceratocystis* sp. infecting mono species such as *Acacias* can be avoided if other forms of nutrients such as calcium and micronutrients are utilised (Nykvist 1998, Lee 2017). Reports show that calcium and combination of micronutrients assist in increasing the resilience of trees towards infections by improving the lignin content of cell walls of roots in reducing pathogen incidences (Rebitanim et al. 2020, Tengoua et al. 2014). This is also true for improving the leaf thickness of plants, formation of cell walls and membranes for *Khaya senegalensis* seedlings (Jeyanny et al. 2009). Besides nutrients, forest managers have to be vigilant in issues related to iron and aluminum toxicity in acidic soils that can further deteriorate plant health in terms of leaf morphology, photosynthetic activities and overall growth of plants, such as demonstrated by fast growing *Eucalyptus* hybrids in controlled environment (Nguyen et al. 2005).

Forest managers need to be adaptive to new technologies which are revolutionising planted forests such as artificial intelligence (AI) in modulating a forest plantation system incorporating climatic data, geographic information system (GIS), robotics, unmanned aerial vehicles, spectroscopy, nutrient applications and risks of natural/anthropogenic disasters via modelling (Sandino et al. 2018, Crandall et al. 2020). A recent study in rubber plantations in Xishuangbanna, China reported how integrating phenological traits with site variations geographical information system improved the accuracy of mapping plantations according to ecological conditions that influence plant habitat and growth (Yang et al. 2021).

Utilisation of suite of technologies will allow forest managers in selecting timber species with enhanced gene improvement technology via modern genomics and nutrient requirements according to topography, irrigation requirement, canopy cover, soil types, pest and diseases factors and monitoring works for enhanced management towards sustainable forest plantations (Cortes et al. 2020). Thus, this review explains how forest fertilisation changed the façade of tropical forest plantation in Malaysia and the research gaps that needs further explorative studies for nutrition management of planted forests.

CONCLUSIONS

The findings in this paper reports the chronological occurrences of forest fertilisation research in Malaysia, which is the first review to date. It further reaffirms the need to reconsider how forest plantations can be successful, provide a sustainable income to the nation and fits into a circular bioeconomy via several strategies. The concept of fertilising forests needs to be revisited on the notion that early nutrient applications based on their functions are necessary at the planting stage, however judicious intermittent applications are recommended to accelerate growth and to avoid pest and disease attacks that can traumatise the forest plantation industry. Thus, fertilisation trials should go beyond glasshouse and initial stages to capture its benefits in the long term. The timing of fertilisation should also be studied on enhancing reproductive and phenological behaviours of trees. Due to the diverse conditions in field planting, researchers should further device how external factors can be embodied in complementing fertilisation for tree growth, vitality and producing durable timber supply in the long run. Furthermore, renewed researches in improved planting materials, species-site suitability indices, mixed agroforestry systems, rejuvenating soil amendments, embracing the 4th Industrial Revolution by utilising cutting edge technologies and silvicultural transformations is pivotal. It is envisaged that the past trends will be a lesson learnt to prompt a revolutionary paradigm shift for the current and future commercial timber plantations in Malaysia.

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