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Expansion of Planted Forests: The Risk of Pesticides Mixtures

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Abstract: Planted forests include forests established through human planting or deliberate seeding. They are systems that offer us timber and non-timber forest products and ecosystem services, such as wildlife protection, carbon sequestration, soil, and watershed maintenance. Brazil has 7.6 million hectares of planted forests, with 72% of the total area occupied by *Eucalyptus* spp. A favorable climate and management and genetic improvement research are the main factors responsible for high productivity. In recent years, the expansion of planted areas has been accompanied by the commercial release of several pesticides, mainly herbicides. A recent change in the Brazilian legislation allows mixing phytosanitary products in a spray tank, having a new approach to managing pests, diseases, and weeds. Antagonism is the main risk of tank mixes, and to reduce the dangers associated with this practice, we review all products registered for growing *Eucalyptus*. This literature review aims to identify the effects of product mixtures registered for *Eucalyptus* reported for other crops. In addition, environmental and social risk assessment has been widely adopted to export wood and cellulose, making the results of this review an indispensable tool in identifying the nature and degree of risks associated with pesticides. The results classify the effects of the mixtures as an additive, antagonistic or synergistic. The use of pesticide tank mixtures has the potential for expansion. However, there are still challenges regarding variations in the effects and applications in different climatic conditions. Therefore, studies that prove efficient mixtures for the forest sector are essential and the training of human resources.

Keywords: acaricides; Brazilian forests; fungicides; herbicides; insecticides

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1. Introduction

Global forests planted with *Eucalyptus* spp. (mostly *Eucalyptus grandis* W. Hill, *Eucalyptus saligna* Sm., *Eucalyptus urophylla* S.T.Blake, *Eucalyptus viminalis* Labill. and the hybrid *E. grandis* × *E. urophylla*) occupy approximately 20 million hectares, with high economic expressiveness, mainly in tropical and subtropical regions [1,2]. Brazil accounts for 38% of the world's cultivated area, and *Eucalyptus* plantations continue to expand [3,4]. Concomitantly with the increase in planted areas, there was an increase in the release of pesticides.

According to the Ministry of Agriculture, Livestock, and Supply (MAPA), 173 formulated products are registered for *Eucalyptus* cultivation, with 3, 6, 15, and 76% of the products being acaricides, fungicides, insecticides, and herbicides, respectively [5]. The approval of new pesticides by MAPA requires knowledge of their isolated effects and possible interactions in tank mixtures.

Pesticide mixtures have been used to pest control simultaneously and reduce management costs [6,7]. Legalizing this practice occurred with the Normative Instruction No. 40 (11 October 2018), which establishes that professionals in the field can prescribe the technique, as long as the agronomic prescription contains the name of the products, incompatibility data, and the indicated culture [8]. The document also states that the recommendation will consider the available scientific information.

The risks associated with tank mixtures mainly concern physical and chemical incompatibility and knowledge of synergistic, antagonistic, and additive interactions among the compounds [9]. In addition, the pursuit of sustainable production in the forestry sector lacks research on the impact of pesticide mixtures [7].

Forest certification is a tool for sustainable forest management [10]. Forests certified with the "Forest Stewardship Council—FSC" system produced 23% of the world's total volume of round wood in 2017 [11]. Within the FSC system is the Pesticide Policy, with three main pillars: classifying chemical compounds as dangerous, restricted, or highly restricted; carrying out an environmental and social risk assessment, and monitoring the use and damage caused by pesticides [12].

Large amounts of pesticides on crops, alone or in mixtures, can cause resistance in agricultural and forestry areas. Thus, in addition to the risks of using these products related to their toxicity, another point that must be considered is the risk of selecting biotypes resistant to pesticides.

Resistance is the capacity acquired by a plant to survive the registered dose of a pesticide that, under normal conditions, would be efficient to control the other members of the same population. The repeated use of products with the exact mechanism of action to control pests, diseases or weeds, in the same crop cycle over the years, without adopting alternative management practices, is the main reason for selecting resistant biotypes in agronomic crops in Brazil. There are still no reports of cases of resistance in Brazilian forest areas. Still, the risk has already been reported, considering the number of pesticides used without the proper rotation of products [13].

Because of the expressive release of *Eucalyptus* crop pesticides, the risks associated with using tank mixtures, and the adoption of sustainable forest management practices, this review sought to verify the effects of pesticide mixtures registered for *Eucalyptus* and described for other crops.

2. Tank Mixing in Brazil

The operational costs of pesticide application are remarkably high [14], resulting in approximately 97% of farmers opting for the joint application of phytosanitary products [14]. For this, pesticides are combined directly in the spray tanks, reducing the entry of machines into the site and, consequently, the cost of application [15]. However, mixing in tanks must be done with care because not all pesticides are compatible. Mixing can alter the pH and electrical conductivity and cause physical incompatibility [16,17], reducing the culture's productivity [18].

Until 2018, the responsibility for mixing agrochemicals rested solely with the farmer. However, the Normative Instruction No. 40 (12 October 2018), MAPA established criteria and procedures to recommend tank mixtures and their prescriptions by professionals in the field [8]. This is because prior knowledge of product compatibility is necessary to guarantee the method's efficacy [17]. In addition, mixtures can cause harmful effects to the environment if they contaminate non-target organisms [19].

In addition to the isolated effects of pesticides, there are risks from the mixture of products, so the growing approval of pesticides in Brazil is a reason for warning. Pesticides classes and similar registrations reached 474 in 2019, more than 4 times 10 years earlier. One hundred and forty-nine pesticides released in Brazil are banned in the European Union [20]; among these, atrazine, and acephate are some of the best sellers in Brazil [21].

The Normative Instruction No. 112 (8 October 2018), MAPA identified *Digitaria insularis*, *Digitaria horizontalis*, *Panicum maximum*, *Brachiaria decumbens*, and *Brachiaria brizantha* as priority pests of phytosanitary and economic importance for *Eucalyptus* cultures. Normative Instruction No. 112 focuses on registering new herbicides for *Eucalyptus* spp. [22]. Consequently, the Brazilian market today has 133 commercial herbicide formulations registered for use in *Eucalyptus*, representing a 200% increase from those reported in 2015 [5,23].

There are 173 registered products in *Eucalyptus* culture, 76% of which belong to the herbicide class [5]. Accordingly, the possibilities of mixtures within this class are more significant than insecticides, fungicides, and acaricides. The registered herbicides have grown significantly in recent years, mainly because of the need to combat difficult species in *Eucalyptus* spp. [22].

Among the herbicides registered for *Eucalyptus* cultures, 32 products are used to control grasses, particularly *Brachiaria* spp. and *Digitaria* spp. (Table 1) [5]. In addition to isolated products, herbicide tank mixtures are used for broader weed control, but these mixtures are not always satisfactory. For instance, mixtures between glyphosate and atrazine are less effective in controlling *Brachiaria* regrowth than isolated products [24].

Reports on pesticide mixtures aimed at forest areas are scarce, but determining these mixtures' effects when applied to crops may help guide management actions.

Table 1. Herbicides registered for the *Eucalyptus* culture are recommended for grass control.

Active Ingredient	Controlled Grass Species
Carfentrazone-ethyl (triazolinones) + clomazone (isoxazolidinones)	*Digitaria horizontalis; Brachiaria plantaginea; Eleusine indica*
Clethodim (cyclohexanediones) + Haloxyfop-P-methyl (aryloxyphenoxypropionates)	*Digitaria insularis; Brachiaria decumbens; Panicum maximum; Digitaria horizontalis; Brachiaria brizantha*
Clomazone (isoxazolidinones)	*Digitaria horizontalis; Cynodon dactylon; Eleusine indica; Brachiaria plantaginea*
Diuron (Ureas) + Sulfentrazone (triazolinones)	*Brachiaria decumbens*
Flumioxazin (N-phenylphthalimides)	*Panicum maximum*
Glufosinate-ammonium (Phosphinic acids)	*Panicum maximum; Melinis minutiflora*
Glyphosate (glycine)	*Sorghum halepense; Andropogon bicornis; Andropogon leucostachyus; Avena sativa; Axonopus compressus; Brachiaria decumbens; Brachiaria plantaginea; Bromus catharticus; Cenchrus echinatus; Cynodon dactylon; Digitaria horizontalis; Digitaria insularis; Echinochloa crusgalli; Eleusine indica; Hyparrhenia rufa; Lolium multiflorum; Melinis minutiflora; Panicum cayennense; Panicum maximum; Paspalum conjugatum; Paspalum dilatatum; Paspalum maritimum; Paspalum maritimum; Paspalum urvillei; Pennisetum clandestinum; Rhynchelytrum repens; Saccharum officinarum; Setaria geniculata; Setaria poiretiana*
Glyphosate-dimethylamine salt (glycine)	*Sorghum halepense; Digitaria insularis; Andropogon bicornis; Andropogon leucostachyus; Avena sativa; Axonopus compressus; Brachiaria decumbens; Brachiaria plantaginea; Bromus catharticus; Cenchrus echinatus; Cynodon dactylon; Digitaria horizontalis; Echinochloa crusgalli; Eleusine indica; Guadua angustifolia; Hyparrhenia rufa; Lolium multiflorum; Melinis minutiflora; Panicum cayennense; Panicum maximum; Paspalum conjugatum; Paspalum dilatatum; Paspalum maritimum; Paspalum notatum; Paspalum paniculatum; Paspalum urvillei; Pennisetum clandestinum; Rhynchelytrum repens; Saccharum officinarum; Setaria geniculata; Setaria poiretiana*

Table 1. *Cont.*

Active Ingredient	Controlled Grass Species
Glyphosate-ammonium (glycine)	*Avena strigosa*; *Brachiaria brizantha*; *Brachiaria decumbens*; *Brachiaria plantaginea*; *Cenchrus echinatus*; *Cynodon dactylon*; *Digitaria horizontalis*; *Digitaria insularis*; *Echinochloa crusgalli*; *Eleusine indica*; *Lolium multiflorum*; *Panicum maximum*; *Panicum maximum*; *Paspalum conjugatum*; *Paspalum notatum*; *Paspalum paniculatum*; *Saccharum officinarum*; *Sorghum bicolor*
Glyphosate-di-ammonium (glycine)	*Brachiaria brizantha*; *Brachiaria decumbens*; *Brachiaria plantaginea*; *Cenchrus echinatus*; *Chloris polydactyla*; *Digitaria horizontalis*; *Digitaria insularis*; *Digitaria sanguinalis*; *Echinochloa colona*; *Echinochloa crusgalli*; *Eleusine indica*; *Oryza sativa*; *Panicum maximum*; *Saccharum officinarum*
Glyphosate-isopropylammonium (glycine)	*Cynodon dactylon*; *Digitaria horizontalis*; *Digitaria insularis*; *Echinochloa crusgalli*; *Eleusine indica*; *Hyparrhenia rufa*; *Lolium multiflorum*; *Melinis minutiflora*; *Oryza sativa*; *Panicum cayennense*; *Panicum maximum*; *Panicum maximum*; *Paspalum conjugatum*; *Paspalum dilatatum*; *Paspalum maritimum*; *Paspalum notatum*; *Paspalum paniculatum*; *Paspalum urvillei*; *Pennisetum clandestinum*; *Rhynchelytrum repens*; *Saccharum officinarum*; *Setaria geniculata*; *Setaria poiretiana*; *Sorghum halepense*; *Sorghum halepense*; *Andropogon bicornis*; *Andropogon leucostachyus*; *Avena sativa*; *Axonopus compressus*; *Brachiaria decumbens*; *Brachiaria plantaginea*; *Bromus catharticus*
Glyphosate-isopropylammonium (glycine) + Glyphosate-potassium (glycine)	*Brachiaria decumbens*; *Brachiaria plantaginea*; *Digitaria horizontalis*; *Eleusine indica*; *Cynodon dactylon*
Glyphosate-potassium (glycine)	*Brachiaria decumbens*; *Avena strigosa*; *Cenchrus echinatus*; *Cynodon dactylon*; *Digitaria horizontalis*; *Echinochloa crusgalli*; *Eleusine indica*; *Luziola peruviana*; *Oryza sativa*; *Pennisetum americanum*; *Saccharum officinarum*; *Brachiaria plantaginea*
Haloxyfop-P-methyl (aryloxyphenoxypropionates)	*Brachiaria brizantha*; *Brachiaria decumbens*; *Lolium multiflorum*
Indaziflam (alkylazine)	*Brachiaria decumbens*; *Brachiaria brizantha*; *Digitaria horizontalis*; *Panicum maximum*; *Digitaria insularis*
Indaziflam (alkylazine) + Iodosulfuron-methyl-sodium (sulfonylureas)	*Brachiaria decumbens*
Isoxaflutole (isoxazoles)	*Cenchrus echinatus*; *Eleusine indica*; *Brachiaria plantaginea*; *Brachiaria decumbens*; *Panicum maximum*; *Digitaria horizontalis*
Isoxaflutole (isoxazoles)	*Brachiaria plantaginea*; *Panicum maximum*; *Brachiaria decumbens*; *Eleusine indica*; *Cenchrus echinatus*; *Digitaria horizontalis*
Oxyfluorfen (diphenylethers)	*Digitaria horizontalis*; *Cenchrus echinatus*; *Eleusine indica*
Pendimethalin (chloroacetamides)	*Panicum maximum*; *Brachiaria decumbens*; *Digitaria horizontalis*; *Brachiaria plantaginea*
Pyroxasulfone (chloroacetamides)	*Brachiaria plantaginea*; *Brachiaria decumbens*; *Digitaria horizontalis*; *Panicum maximum*
Pyroxasulfone (pyrazol) + Flumioxazin (N-phenylphthalimides)	*Cenchrus echinatus*; *Digitaria horizontalis*; *Brachiaria decumbens*; *Brachiaria plantaginea*; *Panicum maximum*
S-Metolachlor (chloroacetamides) + glyphosate (glycine)	*Panicum maximum*; *Brachiaria decumbens*
Sulfentrazone (triazolinones)	*Brachiaria plantaginea*; *Pennisetum setosum*; *Panicum maximum*; *Digitaria horizontalis*; *Cenchrus echinatus*; *Brachiaria decumbens*; *Echinochloa crusgalli*; *Eleusine indica*
Sulfentrazone (triazolinones)	*Pennisetum setosum*; *Panicum maximum*; *Eleusine indica*; *Echinochloa crusgalli*; *Digitaria horizontalis*; *Cenchrus echinatus*; *Brachiaria plantaginea*; *Brachiaria decumbens*; *Echinochloa crusgalli*

Source: AGROFIT, 2021 [5].

3. Forest Stewardship Council

The forest certification system Forest Stewardship Council (FSC) is one of the most internationally recognized in the sector [25] to assure consumers that timber products originate from well-managed forests that respect the principles and criteria of environmental, social, and economic aspects focused on sustainability [26]. In Brazil, the planted area certified by the FSC is 1.5 million hectares [27]. Some of the biggest non-compliance problems for FSC certification are environmental impact and risk monitoring and evaluation [28].

The Pesticide Policy is part of the FSC's Principles and Criteria for forest certification and has been revised to incorporate a risk-based approach to pesticide use [12]. In this case, the danger of the active ingredient is considered and the circumstances under which chemical pesticides can be used [12]. The Pesticide Policy is based on the following considerations: (a) hazardous pesticides are identified and categorized as prohibited, highly restricted, or restricted according to their degree of danger; (b) integrated pest management identifies the need to use a permitted chemical pesticide as a measure of last resort, an environmental and social risk assessment (ARAS) is carried out at different levels to identify the nature and degree of risk together with mitigation measures and monitoring requirements; (c) the policy highlights the importance of repairing and compensating for any damage to environmental values and human health and of monitoring both pesticide use and the impact of the policy itself [12].

The FSC certification policy restricts the use of pesticides that are dangerous to human health and the environment, classified as prohibited products, highly restricted products, or restricted products [12] (Tables 2 and 3). There are 48 products prohibited in certified areas, including acetochlor, alachlor, captafol, carbofuran, DDT, paraquat, and others [12]. The highly restricted product list comprises 120 deltamethrin, bromoxynil, carbaryl, diquat, isoprocarb, and permethrin [12]. The list of local products is even longer with 221 pesticides, some widely used in Brazil, such as 2,4-D, atrazine, diuron, ammonium glufosinate, glyphosate, imidacloprid, and picloram [12].

The growing awareness of the world population on humanity's future has led to the search for innovations that make the means of production more sustainable in various sectors of society [29]. Accordingly, FSC certification is a tool for enhancing eco-labels, as it seeks to improve awareness of environmental impacts, increase stakeholder participation, and improve eco-efficiency [30]. Discussions of the FSC's role in the sustainable forest industry are centered around the possibility of playing a role in forest governance to promote and articulate its potential contributions [28].

Table 2. List of pesticides registered for *Eucalyptus* cultivation in Brazil and their classification by the Forest Stewardship Council—FSC.

Herbicide	Toxicity Class *	PAM **	FSC Classification
2,4-D-triethanolamine + picloram-triethanolamine	5	AM	Restricted
Carfentrazone-ethyl	5	IPO	Unclassified
Clethodim	5	IACC	Unclassified
Clomazone	5	IMA	Unclassified
Chlorimuron-ethyl	5	IAS	Unclassified
Diuron	5	PSII I	Restricted
Flumioxazin	5	IPO	Restricted
Fluroxypyr-meptyl + triclopyr-butotyl	4	AM	Unclassified
Glufosinate-ammonium	5	IGS	Restricted
Glyphosate	5	IESPS	Restricted
Haloxyfop-P-methyl	4	IACC	Restricted
Indaziflam + iodosulfuron-methyl-sodium	5	ICS + IAS	Unclassified
Isoxaflutole	5	IHPD	Restricted

Table 2. *Cont.*

Herbicide	**Toxicity Class ***	**PAM ****	**FSC Classification**
Oxyfluorfen	4	IPO	Restricted
Pendimethalin	4	IMA	Restricted
Pyroxasulfone	5	VLFASI	Unclassified
Saflufenacil	5	IPO	Unclassified
S-Metolachlor	4	VLFASI	Unclassified
Sulfentrazone	5	IPO	Unclassified
Insecticide	Toxicity class *	PAM **	FSC Classification
Acetamiprid	4	AA	Restricted
Bifenthrin	2	SCM	Highly restricted
Bifenthrin + acetamiprid	3	SCM + AA	Restricted
Carbosulfan	2	IEA	Prohibited
Chlorfenapyr	4	UOPDPG	Highly restricted
Deltamethrin	4	SCM	Highly restricted
Etofenprox	4	SCM	Restricted
Fipronil	3	GAA	Restricted
Imidacloprid	4	AA	Restricted
Lufenuron	5	ICB	Restricted
Tebufenozide	Unclassified	EA	Unclassified
Teflubenzuron	Unclassified	ICB	Restricted
Thiamethoxam	5	AA	Unclassified
Zeta-cypermethrin + bifenthrin	3	SCM	Highly restricted
Acaricide	Toxicity class *	PAM **	FSC Classification
Bifenthrin	2	SCM	Highly restricted
Carbosulfan	2	IEA	Prohibited
Chlorfenapyr	4	UOPDPG	Highly restricted
Chlorfenapyr	4	UOPDPG	Highly restricted
Fungicide	Toxicity class *	PAM **	FSC Classification
Acibenzolar-S-Methyl	Unclassified	PDI	Unclassified
Azoxystrobin + difenoconazol	5	RI + ISB	Unclassified
Cyproconazol	5	ISB	Highly restricted
Difenoconazole	4	ISB	Unclassified
Mancozeb	5	MA	Restricted
Metconazole	5	ISB	Unclassified
Metiram + pyraclostrobin	4	MA + RI	Restricted
Pyraclostrobin	4	RI	Restricted
Tebuconazole	5	ISB	Unclassified
Trifloxystrobin	5	RI	Restricted

* Toxicity class according to the manufacturers: (1) extremely toxic, (2) highly toxic, (3) moderately toxic, (4) slightly toxic, and (5) unlikely to cause acute harm. ** Pesticide Action Mechanism (PAM). Source: AGROFIT, 2021; FSC, 2019 [5,12].

Table 3. List of pesticide action mechanisms.

Pesticide Action Mechanism (PAM)			
HERBICIDES	Inhibition of Cellulose Synthesis—ICS	FUNGICIDES	Sodium Channel Modulators—SCM
Auxin Mimics—AM	Inhibition of Hydroxyphenyl Pyruvate Dioxygenase—IHPD	Plant defense inducers—PDI	Inhibitors of the Enzyme Acetylcholinesterase—IEA
Inhibition of Acetoacetate Synthase—IAS	Very Long-Chain Fatty Acid Synthesis inhibitors—VLCFASI	Inhibition of sterol biosynthesis—ISB	Gamma-AminoButyric Acid Agonist—GAA
PSII inhibitors—PSII I	ACARICIDES	Multi-site Activity—MA	Inhibitors of the Chitin Biosynthesis—ICB
Inhibition of Protoporphyrinogen Oxidase—IPO	Sodium Channel Modulators—SCM	Respiratory Inhibitor—RI	Ecdysteroid Agonists—EA
Inhibition of Glutamine Synthetase—IGS	Inhibitors of the Enzyme Acetylcholinesterase—IEA	INSECTICIDES	Uncouplers of oxidative phosphorylation via disruption of the proton gradient—UOPDPG
Inhibition of Enolpyruvyl Shikimate Phosphate Synthase—IESPS	Uncouplers of oxidative phosphorylation via disruption of the proton gradient—UOPDPG	Acetylcholine Agonist—AA	
Inhibition of Acetyl CoA Carboxylase—IACC			

Source: AGROFIT, 2021 [5].

4. Effects of Pesticide Tank Mixtures

Mixing pesticides in a spray tank is a common technique among farmers, but some unexpected effects can occur depending on the type of interaction between the products. Exchanges can be additive when the mixing efficiency of the products is similar to the application of each product; synergistic when the mixture of products presents better results than the isolated application, and antagonistic when the mix of products is worse than each one applied [31].

In agricultural systems, interactions among pesticide mixtures have been established [6], but there is a lack of reports in the forestry sector, more in *Eucalyptus* crops. Therefore, information on pesticides used in crops also recorded for *Eucalyptus* can be a viable solution to fill this gap.

In herbicide mixtures, 72% of those found in the literature include glyphosate. Mixtures with glyphosate were the most cited as antagonistic, corresponding to 12 of the 19 reported (Table 4). Among the alternatives for the efficient control of weeds, mixtures of glyphosate with ethyl carfentrazone, clethodim, chlorimuron-ethyl, fluazifop-butyl, flumioxazin, haloxyfop, quizalofop, and saflufenacil had synergistic effects (Table 4). Among these, glyphosate, flumioxazin, and haloxyfop are restricted by FMC [12] (Table 2), while the others are not classified in any risk category.

The challenges of tank mixtures go beyond the combination of active ingredients, as the same mixtures can have different results, as observed for glyphosate plus 2,4-D (Table 4). These differences may be related to edaphoclimatic variations, dosages used, or species controlled, allowing antagonistic and synergistic interactions for the same product combination.

Table 4. Results of the interaction of herbicide mixtures registered in Brazil for the *Eucalyptus* crop, when used in other crops.

Herbicide 1	Herbicide 2	Herbicide 3	Crop/Weed	Interaction	Source
2,4-D	Clethodim		*Digitaria insularis*	Antagonistic	[32]
		Quizalofop		Additive	
	Quizalofop			Antagonistic	
Atrazine	Metolachlor		*Oryza sativa*	Synergistic	[33]
Clomazone	Alachlor		*Gossypium hirsutum*	Additive	[34]
				Synergistic	[35]
	Diuron			Additive	[36]
	Oxyfluorfen			Synergistic	
	Trifluralin			Additive	
		Diuron		Additive	
Fluazifop-butyl	2,4-D		*Zea mays*	Antagonistic	[36]
	Glyphosate			Additive	
	Glyphosate + 2,4-D			Additive	
Fluazifop-p-butyl	Flumioxazin		*Manihot esculenta*	Synergistic	[37]
	Isoxaflutole			Synergistic	
Glufosinate-ammonium	Saflufenacil		*Amaranthus palmeri*	Synergistic	[38]
Glyphosate	2,4-D		*Ricinus communis*	Synergistic	[39]
			Commelina benghalensis	Additive	[40]
			Cyperus rotundus	Additive	[41]
			Eucalyptus spp.	Synergistic	[42]
Glyphosate	2,4-D		*Zea mays*	Antagonistic	[43]
	Atrazine		*Urochloa plantaginea*	Antagonistic	[24]
		Flumioxazin		Additive	
	Carfentrazone-Ethyl		*Commelina benghalensis*	Synergistic	[40]
			Manihot esculenta	Additive	[44]
			Ipomoea hederifolia	Synergistic	[45]
				Additive	[46]
			Eucalyptus spp.	Additive	[47]
			Commelina benghalensis	Antagonistic	[48]
	Clethodim		*Digitaria insularis*	Additive	[49]
			Leptochloa virgata	Synergistic	[50]
			Bidens pilosa	Antagonistic	
			Digitaria insularis	Synergistic	[51]
			Lolium multiflorum	Additive	[52]
	Clomazone		*Manihot esculenta*	Additive	[44]
	Chlorimuron-ethyl		*Commelina benghalensis*	Additive	[53]
			Crotalaria ochroleuca	Antagonistic	[54]
			Glycine max	Additive	[55]
		Flumioxazin		Synergistic	
			Commelina benghalensis	Additive	[56]
			Manihot esculenta	Additive	[44]
	Fluazifop-butyl		*Cynodon dactylon*	Synergistic	[57]
			Leptochloa virgata	Synergistic	[50]

Table 4. *Cont.*

Herbicide 1	Herbicide 2	Herbicide 3	Crop/Weed	Interaction	Source
Glyphosate	Fluazifop-butyl		*Bidens pilosa*	Antagonistic	[50]
			Lolium multiflorum	Additive	[52]
	Flumioxazin		*Manihot esculenta*	Additive	[44]
			Urochloa plantaginea	Synergistic	[24]
			Commelina benghalensis	Antagonistic	[48]
	Haloxyfop		*Zea mays*	Additive	[58]
			Cynodon dactylon	Synergistic	[57]
			Digitaria insularis	Synergistic	[59]
		2,4-D	*Digitaria insularis*	Antagonistic	[59]
			Digitaria insularis	Additive	[49]
	Metribuzin		*Manihot esculenta*	Additive	[44]
			Cyperus rotundus	Antagonistic	[41]
	Oxyfluorfen		*Commelina benghalensis*	Antagonistic	[48]
	Quizalofop		*Lolium multiflorum*	Synergistic	[52]
	Saflufenacil		*Commelina benghalensis*	Synergistic	[40]
			Ricinus communis	Synergistic	[60]
			Brachiaria decumbens	Additive	[61]
			Conyza bonariensis	Synergistic	[62]
			Ipomoea hederifolia	Synergistic	[45]
			Amaranthus hybridus	Antagonistic	[63]
				Additive	[46]
			Conyza bonariensis	Synergistic	[64]
			Lolium multiflorum	Synergistic	[52]
Glyphosate	Sulfometuron		*Glycine max*	Antagonistic	[65]
Glyphosate-ammonium	Clethodim		*Digitaria insularis*	Additive	[66]
	Haloxyfop			Synergistic	
	Quizalofop			Additive	
Glyphosate-isopropylammonium	Clethodim			Additive	
	Haloxyfop			Synergistic	
	Quizalofop			Synergistic	
Glyphosate-potassium	Clethodim			Synergistic	
	Haloxyfop			Synergistic	
	Quizalofop			Additive	
	Carfentrazone		*Oryza sativa*	Additive	[67]
	Saflufenacil			Additive	
Isoxaflutole	Acetolachlor		*Zea mays*	Additive	[68]
Oxyfluorfem	Haloxyfop		*Digitaria insularis*	Antagonistic	[49]
Quizalofop	Carfentrazone		*Oryza sativa*	Additive	[67]
Quizalofop	Linuron		*Vigna unguiculata*	Synergistic	[69]
Quizalofop	Saflufenacil		*Oryza sativa*	Synergistic	[67]
Saflufenacil	Clomazone		*Euphorbia heterophylla*	Synergistic	[70]
Saflufenacil	Clomazone		*Oryza sativa*	Additive	[71]

In most cases, mixtures between insecticides have synergistic interactions with greater pest control (Table 5). Only bifenthrin combined with acephate and imidacloprid had an antagonistic effect on the control of *Lygus lineolaris* Palisot de Beauvois, 1818 (Hemiptera:

Miridae) [72]. The antagonistic effect of bifenthrin, combined with its highly restricted classification by the FMC [12], is the basis for avoiding its mixtures.

Insecticides mixed with herbicides exhibited additive and synergistic interactions. Mixtures such as glyphosate plus acephate, atrazine plus novaluron, and 2,4-D with chlorpyrifos-ethyl, fipronil, methomyl, and novaluron, performed well (Table 6). Acaricides mixed with insecticides exhibit additive and antagonistic interactions. Mixtures of spirodiclofen with lambda-cyhalothrin + thiamethoxam, phosmet, and thiamethoxam can be used to reduce application costs without enhancing pest control (Table 7).

Insecticides mixed with fungicides have an additive effect (Table 8), except for the combination of chlorothalonil with abamectin. The fungicide addition caused reduced efficacy against *Thrips tabaci* Lindeman, 1889 (Thysanoptera: Thripidae) [73].

The interactions of mixtures among the analyzed fungicides were not negative, and the product combination enhanced the antifungal action of the product. Synergistic effects were obtained by combining propiconazole with iprodione, vinclozolin, mancozeb, and carbendazim with folpet (Table 9). However, only mancozeb is registered for *Eucalyptus* in Brazil and has a restricted classification for use in areas certified by the FSC [5,12]. When combined with herbicides, fungicides do not result in antagonistic interactions (Table 10) and can be applied together to reduce operating costs. However, 40 of the mixtures reported as additives use glyphosate, which is highly restricted by the FSC [12].

Table 5. The interaction of insecticide mixtures registered in Brazil for the *Eucalyptus* crop when used in other crops.

Insecticide 1	Insecticide 2	Crop/Insects	Interaction	Source
Bifenthrin	Acephate	*Lygus lineolaris*	Antagonistic	[72]
	Dicrotophos		Synergistic	
	Imidacloprid		Antagonistic	
	Thiamethoxam		Synergistic	
Deltamethrin	Dichlorvos	*Glycine max* (*A. gemmatalis*)	Synergistic	[74]
Imidacloprid	Acephate	*Apis mellifera*	Additive	[75]
	Cyhalothrin		Additive	
	Oxamyl		Synergistic	
	Thiodicarb	*Sorghum bicolor*	Synergistic	[76]
Lambda-cyhalothrin	Chlorantraniliprole	*Anthonomus grandis*	Synergistic	[77]
Lufenuron	Profenofos	*Glycine max* (*A. gemmatalis*)	Synergistic	[78]
Spiromesifen	Imidacloprid	*Bemisia tabaci*	Synergistic	[79]
Thiamethoxam	Chlorantraniliprole	*Myzus persicae*	Synergistic	[80]
	Lambda-Cyhalothrin		Synergistic	

Table 6. The interaction of mixtures of herbicides and insecticides registered in Brazil for the *Eucalyptus* crop when used in other crops.

Herbicide 1	Herbicide 2	Insecticide	Crop/Weed	Interaction	Source
2,4-D		Chlorpyrifos-ethyl	*Zea mays*	Synergistic	[58]
		Fipronil	*Saccharum officinarum*	Synergistic	[81]
		Methomyl	*Zea mays*	Synergistic	[58]
		Novaluron		Synergistic	
		Permethrin		Additive	
Atrazine		Chlorpyrifos-ethyl		Additive	
		Lufenuron		Additive	[82]
		Methomyl		Additive	[58]
				Additive	[82]
		Novaluron		Synergistic	[58]
		Permethrin		Additive	

Table 6. *Cont.*

Herbicide 1	Herbicide 2	Insecticide	Crop/Weed	Interaction	Source
Glufosinate-ammonium	2,4-D	Lambda-cyhalothrin	*Glycine max*	Additive	[83]
				Additive	
Glyphosate		Acephate	*Gossypium hirsutum*	Synergistic	[84]
		Carbosulfan		Additive	
		Endosulfan		Additive	
		Imidacloprid		Additive	
	2,4-D	Lambda-cyhalothrin	*Glycine max*	Additive	[83]
				Additive	
Glyphosate		Lambda-cyhalothrin	*Gossypium hirsutum*	Additive	[84]
Sulfentrazone		Imidacloprid	*Allium cepa*	Additive	[51]

Table 7. The interaction of insecticide and acaricide mixtures registered in Brazil for the *Eucalyptus* crop when used in other crops.

Insecticide	Acaricide	Crop/Insect	Interaction	Source
Bifenthrin	Spirodiclofen	Citrus	Antagonistic	[85]
Cypermethrin			Antagonistic	
Imidacloprid		*Diaphorina citri*	Antagonistic	[86]
		Citrus	Antagonistic	[86]
Lambda-cyhalothrin + thiamethoxam		*Diaphorina citri*	Additive	[86]
Phosmet			Additive	
		Citrus	Antagonistic	[85]
Thiamethoxam		*Diaphorina citri*	Additive	[86]

Table 8. Results of the interaction of mixtures of fungicides and insecticides registered in Brazil for the *Eucalyptus* crop, when used in other crops.

Fungicide	Insecticide	Crop/Insect	Interaction	Source
Azoxystrobin + benzovindi-flupyr	Methomyl	*Glycine max*	Additive	[87]
Azoxystrobin + cyproconazole	Triflumuron	*Spodoptera frugiperda*	Additive	[88]
Azoxystrobin	Abamectin	*Thrips tabaci*	Additive	[73]
Chlorothalonil	Abamectin	*Thrips tabaci*	Antagonistic	[73]
Iprodione			Additive	
Mancozeb			Additive	
Pyraclostrobin + fluxapyroxad	Lambda-Cyhalothrin	*Glycine max*	Additive	[89]
Tetraconazole	Imidacloprid	*Apis mellifera*	Synergistic	[75]
Tebuconazole	Thiacloprid	*Aphelinus abdominalis*	Synergistic	[90]
Trifloxystrobin + propiconazole	Methomyl	*Glycine max*	Additive	[87]

Table 9. Results of the interaction of fungicide mixtures registered in Brazil for the *Eucalyptus* crop, when used in other crops.

Fungicide 1	Fungicide 2	Fungus	Interaction	Source
Mancozeb	Carbendazim	*Colletotrichum acutatum*	Synergistic	[91]
	Folpet		Synergistic	
Propiconazole	Chlorothalonil	*Sclerotinia homeocarpa*	Additive	[92]
	Iprodione		Synergistic	
	Vinclozolin		Synergistic	

Table 10. The interaction of mixtures of herbicides and fungicides registered in Brazil for the *Eucalyptus* crop when used in other crops.

Herbicide 1	Herbicide 2	Fungicide	Crop/Weed	Interaction	Source
2,4-D		Azoxystrobin + propiconazole	*Triticum aestivum*	Additive	[93]
		Propiconazole + trifloxystrobin		Additive	
	Glufosinate	Pyraclostrobin	*Glycine max*	Additive	[83]
	Glyphosate			Additive	
			Triticum aestivum	Additive	[93]
		Tebuconazole		Synergistic	
Glufosinate		Pyraclostrobin	*Glycine max*	Additive	[83]
Glyphosate		Azoxystrobin	*Panicum texanum*	Additive	[94]
		Pyraclostrobin		Additive	
			Glycine max	Additive	[83]
		Tetraconazol	*Panicum texanum*	Additive	[94]
				Additive	

5. Perspectives for the Forestry Sector Regarding Tank Mixtures

The SWOT analysis addresses strengths, weaknesses, opportunities, and threats. It is a tool for strategic planning [95] and can be used to summarize the current state of tank mixing techniques in the forest sector (Figure 1). Mixing pesticides in tanks is a common technique among farmers, and results are available for crops. This technique in the forestry sector is still developing, but it can expand given its advantages. Based on advances in Brazilian legislation on the use of pesticides and the evolution of phytosanitary practices, tank mixtures can provide several benefits in the management of pests, diseases, and weeds in *Eucalyptus* cultures, such as reduction of operating costs and a decrease in the entry of machines in the area. Together, this results in more significant soil conservation, saving water for solutions, and, in some cases, enhancing pesticide efficacy.

Moreover, pesticide classification by the FSC contributes to the intended use of the products, considering the risks to the environment and human health. At the same time, product mixtures considered to be of restricted use, regardless of their category as listed in this review, can be applied through environmental and social risk analysis (ARAS), which makes this paper an essential tool for scientific, technical consultation.

Some challenges are related to the lack of proven results for efficient mixtures of phytosanitary products in the forestry sector. In addition to targeting the sector's exclusive pesticides, future studies should consider mixtures with fertilizers. The effect variation indicates the need for specific research with foresters, considering different climate and soil conditions and control species. Furthermore, the results reported may vary depending on the applied dosages and non-compliance with the application technology. The lack of trained professionals in the field to assess the effects of mixtures limits the use of this technique. Therefore, practical human resources training and evaluation of results among pesticide mixtures when the method is expanding are essential to direct the actions of forestry companies in Brazil.

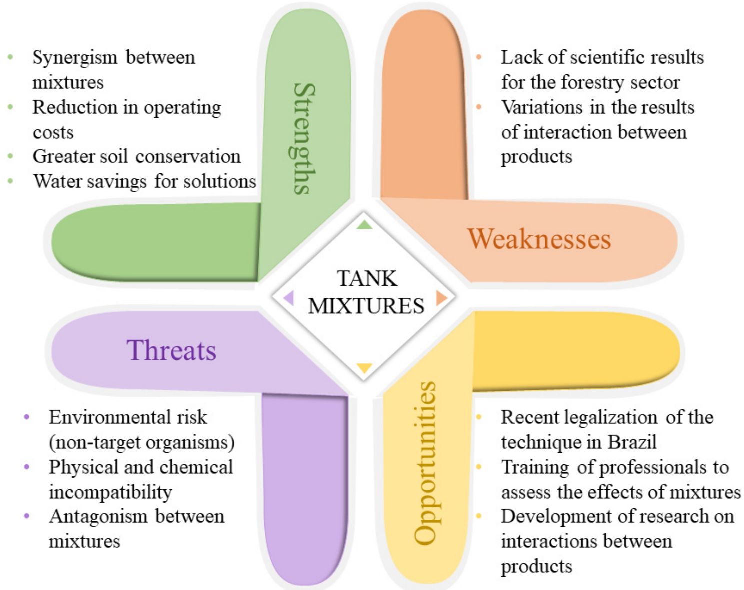

Figure 1. The SWOT analysis summarizes the current status of the tank mixing technique in the forestry sector.

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