PREFACE

Seed health and protection are the first essential steps in the reliable production of economically viable crops. Seed treatment, whether by chemical, physical or biological means, continues to be a vital input into today's agricultural and horticultural production systems.

Since the second symposium on seed treatments held at the University of Kent, Canterbury in 1994, the continuing changes in both technologies and markets have had a significant impact on the treatment of seeds. The loss of organo mercurials and lindane, for example, has accelerated the development and adoption of alterations and advances in new fungicide chemistry are beginning to increase the range and scope of seed treatments, embracing seed protection and influencing the longer term health of crop plants.

Alternative chemicals and the adoption of physiological techniques to enhance crop establishment, are more widely employed. The adoption too, of crop production protocols following the principles of integrated crop management and the increased interest in non-chemical seed treatments and organic production are all having an effect on the use of existing products and the introduction of new ones.

Seed health has long been considered as an important issue in crop establishment. In recent years, the economic changes affecting agriculture and horticulture, have influenced the financial inputs of crop production. A particular consequence of this has led to an increased usage of farm-saved seed. This has raised concerns regarding seed health. Advancement in the speed and accuracy of detection methods should encourage a greater use of seed testing.

Seed treatments need an accurate method of application and this area has warranted a degree of attention with some satisfactory results. But the development of all technologies is then dependent on the successful introduction into the market place. Regulatory authorities are also meeting the challenges of change and a greater degree of harmonisation between countries of the various regulatory requirements for the registration of new products is being felt.

Therefore, this third BCPC Seed Treatment Symposium brings together the current knowledge of seed treatment technology, covering a wide range of major and minor crops. The theme of Challenges and Opportunities is very evident in the range of contributions presented in these Proceedings. The contents provide an important discussion forum for all involved in research, development, application, advice and use of seed treatments.

A J Biddle
Chairman, Symposium Programme Committee

SESSION 1
KEYNOTE PRESENTATION

Chairman and Session Organiser: Dr P Halmer
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Seed treatment technologies: evolving to achieve crop genetic potential

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ABSTRACT

This paper provides a wide-ranging survey of new developments and trends in seed treatment technologies during the last decade, and identifies future directions. The major crops that benefit from the use of seed treatment are cereals, maize, cotton, potatoes, oilseed rape and sugar beet. Seed treatments are being transformed from commodity to high-value status. Active ingredients such as tebuconazole, triticonazole, fludioxonil, silthiofam, imidacloprid, thiamethoxam and fipronil, are providing a broader spectrum of activity and longer-lasting control of diseases and pests in early crop growth stages, better toxicological and ecotoxicological profiles. Modern seed treatment products demand accurate application techniques and quality assurance systems to optimise efficacy, crop safety, and the cost/benefit ratio for the grower. There is increasing interest in the research of germination-enhancement techniques and the role of the seed as delivery vehicle for additional crop inputs. These developments in seed treatments are taking place alongside changes in crop production systems and genetic technologies, and in response to the demands of consumers and growers for environmentally-friendly crop production methods, including non-synthetic crop-protection agents.

INTRODUCTION

Seed treatment is an inherent part of efficient crop production systems. There is no doubt that sophisticated crop protection and nutrition, based on an array of management tools such as herbicides, fungicides, insecticides, genetic protection traits and optimised fertilizer regimes, are critical in the production of food for the growing world population, on a stagnating or decreasing area of arable land, and in accordance with regulatory requirements and Society's needs for sustainable agriculture. Seed treatment in particular, whether by chemical, physical or biological means, continues to be a vital input into today's agricultural and horticultural production systems for the reliable production of economically viable crops.

Seed quality and seed protection are two essential inputs into starting a crop. Seed quality comprises physical and genetic purity, health, viability and vigour. These quality criteria are basically determined by seed production, processing and storage conditions. The protection of seeds and young seedlings against the action of diseases and pests is the primary objective of seed treatment. Seeds may already be contaminated by seed-borne diseases, which start to attack the seed or the germinating or emerging seedling in the planting environment: seedlings and young plants are put further at risk by a variety of soil-borne early-season diseases and pests. However in its broader sense, seed treatment comprises a portfolio of technologies whose objectives are to deliver crop enhancements as well as crop protection - applying bioactive compounds, functional agents like seed coatings, germination enhancements, beneficial microorganisms, micro-nutrients, phytohormones or herbicide safeners, and using specifically-engineered application systems.

In contrast to foliar sprays or granules, where farmers apply the products onto the soil or an already-established crop, seed treatment products are presented in value-added packages with the seed variety. Seed treatment technology is highlighted by these unique features:

- efficient application of the product on the target plant
- reduction of the product load per hectare
- continuous delivery to the plant from a "treatment halo" zone around the seed
- uniform plant-to-plant loading
- the convenience of application in controlled seed-treatment facilities.

Seed treatments are dependent on co-operation between the seed industry and the seed treatment manufacturer.

This paper reviews recent developments, and identifies future directions, in the area of seed treatment, regarding active ingredients, products, formulations and application technologies, and the influences of changing agricultural practices, seed-industry needs and the social and regulatory environment.

In his keynote review paper at the last BCPC Seed Treatment Symposium, Schwinn (1994) challengingly asked whether seed treatment might ultimately become a panacea for crop protection. Certainly, the seven years since then have proved long and eventful, at the pace of change in today's industry. Many new seed products and genetic traits have been developed and introduced into the market. The key players in the seed-treatment business are more or less the same but they have undergone major structural changes, through many mergers and acquisitions. The seed-breeding world too has changed dramatically in similar ways. Meanwhile, the Internet is revolutionizing communication and business relationships, seed customers' and farmers' expectations regarding seed quality are increasing, regulatory requirements are getting tougher and consumers are demanding high-quality products fitting environmentally-compatible production systems.

THE WORLD SEED TREATMENT AND SEEDS MARKET

The world seed-treatment market has a share of ca. 3% of the total crop protection market and is the only segment showing annual growth, at rates of ca. 4-5% compared with the flat performance of the overall crop protection market. With the ongoing introduction of new products for existing and new markets this growth dynamic is expected to continue. In the future growth may come from crops like soybeans and rice that have low treatment rates today, and also from new technologies. In absolute terms the seed-treatment segment had an estimated value of ca. US $800 - 900 M in 2000, dominated by fungicides (58%) followed by insecticides (26%) and mixtures thereof (16%). Seed treatment insecticides have gained a major market share in the past decade, when the corresponding proportions were 76%, 12% and 12% (Schwinn, 1994). From a crop point of view the major markets are cereals (40%), followed by maize (15%), oilseeds (12%), rice (7%), potatoes (7%), sugar beet (6%) and cotton (5%).

Worldwide seed consumption for all crops, including farm-saved seed, had an approximate value of US $30-35 billion in 2000. The commercial market, of which field crops comprise about half, is about 30-50% of this total. The growth of the world seed market will be greatly influenced by the acceptance and continuous introduction of "high-tech" varieties such as hybrids and those with genetic traits that prevent disease or pest attack, tolerate specific herbicides or deliver new agronomic quality traits.

THE REQUIREMENTS OF THE SEED INDUSTRY

For seed treatments to be successful they must provide the seed industry (the commercial customer) and/or the farmer (the end-user) with these specific features:

- Biological activity against diseases and pests
- Convenience in the production of treated seeds
- Good laboratory and field germination performance
- Enhanced germination rate/emergence/uniformity in stressful environments
- Accurate plantability of treated seed with different planting equipment
- Ability to carry-over treated seeds
- Heat and humidity stability without breakdown
- Handling safety
- Visual attractiveness
- Inventory management
- Value added service for growers
- Profitability
- Availability for export (worldwide registrations for the worldwide seed trade)

Table 1. Major historical milestones in chemical seed treatment in the 20th century.

Decade	Event
1920s	Disease control through organic compounds (organo-mercury)
1940s	Introduction of the first seed treatment insecticide (lindane) Introduction of first broad-spectrum seed treatment fungicides (thiram)
1960s	Introduction of first systemic fungicidal seed treatment for seed-borne pathogens (carboxin) Introduction of first broad spectrum seed treatment insecticides (carbofuran)
1970s	Introduction of first systemic seed treatment fungicides for air-borne pathogens (triadimenol, ethirimol) Introduction of metalaxyl for air-borne downy mildew and soil-borne *Pythium spp.* control
1980s	Introduction of tefluthrin as a pyrethroid for seed treatment Ban of mercury-based products in EU countries
1990s	Introduction of new low-rate fungicidal compounds (fludioxonil, difenoconazole, tebuconazole, triticonazole) Introduction of new broad-spectrum insecticides (imidacloprid, fipronil, thiamethoxam) Ban of lindane in EU

Chemical seed treatment was historically the first effective technology developed to control and prevent diseases and pests that damage the crops grown for human consumption and animal feed production. Major milestones in the 20^{th} century are summarised in Table 1. The 1990s were a remarkable decade, which saw the introduction of four important new seed treatment fungicides and three revolutionary seed treatment insecticides.

SEED TREATMENT FUNGICIDES

Fungicidal seed treatments are used predominantly for the following four reasons:

- control of soil-borne fungal pathogens causing seedling blights and root rots, seed rots and pre- and post-emergence damping-off
- control of fungal disease organisms carried on the surface or deep inside the seed
- support of the over-wintering capacity of the young seedling by maintaining a healthy root system and defending its energy reserves against fungal competition for a strong regrowth in spring
- control of early season diseases.

Table 2. Introduction of new fungicidal active ingredients in the 1990s and those currently in prospect from 2000 onwards.

Decade	Chemical Class	Active Ingredient	Company
1990s	Triazoles	tebuconazole	Bayer
		triticonazole	Aventis
		difenoconazole	Syngenta
		flutriafole	Syngenta
		diniconazole	Sumitomo
	Phenylpyrrole	fenpiclonil	Syngenta
		fludioxonil	Syngenta
	Phenylamide	metalaxyl-M	Syngenta
	Benzotriazine	triazoxide	Bayer
	Anilinopyrimidines	cyprodinil	Syngenta
		pyrimethanil	Aventis
	Propanecarboxamide	carpropamid	Bayer
>2000	Quinazoline triazole	fluquinconazole	Aventis
	Hindered silyl amine	silthiofam	Monsanto
	Aminoacid-amide carbamate	iprovalicarb	Bayer
	Imidazolinone	fenamidone	Aventis
	Strobilurin	azoxystrobin	Syngenta
	Benzothiadiazole	azibenzolar-methyl	Syngenta
	Triazole	simeconazole	Sankyo

For the control of the well-known range of seed treatment targets like *Microdochium nivale*, *Pythium spp.*, *Ustilago spp.*, *Tilletia spp.* and *Drechslera spp.* a broad spectrum of active ingredients continues to be available. Table 2 gives an overview of the most important recent compound introductions for seed treatment and an outlook for the coming years. All these modern molecules are the result of investments in screening and development of the research-driven crop protection companies. Besides having favourable mammalian and environmental toxicity profiles, these new compounds are low-rate technologies and offer different mode of actions. Tebuconazole provides loose smut control in cereals with 1-3 g a.i./100kg seeds and metalaxyl-M prevents *Pythium* attack with only 1 g a.i./100kg seeds in maize. Fludioxonil is used on cereals at rates of 5 g a.i./100kg seeds for snow mould and seedling blight control; leaf stripe on barley is controlled with 5 g a.i./100kg and 2 g a.i./100kg seeds with the anilinopyrimidine and benzotriazine compounds, respectively.

The control of *Fusarium* species remains a challenging target. A major break-through was achieved in the early 1990s with the introduction of fludioxonil, which has a unique mode of action (Pillonel & Meyer, 1997) never used before in crop protection. With its penetration into the seed, "halo" formation characteristics and limited translocation into the subterranean part of the hypocotyl, fludioxonil is the current standard for the control of seed- and soil-borne *Microdochium*, *Fusarium, Septoria & Cochliobolus spp.*, which cause damping-off leading to poor plant emergence. Fludioxonil also prevents stem-base browning and snow mould during winter, ensuring a healthy overwintering of the wheat seedlings and a good plant stand in spring (Gehmann *et al.*, 1990; Edwards *et al.*, 1998).

Tebuconazole, triticonazole and difenoconazole are the most prominent representatives of triazole chemistry that are used as seed treatments. The triazoles are the only modern chemical class that offer loose smut control, with tebuconazole giving the best. Beside this unique activity, different triazoles have particular strengths. Triticonazole for example can be applied at exceptionally high rates (for a triazole) of up to 120 g a.i./100kg seeds without any crop tolerance problems, and shows some activity against early-season diseases on the leaves of young seedlings. Difenoconazole has broad-spectrum control properties and provides, in combination with metalaxyl-M, control of foot rot and root rot diseases in extensive cereal production systems. Metalaxyl-M, which belongs to the well-known chemical class of phenylamides, and is the result of intensive chemical engineering to select the active enantiomer, offers unique activity for the control of various *Pythium spp.* and downy mildew on peas, sunflower, maize, oilseed rape and vegetables. The anilopyrimidines, cyprodinil and pyrimethanil, and the benzotriazine, triazoxide, are important combination partners for the control of seed-borne *Drechslera graminea* on barley. Carpropamid belongs to the chemical class of propenecarboxamide and is a new introduction for the control of *Pyricularia oryzae* on rice (Thieron *et al.*, 1998).

New molecules currently being introduced in various countries are fluquinconazole (chemical class: quinazoline triazole) (Löchel *et al.*, 1998) and silthiofam (hindered silyl amine) (Beale *et al.*, 1998). Both offer for the first time the possibility of suppressing take-all, caused by the fungus *Gaeumannomyces graminis f. sp. tritici*, through seed treatment. Fluquinconazole has also some suppressive effects on air-borne diseases like rusts and leaf spots (e.g. *Septoria tritici*). Additional interesting compounds that are diversifying the activity spectrum include iprovalicarb (an aminoacid-amide carbamate), fenamidone (an imidazolinone), azoxystrobin (a strobilurin) and azibenzolar-methyl (a benzothiadiazole). The strobilurins offer the opportunity to control early foliar diseases, but this has to be considered and evaluated in the context of resistance management schemes. Azoxystrobin sets a new standard for *Rhizoctonia solani* control in various crops (e.g. cotton and soybean). Azibenzolar-methyl is a new technology inducing the plant's auto-defence mechanisms (Ruess *et al.*, 1996).

Examples of potential new targets for seed treatment are listed in Table 3. Control of these diseases with existing technologies is either only partial or is not available at all. In addition to unsolved problems there is a continual need to search for new compounds to combat resistance issues as soon they appear.

Table 3. Potential new targets for seed treatment fungicides.

Target (pathogen)	Crop(s)
Soil-borne Diseases	
Gaeumannomyces graminis	wheat
Rhizoctonia cerealis	cereals
Pseudocercosporella spp.	cereals
Polymyxa graminis	cereals
Rhizoctonia solani	sugar beet
Sclerotinia spp.	soybeans
Peronospora spp.	soybeans
Sudden Death Syndrome	soybeans
Phomopsis spp.	soybeans
Spacelotheca reiliana	maize
Fusarium oxysporum	(various)
Verticillium spp.	(various)
Thielaviopsis basicola	cotton
Plasmodiophora brassicae	vegetables
Air-borne Diseases	
Erysiphe graminis	cereals
Puccinia spp.	cereals
Septoria spp.	cereals
Drechslera spp.	cereals
Rhynchosporium secalis	cereals
Claviceps spp.	cereals/sorghum
Cercospora zea-maydis	maize
Pyricularia oryzae	rice
Downy mildews	(various)
Bacterial diseases	(various)

SEED TREATMENT INSECTICIDES

The seed treatment insecticide market has been largely dominated since the early 1940s by organochlorines (lindane), carbamates (carbofuran, furadan, furathiocarb) and pyrethroids (beta-cyfluthrin, tefluthrin). Representatives of these chemistries were for a long time the active ingredient of choice to control soil-dwelling insects. Some carbamates also provided control for early-season pests on the foliage up to 10-15 days after planting. But lindane is now banned as a seed treatment in many countries (e.g. Germany, France, UK) and soon will be withdrawn in others (e.g. Canada), and the carbamates too are coming increasingly under regulatory pressure. New compounds recently introduced into the market for seed treatment insect control are listed in Table 4.

Table 4. Introduction of new insecticidal active ingredients in the 1990s and those currently in prospect from 2000 onwards.

Decade	Chemical Class	Active Ingredient	Company
1990s	Neonicotinoid	imidacloprid thiamethoxam	Bayer Syngenta
	Phenylpyrazole	fipronil	Aventis
>2000	Neonicotinoid	clothianidin acetamiprid	Bayer (Takeda) Aventis (Nissan)

A breakthrough in seed treatment insect control in the past decade has resulted from the discovery of the neonicotinoids by Bayer (Elbert *et al.*, 1990). The neonicotinoids can be subclassified into chloronicotinyl, thianicotinyl and nitromethylene compounds. Imidacloprid, acetamiprid and thiacloprid belong to the chloronicotinyl subclass whereas thiamethoxam (Senn *et al.*, 1998) and clothianidin are representatives of the thianicotinyl subclass (Yamamoto & Casida, 1999).

This chemical class of compounds has allowed, for the first time, the protection of seeds and young seedlings not only against a large number of soil-dwelling insects but also against a broad spectrum of early leaf-feeding and leaf-sucking insect pests. The physico-chemical features of the neonicotinoids ensure their fast uptake by the germinating seed and young seedling. At the recommended use rates the re-distribution of the neonicotinoid compounds in the foliage provides control for up to 40 days after planting against aphids, thrips, whiteflies, leafminers and various other pests. This control of virus-vectoring aphids by seed treatment has proved to be of outstanding value both to growers and the environment. Imidacloprid has been on the market since 1991 and has achieved broad acceptance in many crops and countries, e.g. sugar beet in Europe, cereals in France and cotton in India. Thiamethoxam is currently under worldwide development and registration, and its first market introductions have been mainly in Latin American countries. Recent registrations were granted in canola, cotton, wheat and sorghum in Canada and the USA.

Neonicotinoid chemistry apart, only fipronil (Gaulliard, 1996), which is a representative of the phenylpyrazole class, has gained importance in recent years as a seed-treatment insecticide, especially for the control of soil-living insect pests in France, USA, Brazil and Australia for example.

The introduction of new insecticidal seed treatments has led to a substantial reduction of chemical inputs into the environment on an area basis, either by lowering treatment rates on seeds or by replacing foliar sprays and granular applications in some crops. For example the replacement of lindane-based products in the Canadian canola crop with thiamethoxam-based formulations will reduce the amount of a.i. used per ha by about 70-80%. A further advantage of the neonicotinoids is their favourable toxicological and ecotoxicological profile.

For the future, some important early-season pest problems offer exciting challenges and opportunities for research, innovation and market development (Table 5).

Table 5. Some potential new targets for control by seed treatment insecticides.

Target (pathogen)	**Crop(s)**
<u>Soil-dwelling insect pests</u>	
Corn root worm	maize
Root maggots	canola/oilseed rape, sugar beet
Cutworms	maize
<u>Early leaf-feeding/sucking insect pests</u>	
Lepidopteran pests	cotton, soybean, vegetables
Coleopteran pests	canola/oilseed rape, cotton
Thrips, White Flies, Leaf Hoppers	various (e.g. cotton, vegetables)
<u>Nematode pests</u>	
Soybean cyst nematode	soybean
(Various)	cotton
Root knot nematode	vegetables (e.g. tomatoes)

SEED TREATMENT WITH BIOLOGICALS

In the past decade considerable resources have been allocated to research into natural organisms as biological control agents (BCAs) for the control of plant diseases, either through inoculating them onto seeds, drenching the seed bed or spraying onto leaves. Seed treatment research is mainly focusing on beneficial microbes, both bacteria (e.g. actinomycetes) and fungi, which can either act as synergists for plant growth promotion (where they are better classified as functional treatments) or as antagonists to control soil-borne and superficial seed-borne pathogens, through the mechanisms of parasitism, antibiosis, competition and induced resistance (Baker, 1991; Harman & Nelson 1994; Rhodes & Powell, 1994; Koch, 1996). Special interest exists in finding organisms which can close activity gaps for pathogens that are difficult to control by chemical tools, or that can offer synergism with agrochemicals or help manage resistance to them, and for specific user needs like organic farming. A major hurdle in the commercialisation of economically viable BCAs lies in translating benefits from the laboratory or greenhouse to the field (Scheffer, 1994). In controlled plant-growth conditions the requirements of natural organisms regarding temperature, soil moisture, soil texture and competition with other micro-organisms can be more easily met than under open field conditions where the efficacy of BCAs is quite variable and inconsistent. In general BCAs have to fulfil the same requirements as agrochemicals regarding biological activity, product quality, registration and economy to fit into cost-effective crop protection management systems. Some examples of BCAs used as seed treatments (Fravel & Larkin, 1996) are listed in Table 6.

Table 6. Examples of commercialised Biological Control Agents (BCAs).

Biological Control Agent	Product	Target(s)	Crop(s)
Pseudomonas fluorescens	Biocoat	*Fusarium oxysporum*	raddish
Bacillus subtilis	Kodiak	*Fusarium spp.* *Rhizoctonia solani*	cotton
Bacillus subtilis	FZB 24	*Rhizoctonia solani*	potatoes
Trichoderma spp.	(Various)	soil-borne diseases	various
Pseudomonas chlororaphis	Cedomon	seed-borne diseases	cereals
Gliocladium virens	GlioGard	soil-borne diseases	vegetables
Streptomyces griseoviridis	Mycostop	soil-borne diseases	vegetables

Despite the limited commercialisation of such BCAs to date, research is ongoing in the selection and screening of new strains of already evaluated genera. Other new directions are:

- induction of plant auto-defence mechanisms against diseases and insect pests
- induction of the heat-shock protein pathway for heat-, drought-, salt and cold-stress tolerance
- selection of Plant Growth Promoting Rhizobacteria (PGPR)
- evaluation of *Mycorrhiza spp.* strains to improve nutrient uptake by roots

For the agrochemical industry naturally-occurring organisms, such as bacteria and fungi, are also valuable sources of new classes of active chemicals, whose activity might be optimised by synthetic means. One recent commercial example that was developed through this approach is fludioxonil, which is chemically related to the natural antibiotic pyrrolnitrin. Other natural derivates are the insecticides abametin/emamectin (*Streptomyces avermitilis*), spinosad (*Saccharopolyspora spinosa*) and the fungicides azoxystrobin, kresoxim-methyl and trifloxystrobin (*Strobilurus tenacellus*).

FUNCTIONAL SEED TREATMENTS

Functional seed treatments are defined as materials and processes that are applied to enhance the performance of seed, as distinct from controlling diseases and pests. They include coating and pelleting products (see next section) and also the following:

Film-Coating Polymers and Colorants
Phytohormones

- Micro-nutrients
- *Rhizobia*
- Priming
- Seed-Lot Upgrading

Polymers and colorants are used in film-coating technologies either to enhance the appearance and attractiveness of treated seeds, to reduce the dust-off of agrochemicals, to support the biological activity or to improve the plantability of seeds (even flow in the drill). Colorants also serve as codes to differentiate seed companies or varieties (e.g. with the introduction of transgenic seeds), to enhance the attractiveness of high quality seed and to facilitate warehouse/inventory management. Polymer coating technologies can also manipulate the germination of seeds, e.g. to differentiate the flowering phase in hybrid seed production. Seeds can be drilled prior to the optimal sowing time but the polymer delays the germination until favourable soil moisture or temperature conditions occur. A technology to facilitate hybrid production in maize was recently introduced in the USA under the brand IntelliCoat.

Phytohormones are under research to enhance the germination of small-seeded vegetables (Powell & Matthews, 1988). They will also play a major role in the development of synthetic seeds, which will facilitate the propagation of some species (e.g. sugarcane and sweet potato, where the production of zygotic seeds is difficult) or the hybridisation of species like rice, soybeans, cotton or trees (Cantliffe, 1997).

For some soils (e.g. Latin America, USA, France) it is of benefit to add micronutrients to the seed (e.g. zinc, copper, manganese, molybdenum) to overcome critical deficiencies in the early growth of crops.

In legumes (e.g. soybean) it is quite common to add nitrogen-fixing *Rhizobia* strains to the seed to enhance fertilisation of the plants. Research is on-going by some specialized companies to select better *Rhizobia* strains for nitrogen-fixation and to improve the survival of the bacteria on inoculated seeds.

Seed priming is a technology that stimulates the seed's metabolic processes to ensure a rapid, uniform and high level of germination, which leads to fast seedling emergence and establishment. Several methods (e.g. mannitol or polyethylene glycol osmotica) are now commonly used to prime some high-value seeds (e.g. tomato, leek, onion and carrot). Seed priming is an evolving technology and, due to cost constraints, is currently limited to high-value seeds. Enhancing the economic value by built-in traits may also increase the attractiveness of this technology for large-volume crops like soybean, maize or oilseed rape.

Comprehensive reviews of seed technology were recently published by McDonald (2000), Halmer (2000) and Hill (1999).

DELIVERY SYSTEMS TO THE SEED

Various coating techniques, which are applied as functional treatments to enhance germination performance or change seed handling properties, can also be used to incorporate chemical, biological or functional seed treatment products, for delivery to the germinating seed and young seedling. These techniques are:

- Dressing or Treatment
- Film-coating
- Coating/Encrusting
- Pelleting

Seed dressing or treatment is the basic application technology for chemical or biological seed treatment products. Film-coating polymers are also now quite widely used to apply treatment products, apart from their use in applying colorants for the purposes mentioned above. Research into the application of polymers onto seed has the objective to manipulate the release of active ingredients to the germinating seed either to reduce the risk of phytotoxicity or to act as a slow release depot for the active ingredient over time.

Seed coating and encrusting adds several layers of materials such as fillers, polymers, colorants: the seed shape is still visible but the seed gains some weight. Seed pelleting adds greater proportions of material to shape the seeds for better performance in planting or drilling machines. Both processes are used to apply crop protection agents to seeds. Further research will directed to multi-layering technologies to engineer the delivery of active ingredients to the germinating seed or young plant, to co-apply active ingredients with incompatible physico-chemical characteristics, to combine chemical with biological seed treatments, to improve the stability of the pellet against mechanical stress and to enhance the uptake of water and oxygen during the germination process.

SEED TREATMENT FORMULATIONS

The purposes of formulation research in seed treatment are to make the active ingredients applicable to the seed; to adhere the product to the seed, minimising its abrasion to secure activity; to reduce worker/user exposure (an aspect obtaining increasing attention by the authorities); to improve penetration into the seed surface tissues and to foster uptake of active ingredients by the germinating seed and their translocation into the stem and foliage in early growth stages. Seed treatments come in a variety of formulations: dusts (DS), wettable powders (WS), true liquid formulations (LS), water-based flowables (FS) and formulations with microencapsulated active ingredients (CS). The current trend continues to be towards water-based formulations due to their user-friendliness and regulatory constraints. In general, seed treatment formulation technology is an empirical science, which is strongly influenced by the physical/chemical features of the compounds and only little information is in the public domain.

Future directions of research will aim at the improvement of formulation stability regarding storage behaviour and mechanical stress tolerance to valves and pumps in the application equipment. Treatment applicators will expect that formulations are easier to measure and to clean up after using equipment. A continuing challenge for research will be the distribution of low amounts of straight or diluted formulations evenly onto seeds. Other areas of interest are formulation inerts, which can improve the bioavailability, and hence activity at reduced rates. Inerts have to fulfil increasing regulatory requirements, just as active ingredients do. This will trigger increasing investments into research for new inerts suitable to improve the performance of formulations and the contained bioactive compounds.

THE CHALLENGE OF APPLICATION AND QUALITY ASSURANCE

Seed treatment products are applied either on an industrial scale by seed companies and specialised service providers, or on-farm by the farmer. The challenge of application is often to apply low volumes of an undiluted or diluted formulation onto a very small and uneven surface, and apply them as evenly as possible from seed to seed. For example, depending on the thousand-grain weight, wheat and maize have surface areas of ca. 80 m^2 and ca. 40-60 m^2/ 100kg seed respectively. Poor application processes may impact negatively the cost/benefit ratio for both the seed treater and the farmer. Calibration of the treatment equipment is the most critical part of the treatment process. Over-treatment may injure the seed, and under-treatment may not provide the expected disease or pest control. This has become especially important with low-rate but high-value fungicides and insecticides, which use only very small amounts of active material per unit of seed.

The current application technology for large-seeded crops is mainly based on continuous-flow processes/equipments. Batch treatment systems, already used for small seeded crops like vegetables, will become more important in the future also for large-seeded crops and for treatment-on-demand.

Today there are still some primitive application systems in use, which feed the product through a simple tube onto seeds in a mixing chamber, where distribution is managed by different type of augers. It is obvious that seed-to-seed distribution is limited in quality with this procedure. Spinning-disc technologies or advanced controlled-droplet application (CDA) machines are becoming the standard in modern application technology. These machines allow good seed coverage with lower slurry volumes, shorter drying times and continuous seed flow. The primary distribution of the product on the seed is substantially improved and supported by secondary mixing with augers. These sophisticated and often computerized systems also reduce the chemical exposure both for operators and the environment.

Interesting technologies for on-farm treatment are the so-called "on-the-go" systems, which offer the advantage that only the amount of seed to be drilled is treated. Where seeds cannot be carried to the next season, like soybeans, Bulk On-Site Seed (BOSS) treaters or High Capacity Bean Treaters (HCBT) have been developed.

Future innovations in application technology will be driven by the increasing value of seeds and seed treatment products, and the ongoing need to improve the accuracy of seed loading and seed-to-seed distribution. Both formulation and application technology research will cooperate to achieve the best application quality.

Closely linked to seed application technology is the availability of quality assurance procedures to control treatment quality, and avoid complaints. This need has been triggered by the introduction of high-value modern seed treatment products (e.g. imidacloprid, thiamethoxam, fluquinconazole) and the increasing value of "high-tech" treated seeds. Checks of loading on individual seed batches are performed by the crop protection and seed industry. These are either conducted in the laboratories of treatment manufacturers, seed or service companies, using techniques such as laboratory-based gas or liquid chromatographic (gc, hplc), or by using mobile kits to perform the analysis on-site (Halmer, 1994).

Seed-to-seed distribution is even more important than the loading of individual batches, in order to avoid over- or under-dosing with the above-mentioned consequences of phytotoxicity or poor activity or economic losses. Seed-to-seed distribution characteristics can also be checked with gc or hplc, though it is time-consuming and very expensive. In the future video-imaging based systems will offer fast and cheap processes to provide this service to commercial seed treaters for the enhancement of the application process.

SEED TREATMENT AND SEED TESTING

High quality seed is the basic requirement to establish an optimum plant stand for maximum crop yield and quality, and the major purpose of seed testing is to assess this quality in order to predict the performance under field conditions. Seed quality is affected by many factors, including pathogen infections in the ripening phase, harvest conditions, processing and storage conditions. A distinction is commonly made between the concepts of seed viability and seed vigour. Seed viability is defined as the potential of a seed to germinate under favourable conditions whereas seed vigour is the potential of a seed for rapid, uniform emergence and development into a healthy seedling under a wide range of environmental conditions (Gutormson, 1996a). To assess these qualities a range of laboratory testing methods has been developed for individual species (Gutormson, 1996b). The tests are performed either by official or certified private laboratories, or seed companies, and the most common ones are listed in Table 7.

Table 7. Seed testing methods.

Purpose	Test	Crop(s)
Viability	Optimal Germination	(all)
	Tetrazolium	(many)
Vigour	Cold Germination	maize
	Conductivity	peas, cereals
	Accelerated Ageing	soybeans
	Cool Germination	cotton
	Controlled Deterioration	vegetables

A major issue in the testing of treated seed is that the current test methods have been developed for old or phase-out chemicals. Modern low-rate, highly active and systemic chemicals act in a different way to protective, high-rate chemicals. There are discrepancies between laboratory and field performance, which have to be resolved by developing new reliable tests with good correlations. The seed industry and the seed treatment manufacturers have the common goal of delivering high quality seed to the end-users.

AGRONOMIC CHANGES INFLUENCING SEED TREATMENT

The past decade has seen many changes in agriculture, and the next one will no doubt see more. In particular, seed treatment is being affected by changes in cropping systems, increased seed trade, the introduction of genetically-altered seeds with specific built-in traits and increasing requirements of food processors and retailers.

Set-aside programmes, earlier planting dates, minimum-tillage systems and narrow-row cropping will enhance the predisposition of seeds and young seedling to various diseases. Planting into cool and wet soil can promote attack by *Pythium*. Trash residues from the previous crop result in an increase of the soil- and air-borne inocula of many diseases. Examples are grey leaf spot (*Cercospora zeae-maydis*) or northern leaf spot (*Helminthosporium spp.)* in maize. The same is true for wheat stubble harbouring the foliar pathogens leaf rust (*Puccinia spp.*) and *Septoria spp*. Increased seed trade may enhance the risk of introduction of new diseases into uncontaminated areas, as has happened for instance with sorghum ergot in the USA.

Genetically-altered seed varieties are already grown on more than 40 M ha, mainly in the USA, Canada and Argentina. Seed treatment has an ideal fit with these high-value seeds. For the time being and in the mid-term future, transgenic varieties may provide defence against only some of the important diseases or pests. These varieties will also need the efficient complementary protection that is well provided by seed treatment, in order to deliver "one seed, one healthy and protected plant". There is also a need to implement and re-enforce anti-resistance management schemes, to which seed treatment can contribute the appropriate mode of action. New diseases and pests or so far minor pest and diseases may appear with altered genetics for which seed treatment may offer an effective control.

Food/feed processors and food retailers are demanding high-quality raw materials. Seed treatment contributes to this requirement through the introduction of highly effective compounds against bunt diseases (*Tilletia spp.).* The presence of bunt can exclude the complete harvest of wheat fields for animal feed or the milling industry. Another example of the value of seed treatment is the effective control of silver scurf (*Helminthosporium solani*) on potatoes. This disease makes the tubers unappealing for the fresh ware market. The extent to which seed treatment can contribute to solve the mycotoxin issue on cereal and maize grain is under intensive investigation.

THE REGULATORY ENVIRONMENT

Within crop protection, seed treatment is imbedded in a complex, interlinked network comprising market and regulatory requirements, and the increasing demands of Society about environmental health and safety, and the stewardship of food production. Seed treatment products have to fulfil the same registration requirements as other agrochemicals, which in the USA are driven by the adoption of the FQPA and in the EU by Directive 91/414. Older chemicals like lindane are banned (e.g. France, UK, Germany), others like chlorpyriphos and carbamates are under tough scrutiny, and their uses will or may be restricted. Some countries like France and Denmark are imposing taxes on pesticides, based on their ecotoxicological characteristics. Worker exposure is being subjected to more detailed study. Within economic blocks like NAFTA, EU, MERCOSUR there will be increasing efforts to harmonise cross border regulations to ease trade of treated seed or to reduce non-tariff trade barriers.

SUMMARY OF FUTURE NEEDS

Food and feed production through effective use of the available arable land is a steadily dynamic process, and innovation is a necessity to improve crop yield and quality, and to secure supply for the increasing world population. Seed treatment has made its contribution to this process in the past by combating such serious diseases as bunt on wheat, for example. Today a wide array of seed technologies is available to protect plants and the environment.

Nevertheless, as this paper has shown, there are still a lot of unsolved problems and new ones waiting for resolution by modern seed technologies. There is continuous need for active ingredients with novel specific activities and new modes of action, with improved user-, consumer- and environmental-safety profiles and attractive cost/benefit ratios. Formulation and seed application technology will contribute to the more efficient, accurate and less wasteful use of existing and new active ingredients, and packaging developments will provide safer handling characteristics. One can also speculate that seed treatments may be developed to switch on or off specific plant genes, or to enhance genetic traits by supplying a continuous trigger mechanism, e.g. to defend the plant, to produce specific proteins or to help move agriculture into areas where cold, salt and drought tolerance are needed to raise crops.

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