Review Article

Probing Acid Sulphate Soils for Sustainable Rice Production in Kuttanad: Challenges and Solutions

Abstract

Acid sulphate soils of Kuttanad region in Kerala belongs to the category of problem soils, where crop production can be achieved through extensive soil management. Existence of jarosites, Fe, Al and Mn causes severe acidity in soil, while saline water intrusion due to nearness of sea can add salinity concerns. In addition, these soils were carbon rich with the existence of profound organic matter content, but biased with nutrient status of soil. Hence rice (*Oryza sativa* L.) is difficult to grow in this soil. Apart from the conventional practice of liming, use of organic amendments including rice husk ash, biochar, green manures and more could manage the acidic nature of soil to an extent and impart consistent nutrition without deterioration. Use of newly introduced genetic tolerant varieties, adaption of phyto-mining techniques and other critical land amendment practices can efficiently manage these soils for rice cultivation. The purpose of this review is to comprehend the soil properties and management strategies of acid sulphate soils of Kuttanad in order to produce rice as well as support further researches.

Keywords: Acid sulphate soil, Acidity, Kuttanad soil, Rice, Soil Carbon, Soil management

Introduction

Kuttanad is the region which is identified as the paddy crock of Kerala. This unique agricultural tract stretched out to 854 sq. km lying 0.6-2.2 m below mean sea level (Aparna *et al.*, 2020), and is the largest wetland habitat in India (760 19' to 760 33' E; 90 17' to 90 40' N). The Vembanadu lake, the largest Ramsar site in India, is surrounded by a huge delta formed by five rivers Achenkovil, Pampa, Manimala, Meenachil, and Moovattupuzha, which flow down from the Western Ghats (Raya *et al.*, 2014). Kuttanad is comprised of a diverse range of habitats and fragmented landscapes, including rice fields, rivers, marine overlaid backwaters, ponds, garden lands and marsh lands. Acid saline soils of this region are largely covered with water year-round, and in the summer, it is prone to saltwater intrusion from adjacent lakes and rivers (Neenu *et al.*, 2020).

Around 15000 ha of the rice fields in Kuttanad are consisted of acid sulphate soils, which is Typic Sulfaquent and are considered as extensively problematic farm land (Indira and Covilakam, 2013). Under the soil morphology, Kuttanad soils are categorized into Karappadams (33000 ha), Kayal lands (13000 ha) and Kari lands (9000 ha) (Chattopadhyay and Sidharthan, 1985; Aparna *et al*., 2020). Based on geomorphology, soils, and salinity intrusion, the Kuttanad region is split into six agronomic zones namely north Kuttanad, kayal lands, Vaikkom kari, upper Kuttanad, lower Kuttanad, and Purakkad kari. In accordance with, Raya *et al*. (2014) the key crop of Kuttanad is paddy, and it is farmed mainly in puncha season (November - March). About 20% of the total rice production of Kerala state is reported from Kuttanad. The region is warm and humid, with moderate seasonal temperature variation (21-38°C) and 300 cm of average annual rainfall, 83 percent of which falls during monsoon seasons from June to October and November to January.

As stated by Padmakumar (2013) the Food and Agriculture Organization (FAO) recognized Kuttanad farming community as Globally Important Agricultural Heritage System (GIAHS) for its inventive and traditional farming practices in below-mean sea level environments. Traditional agricultural methods developed and long practiced by pioneering farmers are seen as the most relevant in the current age of global warming along with sea level rise, due to their importance for climate resilience and adaptation.

Nature and properties of Kuttanad soils

The soils of the Kuttanad tract are quite acidic, saline, and rich in organic carbon. The subsoil strata in a few areas of this delta contain pyrites, which when oxidized, produce extremely acidic water (Nath *et al*., 2016). Although the effects of an aquic moisture regime diminish their intensity, waterlogging, acidity, and the toxicity of iron and aluminum still pose dangers to rice farming. The tract is subject to seasonal saline intrusion from the sea during the summer and frequent flooding during the monsoons (Thampatti and Jose, 2000). Soils of Kuttanad (Fig. 1) fall within the Entisols order, the Aquents suborder, the Great Sulfaquents group, and the Typic Sulfaquents subgroup (Beena, 2005). Six soil series reported are Ambalapuzha, Purakkad, Thottapally, Thuravur, Kallara and Thakazhi. The acid sulphate character of the soil as well as the existence of organic debris that has not yet decomposed gives Kari soils in Kuttanad a lower pH. The majority of the organic residue in these soils are ligno-protein complex, which includes significant amounts of lignin, ether and alcohol soluble materials, as well as some cellulose and polyceronoides. It has been found that the Kari soils and the fossilized woods connected to them contain a variety of sulphide and sulphate forms of ions, including free and organically coupled forms (Neenu *et al*., 2020).

Fig. 1. Field view of acid sulphate soil of Kuttanad prepared for rice cultivation

Physical Properties

The color of Kuttanad soils, which ranges from dark brown to black, indicates how rich the soil is in organic matter. The soils have a sub-angular blocky structure, are plastic and sticky, and range in texture from sandy to clayey. Random layers of humus and lime shells are also present (Thampatti, 1997). Kuttanad clay has a specific gravity of 2.02 mg m^{-3} and a maximum dry density of 1.36 mg m^{-3}, with a natural moisture content of 90% but also an ideal moisture content of 33% (Bindhu and Ramabhadran, 2011). The range of bulk density values found in Kuttanad soil was 0.79 - 0.99 mg m^{-3}. The soil in Kuttanad was determined to have a pore water salinity of 4.49 g L^{-1}. The inter-particle forces can be increased by the pore water salinity, which seems to be very high (Suganya, and Sivapullaiah, 2015).

Physical characteristics including water holding capacity, pore space and hydraulic conductivity in Kuttanad soils gradually increase with depth because of high clay and organic carbon content (Thampatti and Jose, 2000). Despite the high clay content in Kuttanad soils, due to the presence of significant amount of organic matter, these soils have high value for hydraulic conductivity. The profile development in this area was also constrained by unusual location of Kuttanad. Nearness to sea caused the effects of tidal incursion and the existence of various rivers led to rivulet deposition during the monsoon season even for a brief time, that have decelerated the alterations in the physical properties.

Chemical Properties

Kuttanad soils had a pH range of 2.5 to 5.2 (Indira and Covilakom, 2013) and there was no clear pattern of variation has observed in chemical characteristics of Typic Sulphaquents. On assessing the current acidity parameters with those recorded during the pre-barrage era (before thannermukkom bund around Kuttanad region), an increase in acidity has noted in post barrage period (Kabeerathumma, 1969; Money and Sukumaran, 1973; Högfors-Rönnholm *et al.*, 2020; Sarangi *et al.*, 2022). The severe acidity of these soils is related to the acid discharge from the sulfuric horizon of acid sulphate soils. In order to reduce the exchangeable acidity of soil, replacement of $A1^{3+}$ with Na^{+} and Mg^{2+} is possible through saline water intrusion in Kuttanad due to the nearness to sea (Thampatti and Jose, 2000; Hue, 2022).

With regard to EC, climate variation changed the tidal and fluvial influence on chemical attributes. Compared to the pre-barrage period, there was a significant drop in the electrical conductivity during the post-barrage duration (Thampatti and Jose, 2000), due to the avoidance of saline water infiltration from the sea, which was the main source of salts. Hence mildly salinized soils have replaced heavily salinized soils and salinity reduced by 90% with CEC for of 8.60 c mol (+) kg^{-1} and AEC of 3.49 c mol (-) kg^{-1} (Arya Lekshmi, 2016). The chemical properties (Table 1) as well as nutritional behavior properties of acid sulphate soils varied after 2018 flood of Kerala (Rohith *et al.*, 2023)

Table 1. Chemical properties of acid sulphate soil

OC	4.66
EC (dS m^{-1})	0.06
OC (%)	3.34
N (kg ha^{-1})	362.5
P (kg ha^{-1})	24.8
K (kg ha^{-1})	185.6
Ca (mg kg^{-1})	480
Mg (mg kg^{-1})	165
S (mg kg^{-1})	16.2
B (mg kg^{-1})	0.52

Fe (mg Kg^{-1})	280
Mn (mg kg^{-1})	2.75
Zn (mg kg^{-1})	1.55
Cu (mg kg^{-1})	1.20

Paddy fields are seen to have high levels of organic carbon, compared to other crops like coconut, which are excellent carbon sinks and produce far less methane (Chacko *et al.*, 2014). Labile carbons serve as an active carbon pool, where soil microbial activity is high and significantly contribute in soil organic carbon quantity and soil quality (Jinbo *et al.*, 2006; Yang *et al.*, 2009). The organic carbon content in acid sulphate soils of Kuttanad ranges between 2.46 and 8.89 percent and the soil organic carbon stock is about 115 mg ha^{-1} while other carbon fractions like water soluble carbon (107 mg kg^{-1}), labile carbon (8.30 mg kg^{-1}), particulate organic carbon (7%), mineralizable carbon (2.5 mg kg^{-1}) and microbial biomass carbon (315 mg kg^{-1}) were reported over the top. Also, organic acid fraction *viz.*, humic acid and fulvic acid are 2.6% and 6.34%, respectively in paddy fields (Gladis *et al.*, 2020).

Biological Properties

Soil metabolism carried out by microorganisms, enable fertility preservation and rice production enhancement with various processes including mineralization of soil organic nitrogen and decomposition of rice, straw and compost added to soil (Kikuchi *et al.*, 2007). Biogeochemistry of wetland paddy soils include biogeochemical cycles, plant nutrient mechanisms, microbial transformations, soil nutrient transformations, pollution removal, heavy metal chemistry, atmospheric exchange and sediment movement (Schoner *et al.*, 2009). Microbial dynamics of rice fields exhibited the presence of 11 bacterial species, whereas 15 species were reported from fish-rice rotational farming soil, in which *Bacillus* spp., *Klebsiella pneumoniae*, *K. oxytoca,* and *Pseudomonas spp*. were the isolates found most often in paddy fields. The isolation of sulfur oxidizing and sulfur reducing bacterias from acid sulphate soils of Kuttanad confirms the establishment of bacterial sulphur cycle, where organic sulphur forms are transformed to sulphuric acid via inorganic sulphides and sulphates. Also, sulfate-reducing bacteria can thrive in anaerobic environments with dissolved sulphate and labile organic carbon (Neenu *et al.*, 2020).

The soil microbial biomass, which makes about 2-4 % of the total carbon pool in rice field belongs to labile carbon, that shows rapid variations in soil (Reichardt *et al.*, 1997) and regulates the breakdown of organic materials and nutrient recycling in soil. Therefore, preservation of viability and functionality of the terrestrial ecosystems are crucial (Dhanya, 2017). On considering the enzyme activity of soil, microbial generated and deposited enzymes (Gianfreda and Ruggiero, 2006) as well as available soil organic matter content (Ikoyi *et al.*, 2020) influence the rate of enzymatic reaction. Water logging conditions similar to acid sulphate soils of Kuttanad affected the activity of multiple enzymes *viz.*, glucoside, amidase, phosphatase, and arylsulphatase (Xiao-Chang and Qin, 2006).

Major constrains in crop production

Monsoon Flood

The topographical features of Kuttanad are unique. Even though rice is considered as the major crop under cultivation, it is not possible to cultivate it during monsoon season as the whole area is submerged for entire season. Since the area is water-logged, cultivation is carried out by enclosing small areas within dykes or bunds after pumping out the water. Following April, due to high tide, saline water intrusion may occur (Jayan and Sathyanathan, 2010) constantly in this region.

Soil Salinity

Accumulation of soluble salts through the periodic saline water inundation and infiltration along with the severe acidity acts as a yield limiting factor of the soil (Devi *et al.*, 2017). After April, sea water entry occurs during hightide causes saline water intrusion (Jayan and Sathyanathan, 2010) with the aggregation of chlorides and sulphates of Ca, Mg and Na ions.

Soil Acidity

Nutrient stress to rice caused by soil acidity (Mandal *et al*., 2003) is a major barrier to rice production. Sulphuric acid development by the oxidation of pyrites keeps the soil reaction below 4.0 (Neenu *et al*., 2020). Formation of acid components is the result of deep penetration of oxygen into iron pyrite layer. As the water table rapidly surged up with the rainfall, Al, Fe and Mn are also brought to the topsoil, which extends the acidity and toxicity limits (Minh *et al*., 1998) and abundance of Fe, Al and Mn may cause P deficiency to plants (Zaidi *et al.,* 2009).

Fe, Al and Mn Toxicity

Kuttanad soils are rich in Fe, Mn and Al concentration. Continuous submergence of Kuttanad soils maintains the concentration of these toxic substances. The extractable and water-soluble Al content of these soils also increased due to the persistence of a pH below 4.5 (Indira and Covilakom, 2013; KAU, 2016). Draining out this toxicated water to the external canals may cause the termination of aquatic organisms (Nair and Pillai, 1990). Typical Fe toxicity symptoms are generally manifested as tiny brown spots starting from the tips and spreading towards the bases of the lower leaves and purple bronzing, yellow, or orange discoloration of the lower leaves may occur (Sahrawat, 2005).

Low Nutrient Content

In the addition to iron and aluminum toxicity and harmful salinity, the deficiency of phosphorus and bases like Ca, Mg, K, Zn, Cu deficiency is the most important problem of acid sulfate soils (Osman and Osman, 2018). The presence of excess quantities of Al, Fe and H in soil had antagonistic effects on bases (Bindraban *et al.,* 2020). The extent of deficiency may vary with parent material and other soil forming factors.

Soil and nutrient management in Kuttanad soils

Reclamation and management of acid sulphate soils cannot be done by one single method, but the integration of both traditional and modern practices made it possible. One among those practices is the application of liming materials and manures. The soil acidity can be reduced to greater extend by liming and leaching, which in turn improve soil productivity. Another technique for managing acid sulphate soil is to avoid disturbing or draining the iron pyrite layer by controlling water table during dry season, so as to curb penetration of oxygen into pyrite layer (Dhanya and Gladis, 2017).

Regulation of nutrients and its application has been carried out over the years, for its effective fulfilment in acid sulphate soils. Among which, soil amelioration against acidic condition should be done first by adopting the practice of liming in Kuttanad and this can enhance the chemical, biological and physical properties of acid sulphate soil (Bolan, 2003, Moran-Rodas *et al*., 2023). Thereby yield limiting factors like low pH and resultant problems such as iron toxicity and reduced availability of other nutrients are resolved. Burnt lime shell (calcium oxide) is considered as the most common liming material used in the conditions of Kerala but on account of cheaper cost, dolomite is also in usage (Devi *et al*., 2017). KAU (2016) has recommended application of dolomite @450Kg ha^{-1} as two splits. In a comparative study on lime and dolomite, Devi *et al*. (2017) pointed out that lime could neutralize the pH effectively, meanwhile dolomite enhances the crop growth and yield. The application of ameliorants enhances the phosphorous availability in soil as well as the application of dolomite, lime or rice husk ash can effectively reduce acidity in very strongly acidic soils of Kuttanad region and also, they can improve soil available Ca and Mg.

Use of Biochar and organic matter application is also followed in Kuttanad soils. Biochar is an organic amendment, with slightly alkaline pH (7.9), therefore in high concentration it can reduce soil acidity and also can be substitute for lime materials (Rodríguez *et al*., 2009; Masulili, 2010). In a comparative study of Padmakumar and Thomas (2013), on the effect of biochar and other selected amendments on rice growth and soil properties, they concluded that biochar application would reduce leaching, increase N retention and P and K availability, enhance microbial biomass, improve water holding capacity, expand soil carbon pool and increase rice yield. Biochar has higher CEC, so it has the ability to supply more Ca, Mg and potassium. In addition, organic matter could supply significant amount of NPK than other amendments. Application of organic matter provides an alkalizing effect in acid sulphate soils than addition of inorganic salts (e.g., Ca_2SO_4). It is well known that carbonic and other organic acids are produced by organic matter oxidation. Commonly used organic matter (OM) sources are plant residues that can improve soil fertility, recycle nutrients and maintain moisture content. OM is cheap and easily available for farmers. Organic compounds such as sodium malate, sodium citrate, calcium oxalate or calcium gluconate can raise soil pH (Yan *et al.,* 1996, Pocknee and Sumner, 1997).

According to Thampatti *et al.* (2005) and Mini and Lekshmi (2021) lime application is the first practice to resolve the Fe-toxicity problems. Also, Thampatti *et al.* (2016), mentioned about phytomining, an exploitation of phytoremediation potential of few promising aquatic macrophytes for the removal of Fe from acid sulphate wetland ecosystems. Conforming to this they found that *Eichhornia crassipes* remove more iron from the ecosystem. In addition, Thampatti *et al.* (2005) studied on the Fe toxicity management by integration of genetic tolerance and nutrition. Integration of genetic iron tolerant rice variety Phalguna with proper nutrition of 150% dose of P and K may enhance rice yield. Influence of liming was significant at higher doses of N P&K fertilizers, indicating the need for a higher level of nutrients for rice in Fe toxic acid sulphate soils.

Continuous P application cause solubilization of adsorbed P, results in high quantity of available P in soil (Koruth *et al*., 2014). Surplus P in soil solution has the potential to cause deficiencies in Zn, Ca, and B (Yuan *et al.*, 2022). In addition to causing these deficiencies, it also contributes to eutrophication, which results from both degraded highland soils and acid sulphate soils below mean sea level, which pollutes water bodies. Insoluble P sources, such as rock phosphate and bone meal, can effectively be used in an acidic upland environment to make up for P deficits (Sureshkumar *et al*., 2018).

Higher K fertilizer application can limit the activity of Fe and Mn in soil solutions and it could boost K absorption (Priya *et al*., 2007). This can be regarded as a useful technique for controlling Fe and Al toxicity. Acidic soils must be limed, which calls for the timely and careful administration of K fertilizers only after the lime has been evenly distributed; otherwise, K absorption will undoubtedly be hampered. The prevalent farming method of incorporating straw into acid sulphate soils in Kuttanad typically improves the K status, hence skipping potassium fertilizers has not been observed to have a negative impact on grain and straw yields. If low K status is noticed before cropping season even after straw incorporation, use of a marginal dosage of K at the rate of 15 kg K_2O ha^{-1} is advised for the crop (Koruth *et al.*, 2014).

Table 2. Management practices for the major constraints in acid sulphate soils.

Major constraints	**Possible Management**	**References**
Monsoon flood	• Irrigation scheduling • Drainage management • Application of organic matter • Alteration in nutrient timing • Optimized plant density • Selection of suitable variety • Application of soil amendments • Establish buffer strips	Osterholm *et al*., 2015; Fitzpatrick *et al*., 2017; Varughese and Mathew, 2023
Soil salinity	• pH management using gypsum (calcium sulfate) • Field margins • Periodic soil monitoring • pH neutralization • Regulate the use of potassic fertilizers • Reduced plant population • Manage the soil EC level	Machado and Serralheiro, 2017; Osman and Osman, 2018; Van Mensvoort and Dent, 2020
Soil acidity	• Lime application (calcium carbonate) • Sulfur management • Application of organic amendments • Avoid prolonged water logging • Buffer strip establishment • Resistant varieties • Regulate the fertilizer application • Controlled irrigation • Neutralize the soil pH	Thampatti e*t al.*, ;2005 Devi *et al*., 2017; Mini and Lekshmi, 2021, Devi *et al.* 2023
Fe, Al and Mn	• Lime amendment	Ganeshamurthy *et al*.,

Toxicity	• Use tolerant crops • Use cover crops • Incorporate antagonists to the soil • Application of organic matter • Use chelating agents • Use phytoremediation techniques	2016; Sureshkumar *et al.*, 2018; Pandey, 2020, Devi, 2021; Ebimol *et al.*, 2023
Low nutrient content	• Liming to increase pH • Organic matter management • Regulate the use of phosphoric fertilizer • Use ammoniacal fertilizers • Reduce the use sulphate fertilizers (or sulphur fertilizers) • Use slow release fertilizers • Application of organic soil amendments • Split application of fertilizers	Mini and Lekshmi, 2021, Devi, 2021, Devi *et al.*, 2023, Rohith *et al.*, 2023

To address the issue of magnesium insufficiency, 80 kg $MgSO_4$ ha^{-1} is recommended (KAU, 2016). To reduce leaching losses, however, this ought to be done in as many splits as feasible or by fertigation. In terms of Sulfur, is present as pyrites and jarosites in acid sulphate soils that have been submerged. Due to sea water inundation, a significant amount of sulphate sulphur is also present in the solution phase in the acid saline soils of Kuttanad during the high tide phase. If these flooded soils are dried, it leads to oxidative reactions which form sulphuric acid (H_2SO_4) and it may result in the production of very acidic soils (Koruth *et al.*, 2014). Due to the development of insoluble sulphides such as chalcocite (Cu_2S), chalcopyrite ($CuFeS_2$), and sphalerite [(Zn, Fe) S] in an anaerobic condition, an excess of sulphur in acid sulphate soil can result in shortages in Zn and Cu (Sureshkumar *et al.*, 2018).

Due to ion competition, excessive amounts of Al, Fe, and Mn in soil solutions can also produce Zn insufficiency. The current suggestion is 20 kg of $ZnSO_4$ per hectare or foliar spraying of a 0.5% $ZnSO_4$ solution (1 kg of $ZnSO_4$ plus 0.5 kg of lime in 200 L of water ha^{-1} to prevent phytotoxicity or 5 g of $ZnSO_4$ plus 2.5 g of lime per litre of water) (KAU, 2016). Additionally, it was observed that applying 20 kg $ZnSO_4$ ha^{-1} to rice in Kuttanad has a residual impact that lasts for five years (Koruth *et al.*, 2014). Acid sulphate soils of Kerala exhibits copper deficiency due to high level of organic matter which forms insoluble complexes with Cu (Kabeerathumma and Patnaik, 1978; Thampatti, 2022). Application of $CuSO_4$ at the rate of 2 kg ha^{-1} is recommended to correct the deficiency. Seedling dip in 1% copper sulphate solution or soaking of seeds in 0.25% copper sulphate solution is recommended for rice (KAU, 2016). Acid sulphate soils of Kuttanad are deficient in boron due to boron sorption or occlusion on the surfaces of iron and aluminum oxide (Sanyal and Bhattacharyya, 2012). Application of 10 kg ha^{-1} of borax is recommended in case of deficiency (KAU, 2016).

Along with the fore mentioned practices, there are certain other techniques, that can be followed in acid sulphate soils of Kuttanad (Table 2). In addition to them, Shrimbs are grown in flooded soils of Kuttanad along with rice to make use of brackish water and to compensate the losses of rice due to flooding. This system keeps the sulphitic material flooded and thereby stops acid generation (Xuan, 1993). This arrangement also reduces the production cost of rice since the soil is soft and clean (Jayan and Sathyanathan, 2010).

Future line of work

The researches on problematic soils, particularly acid sulphate soils are constrained due to the lack of information, even though these soils have great research opportunities in crop production. On considering the long running research potential of acid sulphate soil there are different opportunities to establish, such as

1. Mapping of acid sulphate soils for more accurate predictions and NDVI approaches (Estévez *et al.*, 2023).
2. Creation of cost-efficient approaches for large scale characterization (Nyman *et al.*, 2023).
3. Researches on customized slow release fertilizers to improve nutrient release and delivery in soil (Rohith *et al.*, 2023).

4. Finding the management prospects for carbon neutrality of the particular region.
5. Machine learning models to predict the pH, carbon and nutrient toxicity of these soils.
6. Statistical approaches to identify variables predicting sulphide clays, nutrient bias and ionic exchange factors of the soils.

Conclusion

Kuttanad is a region lying below mean sea level with a unique acid sulphate soil, where rice is the major crop under cultivation. Kuttanad is cited for its diverse soil characters and model farming systems. These soils are rich with acid forming components which keeps the soil pH below 4.5 and also sea water intrusion increased the salt content in soil. Strong acidity may result in toxicities of Al, Fe, soluble salts, Mn and H_2S contents, which limits rice growth and other nutrient uptakes. Soil organic matter and carbon pools are also significantly influenced soil quality and availability of nutrients. There are several studies on distinct constrains in rice production *viz*., salinity, acidity, flood, nutrient toxicity and more, that directs towards their approach on crop production limitation as well as deterioration of soil nutrient status, microbial population and genetic qualities. In order to effectively manage the constrains, integrated approaches as well as organic approaches are commonly followed in Kuttanad region. Scientifically proven methods are also existing in the current scenario, but lacking acceptance in between common people. Even though various methods are followed by the natives, liming is the most well undertaken practice. Split application of fertilizers along with regulated nutrient selection and supply helped to enhance the nutrient status of the soil. These studies on nature and characteristics of Kuttanad soils can support the knowledge development on effective handling of management techniques in acid sulphate soils.

Declaration of Competing Interest

The authors report no conflict of interest

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