Vol. 17(3), pp. 70-84, July-September 2025
DOI: 10.5897/JPBCS2025.1067
Article Number: 20D7E9973645
ISSN 2006-9758

http://www.academicjournals.org/JPBCS

Journal of Plant Breeding and Crop Science

Review

Research trends in pollination control bags: A bibliometric analysis

Daljit Singh Virk[1]* and Hannah Senior[2]

[1]School of Environmental and Natural Sciences, Bangor University, Bangor, Gwynedd, Wales LL57 2UW, UK.
[2]PBS International, Salter Road, Scarborough, YO11 3UP, UK.

Received 22 May, 2025; Accepted 11 July, 2025

Pollination control bags (PCBs) are essential in plant hybridisation for preventing external pollen contamination and ensuring genetic purity. While conventional materials like kraft paper, plastic, and muslin cloth are inexpensive, they often lack durability and fail to regulate critical internal microclimate factors. Nonwoven synthetic fabrics, such as heat-bond polyester and spun-bond polypropylene, offer superior alternatives due to their customizable properties, which can lead to better seed yield, reduced mold growth, and more effective heat management. This review critically analyses published research on PCBs used in hybridisation across diverse commercial plant types. However, this review shows that research is very limited with significant gaps, including a lack of economic analyses of various fabric types, standardized metrics for microclimate parameters, understanding of long-term physiological and microbial effects, limited data on nonwoven fabrics across diverse crops, insufficient regional and germplasm-specific studies, and limited information on seed quality impacts beyond seed set. Addressing these gaps through research will facilitate more effective, sustainable, and economically viable pollination control strategies, thereby enhancing crop improvement programmes through improved environmental control and genetic preservation.

Key words: Pollination control bags, seed production, genetic purity, nonwoven fabrics, hybridisation, pollen contamination.

INTRODUCTION

Pollination control bags (PCBs) are crucial tools for hybridisation in plant breeding programmes as they isolate flowers or entire plants during key reproductive stages, safeguarding them from external contaminants, pests, and environmental factors that could compromise their integrity and genetic identity (Demirel and Cranshaw, 2006; Clifton-Brown et al., 2018; Gupta et al., 2022). The many types of PCBs range from kraft paper (Pickering, 1977; Dahiya and Jatsara, 1979), cloth (Neal and Anderson, 2004; Gupta et al., 2022), plastic film (Schertz and Clark, 1967; Smith and Mehlenbacher, 1994; Gitz et al., 2015), fine mesh fabrics (Nel and van Staden, 2013; Vogel et al., 2014), and nonwoven materials (Vogel et al., 2014; Adhikari et al., 2015). The choice of bag type depends on several factors such as crop type, flower size, environmental conditions, and the required duration of protection. For instance, kraft paper bags are traditionally used for crops grown in the summer and requiring a shorter period of inflorescence

*Corresponding author. E-mail: dsvirk2012@gmail.com.

Figure 1. Nonwoven synthetic bags over *Brassica napus* plants in PAU Ludhiana, India. These bags remain intact as they are stronger than the usually used muslin cloth bags which collapse on the plant.
Source: Gupta et al. (2022).

covering such as maize (*Zea mays*), rice (*Oryza sativa*) and sorghum (*Sorghum bicolor*) and primarily due to their easy availability and lower cost (Gitz et al., 2015). More durable plastic or synthetic bags may be necessary in crops where PCBs are susceptible to damage during adverse weather conditions such as rain and storms, including crops like sorghum (Gitz et al., 2013; Schaffert et al., 2016; 2018). Additionally, long-term protection from environmental hazards—such as heavy rains and strong winds—as well as insect infestation, may be required for certain crops like trees (Clifton-Brown et al., 2018; Heine et al., 2022) (Figures 1 and 2).

While technology in many other areas of plant breeding have advanced at pace over the last 30 years, understanding about the influence of PCBs is remarkably scant even though they remain integral to plant breeding success for artificial hybridisation between selected parents. Questions about the quality and suitability of pollination control methods are frequently overlooked and low cost is usually preferred without considering how these choices impact pollen viability, seed set, or overall breeding efficiency (Gaddameedi et al., 2017; Clifton-Brown et al., 2018; Gupta et al., 2022; Heine et al., 2022). This tendency arises from the assumption that all pollination bags function similarly, an assumption that does not hold up when comparing the diverse pollination needs of various crop plants (Clifton-Brwon et al., 2018). However, research demonstrates the importance of choosing the right type of bag for the specific crop and climate, with studies showing significant differences in outcomes which have considerable implications for a breeding programme when comparing performance of pollination control alternatives (Schaffert et al., 2016, 2018; Clifton-Brown et al., 2018; Gupta et al., 2022).

Nevertheless, progress has been made in improving the efficiency of PCBs and some advances include (PBS International, 2025 a, b, c): 1. Improved materials- Traditional materials like paper and cloth have been supplemented by more durable and breathable options, such as non-woven fabrics which better withstand environmental conditions and provide optimal air flow to prevent moisture buildup and biodegradable materials (Schaffert et al., 2016, 2018; Clifton-Brown et al., 2018); 2. Enhanced designs- Pollination bags have become more ergonomic and easier to apply, reducing labour costs and increasing efficiency. Some designs incorporate windows for monitoring (Schaffert et al., 2016, 2018; Bonneau et al., 2017), tie more securely, or designs that encourage the bag to stay open around the plant (Heine et al., 2022); 3. Tailoring to specific applications - Pollination control products have sometimes been tailored for specific crops and breeding objectives. For example, trials of multiple materials and designs have been carried out to maximise seed yield and minimise labour in controlled mass

Figure 2. Kraft paper (in front with hole on top) and nonwoven synthethic pollination control bags (white) on sorghum plants.
Source: Schaffert et al. (2018).

Figure 3. A nonwoven bag with window on a Cannabis plant (left) and nonwoven (white) and kraft paper (brown) bags on loblolly pine trees (right).

pollination of Loblolly Pine (Heine et al., 2022); 4. Integration with technology- In some cases, pollination control materials can be integrated with other technologies, such as sensors or data collection systems, to provide more precise and efficient management (Trammell et al., 2020; Gupta et al., 2022) (Figure 3).

This review will provide a comprehensive comparison of the different types of PCBs used in hybrid seed production and plant breeding. It will explore how various materials and designs perform under different environmental conditions and the implications of recent innovations on sustainability, ease of use, and cost-effectiveness. By focusing on the practical applications of these bags across diverse crops and trees, this review aims to underscore the critical role that quality materials play in breeding success and pollination control efficiency.

PROPERTIES AND PERFORMANCE OF PCBs ACROSS DIFFERENT CROP PLANTS

Desirable characteristics of PCBs

To work effectively, a pollination control product must

Table 1. Important pollination control bag traits that influence the seed outcomes.

Property	Example(s) of impact on plant breeding and seed production	Example(s) of when this might be important
Pollen and/or pollinator exclusion	Unintended genetics among progenies ((PBS Intl., 2025 a,b,c). Research clarity and/or genetic gain reduced (PBS Intl., 2025 a,b,c).	Controlled crossing.
Strength	Torn bags especially after rains or storms allow pollination by unintended sources and pest damage (Bonneau et al., 2017; Light et al., 2023; PBS Intl., 2025 a,b,c).	Breeding in outside environment. PCBs is in situ for a long period of time.
Water permeability	Loss of plants and/or seed yield to disease	Plants susceptible to mold (Gaddameedi et al., 2017). Large amounts of foliage enclosed.
Durability over time	Bags weakened by UV light will tear more easily. Re-use of PCBs may be desirable (PBS Intl., 2025 a,b,c)	PCB in situ for a long time (e.g. protecting fruit to maturity). PCBs to be re-used (PBS Intl., 2025 a,b,c).
Rigidity	If the material abrades the flowers, it can cause damage or abortion (Gaddameedi et al., 2017).	To hold the PCB away from the plant.
Softness	Overtightening around stems damages the plant. Small gaps where secured around the stem permit entry for pollinating insects.	The PCB has to be secured around a delicate stem.
Smoothness	Enables maximum quantity of pollen to be extracted (PBS Intl., 2025 a,b,c). Prevents damage to plant / flowers.	Pollen collection (pollen grains do not stick to the fabric). Delicate flowers / plants that could be damaged by abrasion.
Light transmissibility	Can impact seed colour or plant growth (PBS Intl., 2025 a,b,c). Can affect heat build-up.	Whole plant enclosed (photosynthesis impeded).
Temperature control	Pollen viability is reduced, affecting fertilisation and seed set.	Ambient conditions are already warm (Trammell et al., 2020; Gupta et al., 2022).
Usability	Usability can affect the amount of labour required and/or number of crosses possible in a given time (Bonneau et al., 2017; Trammell et al., 2020; Light et al., 2023).	Many bags to be applied. Close inspection of plants required.

prevent unintended pollen from reaching the flowers (Gupta et al., 2022; Stevanato et al., 2024). However, enclosing a plant in any kind of cover changes the microenvironment around the plant part such as relative humidity, temperature or light availability-including relative availability of light across the spectrum (Gitz et al., 2015; Trammell et al., 2020; Gupta et al., 2022). Ideal PCBs not only exclude pollen but also create an internal environment as close to natural as possible, all while ensuring the end-product is easy to use (Bonneau et al., 2017). This means that the desirable properties of PCBs are numerous (Table 1), and the ideal combination of properties can vary widely with the circumstances in which it will be used. To complicate further, desirable properties may be broadly antithetical to each other (e.g. pollen exclusion and breathability). This means that optimisation across a range of properties is always the goal. The relative importance of these characteristics is influenced by the environment in which it's being used (e.g. tropical climate vs temperate) and the plant type (e.g. size of pollen grains, sensitivity to disease, amount of the plant that needs to be covered).

Materials used in PCBs

This study classifies PCB materials as used traditionally and nonwoven. The latter are more advanced materials in search of an optimal PCB type.

Materials traditionally used for PCBs

Traditionally the products used for pollination control are versions of products widely available for other purposes such as food packaging. These possess a combination of desirable properties and certain drawbacks. Widely used materials are indicated in Table 2. Traditional PCBs are often selected without thorough consideration by breeding programme managers. Choices are

Table 2. Materials traditionally used for PCBs.

Bag type	Typical polymer/ base fibre	Common manufacturing process	Example crop applications	Pros	Cons
Glassine paper	Cellulose, glazed paper.	Wood pulp extracted, wet laid.	Wheat, barley, millet (Foster, 1968)	Inexpensive; good light transmission; and low	Breaks easily in rains and bird damage.
Kraft paper	Cellulose	Wood pulp extracted, wet laid.	Pine trees, sorghum, corn (Pickering, 1977; Gitz et al., 2015; Heine et al., 2022)	Strong when dry and inexpensive.	Poor light transmission; fragile when wet; and holds water.
Plastic film	Polythene, polypropylene	Film blown	Wheat, oil seed rape / canola (Schertz and Clark, 1967; Subrahmanyam, 1977; Schaffert et al., 2016)	Inexpensive and high light transmission.	Prone to overheating and not breathable
Canvas	Cotton fibre	Weaving	Oil palm (Bonneau et al., 2017)	Strong and readily available.	Not very breathable; heavy; hard to get a good seal; and holds water and attract bacteria due to cellulose.
Muslin	Cotton	Weaving	Cotton, millet, mustard (Gupta et al., 2022)	Low weight; dries quickly; water and air permeable.	Not very pollen proof
Mesh	Polyethylene, Polypropylene, polyester, nylon.	Various (e.g. welding, knitting)	Brassicas, cucurbits (Nel and van Staden, 2013; Vogel et al., 2014)	Water and air permeable	Typically not very pollen proof

sometimes inherited from predecessors, with modifications only made in response to specific issues such as a particularly dry season that increases bird attacks on paper bags to access the seed contained inside or damage from excessive rains and storms (Schaffert et al., 2016, 2018). Alternatively, the choice may result from limited budgets, especially when spending on consumables is 'siloed' from other costs such as labour or investment in biotechnology which produces the germplasm for crossing. Finally, the acceptable standards of genetic contamination in breeding programmes were primarily based on phenotypic assessment and were less strict than those recently established using genetic markers, which have increased costs in breeding processes (Gupta et al., 2022).

Nonwoven materials close the gap between traditional and optimal PCBs

Nonwovens are textile materials made by bonding fibres together instead of by the more complicated traditional spinning and weaving processes (Fead, 1960). They combine a wide range of properties for an optimal PCB. First, nonwoven materials are typically made from biopolymers (e.g. cellulose) or synthetic polymers (e.g. polyester). The choice of polymer and the specific grades or quality of the polymer gives different properties to the resulting fabric such as UV stability. This affects the overall performance of the end-product. Second, the manufacturing process influences the end materials' properties. Unlike a plastic film (a uniform and typically non-porous layer of polymer), nonwovens are made from fibres interlocked or bonded using mechanical, chemical or thermal processes (Nonwoven industry, 2021). The shape and density of the fibres, the architecture of fibres within the fabric and their method of bonding all contribute to the end material being appropriate for tasks as diverse as a material used as felt or carpet and one used to make nappies or tea bags. Finally, the materials may be surface treated e.g. coated, treated or laminated to add or change properties. For instance, a fragile and thin layer of nanofibers which are effective at stopping particles may be reinforced by a more robust layer of some other material.

Nonwoven fabrics have many advantages for PCB constructions: 1. Pollen proofing- can be enhanced primarily due to the physical complexity of the fibre architecture of the nonwoven fabric even when PCBs have larger pore size than the pollen grain (Gupta et al., 2022). Thermal bonding of multiple layers of synthetic fabrics creates interconnected pores and tortuous pore paths through the fabric thickness (Wang and Gong, 2006). This torturous path can prevent the passage of pollen yet allows exchange of air and moisture; 2. Better micro-environmental control within the bags reduces fungal development and improves seed set (Gaddameedi et al., 2017); and 3. Durability and intactness improve seed output over traditional paper bags and possibility of reusability reduces waste (Vogel et al., 2014; Bonneau et al., 2017; Gupta et al., 2022).

Micro-climate within PCBs: Humidity and temperature management

The type of fabric PCBs are made from greatly influences the micro-environment within them such as temperature and humidity. Therefore, identifying fabrics that create appropriate environmental conditions within the bag is crucial (Foster, 1968). Gitz et al. (2015) compared the microenvironments within novel spun-bond polyethylene and brown paper bags in sorghum. A considerable increase in temperature was measured within brown bags throughout the season as compared to ambient temperatures. However, temperatures within polyethylene bags were lower than paper bags because of air permeability. Humidity was lower in soft polyethylene bags than hard polyethylene and paper bags that resulted in molds especially in recently irrigated plants. Hayes and Virk (2016) found in Miscanthus that duraweb® bags exhibited a narrower range of temperature and humidity than those shown by the Orchard and Glassine bags which could impact the success of crossing and seed set rate. The duraweb® bags made from nonwoven polyester seemed to allow air-permeability and moisture absorption for micro- environmental adjustments conducive for better seed set and development.

Nonwoven synthetic bags perform better in managing both humidity and temperature because their breathability allows moisture to escape and thereby minimizing the risk of fungal growth and seed damage caused by excess humidity (Gaddameedi et al., 2017). In terms of temperature control, nonwoven synthetic bags can help stabilize internal temperatures, even when exposed to variable external conditions. This can reduce the likelihood of overheating within the bag, making nonwoven synthetic bags an excellent option for protecting sensitive crops in various climates (Gupta et al., 2022). Trammell et el. (2020) in grasses and Gupta et al. (2022) in Brassica reported that nonwoven fabrics had slightly higher average temperature and lower humidity than the outside which set a conducive microclimate for higher seed set and disease-free seed. The mean temperature in nonwoven synthetic bags, in Brassica, was about 5°C higher than outside and cloth bags, but with lower average humidity (Gupta et al., 2022). Based on seed output, they concluded that nonwoven PCBs offered better options for replacing paper or muslin cloth bags in Brassicas. This conclusion supported that of Hayes and Virk (2016) in Miscanthus, who reported the superiority of nonwoven duraweb® fabrics for better seed set rate.

Clifton-Brown et al. (2018) assessed internal PCB temperature and vapour pressure density (VPD) measured over a time course in controlled environment conditions for different bag types. The nonwoven fabric PCBs had significantly lower temperature increase than the cellulose bags. The higher temperatures in PCBs were found to significantly increase the VPD. Hayward et al. (1986) measured temperature within seven types of bags in the glasshouse and outside. The rise of temperature in the bags outside over the ambient fell in two categories for temperature with glassine, cellophane and paper-plus-clear side of polypropylene bag facing the lamp in one group and having significantly higher temperature than paper, terylene and paper-plus-polypropylene bag clear side towards the lamp in the second group. Inside a glasshouse the paper-plus-polypropylene bag with the clear side facing the lamp showed significantly higher rise in temperature of 14.2°C versus all other bags. Water loss from different bag types ranged from 0.01 g h^{-1} from a polythene bag to 1.7 g h^{-1} from the paper-plus-polypropylene with the clear side facing the sun.

Hayward et al. (1986) also measured relative humidity (RH) along with VPD values in the seven bags, The polythene bag was found to be significantly more humid than other bags with RH=80%, 26.6% above ambient, VPD 0.8 kPa below ambient. The other bags showed a small range of variation, having RH 0.2 to 7.4% higher than ambient and VPD 0.03-0.44 kPa below ambient.

Ball et al. (1992) investigated the impact of different pollination bag types and materials on the spike temperature of wheat (*Triticum aestivum* L.). When dialysis tubing or white onion skin typing paper showed 2 to 3.5°C temperature differences between bag types at noon on clear days; the dialysis tubing bag produced the highest spike temperatures reaching to 6°C above air temperature. In the second experiment, the spike temperature was highest with a glassine bag and lowest with a bag of white onion skin typing paper reaching to 4 to 6°C difference at noon on clear days with temperatures inside bags 8°C above air temperature. Such high temperatures were physiologically damaging the seed when air temperatures are high.

Plastic-film bags are less effective for humidity control, which can lead to a high-humidity environment resulting in fungal issues that can cause potential damage to the seeds (Gitz et al., 2015). Furthermore, plastic is not breathable and often traps heat, creating localized "heat pockets" inside the bag. This characteristic increases the risk of overheating, especially when the bags are exposed to direct sunlight in hot weather, making plastic- film bags a less suitable choice for plants that require a stable temperature for successful pollination. Gitz et al. (2015) reported that hard and soft form Tyvek spun bond polyethylene bags in sorghum resulted in 10 to 15°C higher temperature than the outside but heating in these bags was lower than in paper bags due to their air permeability. Spun polyethylene bags maintain near ambient conditions, which can be beneficial for self-pollinating plants (Gitz et al., 2015). Micro-fibre bags maintain lower relative humidity and moderate temperature increases compared to polythene and sponge (polythene with foam rubber stoppers) bags, which can lead to better seed yields and cone survival in species like *Pinus patula* (Nel and van Staden, 2013).

Hayes and Virk (2016) compared Glassine (glazed paper), Orchard (wet strength kraft paper) and nonwoven air-permeable polyester bags in Miscanthus. The range of temperature and humidity found within the nonwoven bags compared to the Orchard and Glassine bags was much smaller and tighter control of temperature and humidity in them had a positive effect on crossing success and seed set rate.

Paper bags offer a moderate level of water retention, as they can absorb moisture but may also trap it, leading to the potential buildup of unwanted humidity (Schaffert et al., 2018). While they do allow for slightly better ventilation than plastic bags, they are still not ideal for plants sensitive to high moisture levels as some of the water is absorbed into the fibres of the bag rather than evaporating away entirely (Clifton-Brown et al., 2018). Regarding temperature, paper bags can quickly absorb and retain heat, especially under direct sunlight, leading to a moderate risk of overheating. This makes paper bags less suitable for use in hot climates or for plants that are sensitive to temperature fluctuations. Paper bags are also prone to bad weather damage due to rains and high winds (Gitz et al., 2013; Schaffert et al., 2016). McAdam and Hayward (1985) in ryegrass reported that the transparent cellophane bags had the highest temperature inside the bags, varying from 5 to 10°C above glasshouse temperature. The paper-plus- polypropylene bag with a clear window facing the sun had temperature like the cellophane. The temperature inside the latex bag was midway between the cellophane and the terylene.

Muslin bags, known for their breathability, offer an alternative that balances both humidity and temperature control effectively. These bags allow air to circulate freely, which enables moisture to evaporate naturally while retaining minimal humidity within the bag. This characteristic makes muslin bags a favourable choice for plants that require low moisture conditions during pollination. Additionally, muslin bags prevent significant heat buildup by allowing for moderate air circulation. This makes them a good option for various climates, especially in warm or temperate environments where preventing overheating is essential. Gupta et al. (2022) showed that muslin cloth bags, commonly used in Brassicas, performed next to nonwoven bags in terms of slightly lower average temperature and humidity.

Some synthetic bags create a more conducive micro-climate for seed development, enhancing seed set and quality (Gaddameedi et al., 2017; Gupta et al., 2022). Also, Gupta et al. (2022) reported in Brassica that the re-used (old bags) bags of DWB03 fabric showed the similar microclimate and seed output to new bags. Since a PCB covers reproductive structures of the plant, elevated inside temperature (Ball et al.,1992; Gitz et al., 2015) is bound to impact the seed set because of reduced pollen viability (Chowdhury and Wardlaw, 1978; Harsant et al., 2013) and or seed set (Prasad et al., 2006). Along with rise in temperature, high humidity can also directly reduce the seed set (Foster and Wright, 1970) or by creating micro-climatic conditions that are more favourable for diseases and pests to develop (Yun et al., 2017).

These studies suggest that the type of pollination control bag material significantly affects micro-climate conditions, with nonwoven synthetic and spun polyethylene bags maintaining more favourable temperature and humidity levels compared to traditional paper and polythene bags, thereby improving seed yield and quality.

Effect of colour of pollination bags on seed output

Very few studies compared the impact of colour of PCBs on seed output. Clifton-Brown et al. (2018) reported light transmission (%) across the 350 to 800 nm wavelength for a range of coloured PCBs along with their biological effect on Arabidopsis. Black and blue PCBs had low light transmittance beyond 550 nm and plants produced no seeds.

Green peaked high transmission around 500 nm and resulted in low yields of heavy seeds. Red PCBs had low transmission until 550 nm but highest of all colours in the higher range. Brown PCBs had generally low transmission. Red and yellow PCBs had intermediate yield and seed weights.

White bags filtered wavelengths below 400 nm, but all wavelengths were equally transmitted above 400 nm. There was no significant difference in seed yield for the white nonwoven PCB or standard cellulose control bag. In general, coloured PCBs were detrimental to seed yield and use of white materials was recommended.

Testing pollen proofing

Ensuring the integrity of cross-pollination by excluding external pollen contamination is the primary function of flower isolation with PCBs. The effectiveness of these bags in blocking airborne pollen from entering and contaminating relies on their material, porosity, structure, and deployment technique. A range of studies have demonstrated that various pollination bags made from materials such as parchment, cloth, and synthetic fibre (e.g., nylon, polyester) can successfully exclude pollen, though the effectiveness may vary depending on factors like pollen size, porosity and weather conditions. Gitz et al. (2015) reported the potential for pollen transmission through hard form (HfT) and soft form (SfT) spun polyethylene pollination bags as compared to traditional paper pollination bags in sorghum. No difference in pollen transmission through Paper and HfT was found. Although SfT allowed 35 - 40% wind borne pollen through the pores as compared to controls, male sterile plants covered with SfT produced only 30 seeds/panicle, about 1% of a self-pollinating fertile plant. They suggested that SfT could adequately reduce or eliminate cross-pollination in self-pollinating plants while maintaining near ambient environmental conditions.

McAdam and Hayward (1985) assessed the impermeability of bags to pollen of ryegrass using PGI (phosopho-glucoisomerase) isozyme starch gel electrophoresis system. They compared 7 bag types that included non-woven Terylene, striped paper, latex, paper, paper-plus- polypropylene and cellophane as control. The three types of bags of nonwoven Terylene and latex showed no contaminants and appeared to be impermeable to ryegrass pollen. McAdam and Hayward (1987) tested three grades of polyester and three types of paper bags for their permeability to grass pollen (*Lolium perenne*) using PGI isozyme studies (Griffiths and Pegler, 1963). Any pollen passing through the crossing bag and pollinating the plant was detected by assaying its progeny for PGI isozymes. The results obtained allowed differentiation of the various materials for their suitability for pollen proofing.

In oil palm, blank pollinations with talcum powder are made to assess pollen contamination. Bonneau et al. (2017) reported no contamination with nonwoven polyester bags compared to canvas and HDPE (high density polyethylene) bags. Weevils and other insects were noticed in canvas bags that compromised their pollen proofing. Adhikari et al. (2015) tested the efficacy of a polyester bagging method in blocking extraneous pollen in allogamous switchgrass using molecular markers on seeds of progeny and parents. They found no outcrossing contaminants from different nonwoven polyester bags. Trammell et al. (2020) grew hexaploid tall fescue plants in nonwoven polyester tents that were surrounded by tetraploid rye grass as pollen donors. The two types of grasses hybridise, and detection of chromosomal recombination shows pollen contamination. They concluded that nonwoven fabrics did not allow pollen contamination. In more recent research, Stevanato et al. (2024) used molecular fingerprinting techniques on seeds developed under nonwoven fabric single-plant tents enclosing cytoplasmic male sterile plants. They reported no deterioration in genetic purity from foreign pollen contamination in sugar beet. These results confirmed those of Townson et al. (2020) based on analysis of agronomical traits in sugar beet. Gupta et al. (2022) used molecular markers and reported that nonwoven PCBs were fully pollen proof as no seed set on cytoplasmic male sterile plants in Brassica species were of hybrid origin.

Neal and Anderson (2004) compared four fabrics commonly used as exclusion bags in studies of pollination and reproductive biology and reported that the permeability of fabrics to wind-borne pollen, as measured by deposition on both horizontally and vertically oriented slides, decreased with pore size. They concluded that bags with mesh size smaller than most pollen grains are impermeable to pollen. However, material for such bags is very expensive. In addition, it was also observed that bags with even moderately small pore size, such as pores (approx. 200 micron) in twisted fibre cotton muslin, offered highly significant barriers to passage of wind-borne pollen. Such bags are sufficiently effective in most large-sample-size reproductive biology studies.

An important aspect of fabric influencing the pollen proofing ability is permeability and pore size since larger pore sizes may allow through pollen grains. However, in nonwoven materials the porosity can only be used for preliminary selection of pollen proof bags, but it does not actually give any indication of extent of pollen proofing. Gupta et al. (2022) evaluated nonwoven bags with larger pore size than the pollen size of Brassica species investigated and reported completely pollen proof characteristic of DWB03 bags primarily due to the physical complexity caused by the fibre architecture of the nonwoven fabric used. This is because nonwoven fabric samples are characterized by multiple filtration layers of interconnected pores and tortuous pore paths through the fabric thickness (Wang and Gong, 2006). This torturous but purposefully effective filtration of pollen through larger pore size may not assure totally impermeable conditions, yet it provides a trade-off in pollination performance while allowing exchange of air and moisture. All the fabrics of PCBs used by Gupta et al. (2022) provided an acceptable filtering level of co-optimization of pollen exclusion in their experiments.

Comparing performance of different bag types for agronomic traits

Nonwoven synthetic PCBs have been shown to significantly increase seed yield compared to traditional kraft paper or muslin cloth bags. For instance, in Brassica species, synthetic bags produced 47% more seeds per bud and 57% more hybrid seed set on CMS lines than muslin cloth bags (Gupta et al., 2022). Similarly, in switchgrass, micromesh fabric bags resulted in a four to tenfold increase in seed production compared to paper bags (Vogel et al., 2014).

Small brown paper bags improved seed quality and weight in crosses of Hordeum species by potentially influencing light exposure in the covered spikes (Pickering, 1982). Polyester bags outperformed HDPE and canvas bags in oil palm seed production, yielding more seeds and offering better protection against insects and water damage (Bonneau et al., 2017).

Newer bag types, like plastic mesh and nonwoven fabric bags, aim to address the issues of moisture buildup, airflow control, and durability while also maintaining good levels of isolation to prevent genetic contamination. Nonwoven bags excel in performance on a range of crop plants (Table 3).

In loblolly pine, prototype pollination bags produced by PBS International Ltd (PBS bags) significantly increased cone survival and seed yield compared to traditional kraft paper bags. Female strobili bagged in prototype PBS-I2 were over three times more likely to survive to cone harvest than strobili inside the traditional kraft paper pollination bag. The PBS bags were more efficient in installation and removal, contributing to better seed production outcomes (Heine et al., 2020, 2022).

In sorghum, nonwoven polypropylene bags significantly improved panicle and seed weight and reduced bird damage and grain mold compared to Kraft paper (Schaffert et al., 2016, 2018; Gaddameedi et al., 2017). In sugar beet, wheat and grasses nonwoven polyester bags showed improved seed quality and yields (Clifton-Brown et al., 2018).

In general, nonwoven polyester and polypropylene modern materials outperformed traditional materials by improving pollination success, enhancing seed quality, and or providing better environmental control (e.g., reduced condensation in the bags). These newer nonwoven materials resulted in reduction in bird damage and mold growth, while significantly boosting seed yields in crops like sorghum (Schaffert et al., 2016; 2018; Gaddameedi et al., 2017).

The traditional bags often had issues such as tearing (paper bags) or being too heavy (cloth or burlap bags). They provided basic isolation but had poor durability and ventilation, especially in humid conditions. Plastic bags while being effective in isolation, they lead to problems like moisture buildup due to poor airflow, which could reduce seed viability.

The shift towards using alternative materials like nonwoven polyester and polypropylene bags for controlled pollination addresses many challenges found in traditional bags. These newer materials improve pollination efficiency, seed yield, and quality while reducing issues like moisture retention, contamination, and bird damage (Figure 4).

Protection against external damage including pests, diseases and birds

Although PCBs are essential for artificial hybridisation by enclosing reproductive plant parts, plant breeders tend to allocate minimal resources to the quality of these bags relative to the total cost per cross, often continuing inherited practices. This is even though inexpensive PCBs made of paper and cellulose are highly susceptible to damage from birds (Gitz et al., 2013), insects (Demirel and Cranshaw, 2006), wind (Bridgwater et al., 1998), water, and diseases (Windham and Williams, 2007). They also require deliberate daily shaking for pollen dispersion and are vulnerable to slugs and ants that often eat paper bags and the wet glue along the seams, which can give way after rain exposure (Bonneau et al., 2017). Parchment paper PCBs are prone to stress tearing as the plant's growth pushes the seams apart, while muslin cloth bags tend to collapse onto the plant and become wet from dew at night, creating a conducive environment for diseases and pests (Gaddameedi et al., 2017). Certain synthetic bags are better in their strength and intactness than traditional bags (Bonneau et al., 2017).

Pollination bags can also influence the interaction with insects and the environment. For example, polyester bags in oil palm production were more effective in preventing weevil entry that results in cross contamination compared to canvas bags, which is crucial for maintaining seed quality (Bonneau et al., 2017). Additionally, permethrin-treated bags reduced pest numbers and increased seed yields in canola crossing (Demirel and Cranshaw, 2006).

Synthetic bags, such as those made from polyester and polypropylene, offer superior resistance to rain and wind, reducing the risk of damage during adverse weather conditions. They also allow aeration to minimize fungal development particularly during the rainy season, as reported in sorghum breeding (Gaddameedi et al., 2017). Bird damage poses a significant challenge in maintaining plant germplasm and conducting hybridisation in crops grown in areas with high populations of predatory birds. Nonwoven polyester bags support higher seed retention and yields compared to lighter materials like paper or muslin bags, which are more easily compromised. For instance, research on sorghum demonstrated significantly reduced bird damage and improved seed development when nonwoven polyester bags were used (Schaffert et al., 2016, 2018; Gaddameedi et al., 2017). In contrast, traditional paper bags are prone to tearing and dislodgement under moisture and high winds, making them more susceptible to bird damage (Gitz et al., 2013). Additionally, adverse weather conditions such as heavy rain and strong winds can worsen damage across all bag types, leaving seeds exposed to both birds and harsh environmental elements, which diminishes crop quality and yield. Overall, nonwoven synthetic bags have shown consistent superiority of strength against bird damage.

ECONOMIC ANALYSIS OF PCBs

A comprehensive economic evaluation of various pollination bags is limited; however, existing studies offer preliminary insights into their cost-benefit profiles. It is essential to recognize that breeders primarily focus on propagating genetic stocks and accelerating breeding cycles rather than producing commercial crops. During early segregating generations, seed quantities are small,

Table 3. Comparison of bag types for different agronomic traits in different crop plants.

Type of plant	Type of bag	Material of bag	Comparative effect (vs. standard)	Standard	References
Loblolly pine	1. PBS A,B,C,D; 2. 11 PBS bag types; 3. Various micro-fibre bags	1 and 2. All nonwoven polyester 3. Polythene and micro-fibre (woven), Cellulose	1. PBSA2 showed three times higher odds of survival of cones at harvest than control. 2. Increases over control: 2% with PBS-E for cone length; 4% with PBS-C for Cone width; 7% with PBS-E for count of fertile seeds; 7% with PBS-12 for proportion of filled seeds; and 10% with PCB-12 for predicted seed yield and 30% for strobilus survival. 3. Cone survival 36 to 46% with micro-fibre bags compared with 19 to 32% with polythene bags.	1 and 2: Kraft paper. 3: Open pollinated control.	1. Heine et al. (2020); 2. Heine et al. (2022); 3. Nel and van Staden (2013)
Oil palm	Duraweb®	Nonwoven Polyester	13% more seeds per bag over HDPE bags; 6% more seeds per bag over canvas bags	High density polyethylene (HDPE); Canvas bags	Bonneau et al. (2017); Light et al. (2023)
Wheat	1. Parchment Paper Bag 2. A, B, C1, C2, D, E	1. Parchment Paper 2. A=polypropylene and rest all nonwoven polyester	1. 5% increase in seed quality; 2. 21% higher 1000 seed wt with A and 33% higher with C2 over N standard.	1. Open pollination or simple paper bags for hybridization. 2. N=Polypropylene	Clifton-Brown et al. (2018); Ball et al. (1992).
	Synthetic SG1	Nonwoven polypropylene	25% more Panicle wt; 29% more seed wt; 34% more av seed wt.	Kraft paper	Scheffert et al. (2016, 2018)
Sorghum	Synthetic SG1	Nonwoven polypropylene	-99% less bird damage; 2% more seed wt; -35% less grain mold.	Kraft paper	Gaddameedi et al. (2017)
	Synthetic SG1, SG2	Nonwoven polypropylene (SG1), Polyester (SG2)	0 Bird damage as against 75% with standard; 104% more panicle wt with SG1; 552% more grain wt of panicles with SG2	Kraft paper	Schaffert et al. (2016, 2018)
Sugar beet	1 and 2. DWB10, DWB23, DWB24 3. A, B, C	Nonwoven polyester A= polypropylene and all others nonwoven polyester	All bags equally pollen proof with standard using agronomic traits and molecular markers. All nonwoven types similar	1 and 2: DWB01 (nonwoven polyester). 3: K non-woven polypropylene mesh	Townson et al. (2020); Stevanato et al. (2024); Clifton-Brown et al. (2018)
Forest Trees (Pinus spp)	Kraft and nonwoven	Kraft paper and polypropylene	Three times more female strobili survival in nonwoven over kraft paper bags.	Kraft paper and kraft paper with wire	Heine et al. (2020; 2022)
Arabidopsis	A, B, C1, C2, D, E	A= polypropylene and others nonwoven polyester	576% higher seed wt with A and 16% higher total seed wt with C2	Polypropylene	Clifton-Brown et al. (2018)

Table 3. Cont'd

Grasses	1. Paper bag 2. DWB10, DWB24	1. Kraft Paper 2.Non-woven polyester tents	3-5% reduction in genetic contamination; DWB10 showed 36% increase in seed yield and 3% for seed weight in 2019 over control; both fabrics were pollen proof with no contamination.	No bags or simple paper bags. Non-woven polyester duraweb fabric	Trammell et al. (2020)
Miscanthus	Duraweb A,B,C	Nonwoven polyester and A= Polypropylene and others polyester	15 % higher successes of crosses and all bag types on par	1.Glassine or glazed paper 2. Polyester	Hayes and Virk (2016); Clifton-Brown et al. (2018)
Sunflower	Cloth bag	Cotton	Seed yield increased significantly under cloth bags with assisted pollination. Seed yield was higher in open pollination.	Cloth bags	Sumangala and Giriraj (2003)
Mustard	DWB3	Nonwoven polyester	47% more seeds per bud over parchment bags; 38% more seed yield over muslin cloth bags; 57% higher seed set on CMS line under muslin cloth bags; and 100% pollen proof using molecular markers and CMS lines.	Parchment paper and Muslin cloth	Gupta et al. (2022)

and off-season growth facilitates accelerate generation advancement. The complete loss of progeny due to bird damage or weather can be irreplaceable, endangering entire breeding efforts and wasting labour. However, key finding from various studies are as follows (Table 4).

Gaddameedi et al. (2017) reported that nonwoven fabrics provided the highest economic benefit in sorghum, largely due to their superior micro-climate control and durability, which lowered seed loss from mold and pests. Schaffert et al. (2016) also found that nonwoven bags, despite higher initial costs, enhanced effectiveness by reducing bird damage and improving seed purity, thus offering long-term savings. Economic analysis of seven types of bagging materials after fruit set for protection in Litchi fruit showed that pink polypropylene bagging with highest gross returns, net returns and added returns in all the experiments was found to be most effective type of bagging (Singh et al., 2022).

Factors influencing cost-effectiveness

Initial cost

Nonwoven synthetic fabrics typically involve higherupfront costs but are more cost-effective over time because of their strength and possibility of reusability (Gupta et al., 2022). Plastic bags strike a balance between durability and affordability but are nonbreathable (Schaffert et al., 2016). Cheaper paper or muslin bags are often single use, leading to repeated replacement costs, especially under adverse weather conditions (Gaddameedi et al., 2017; Gupta et al., 2022).

Seed output

Higher seed yields are often associated with better micro-climate control provided by synthetic fabrics. For example, Vogel et al. (2014) demonstrated increased seed production in switchgrass with micro-mesh polythene bags. Similarly, plastic bags help maintain stable temperature and humidity, critical for seed set in cereals and oilseeds (Schaffert et al., 2016, 2018).

Seed quality

Better micro-climate regulation with nonwoven Materials results in improved seed viability and germination compared to paper bags, which can retain excess moisture and damage seed quality (Townson et al., 2020; Stevanato et al., 2024).

Labour and handling

Lightweight but strong bags, particularly

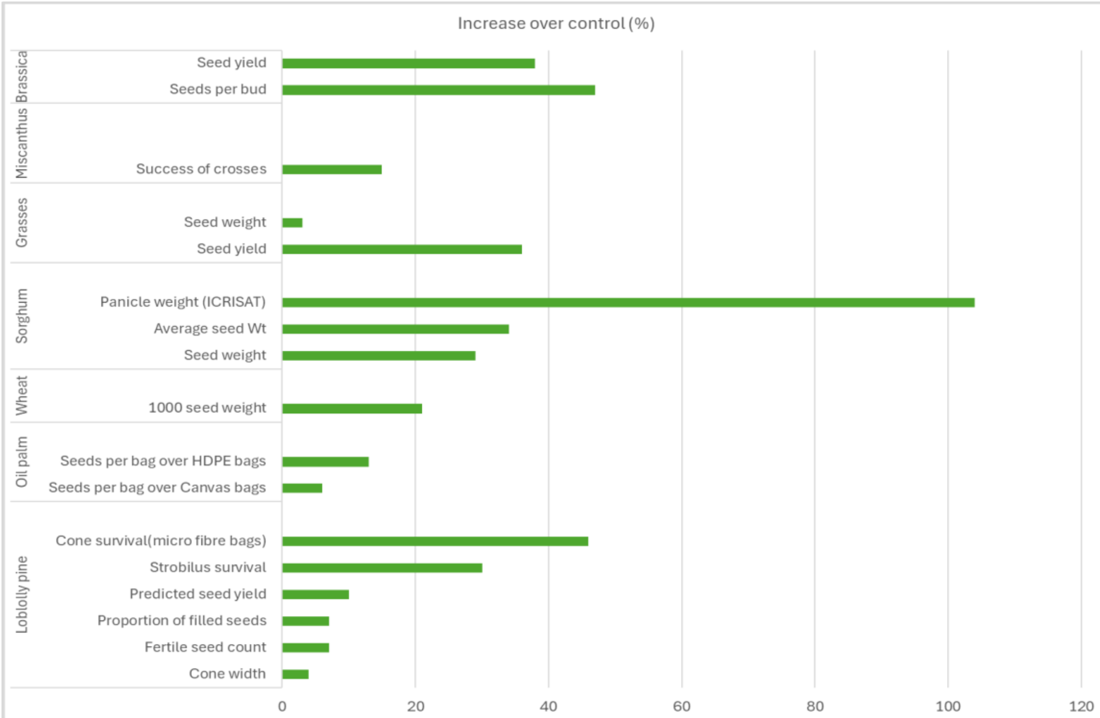

Figure 4. A sample of per cent increase with nonwoven pollination control bags over the control practice for different traits of some crop plants as reported by various researchers and as summarised in Table 3.

nonwoven, are easier to handle, reducing labour costs during installation and removal and excluding the need for re-installation of damaged bags in bad weather or bird attack. Their reusable options can lead to substantial long-term savings, though considerations include cleaning, maintenance, and potential damage (Hayes and Virk, 2016; Bonneau et al., 2017; Clifton-Brown et al., 2018; Gupta et al., 2022).

Impact on micro-environment and bird damage

Bag material influences micro-environment conditions critical for optimal pollination. Nonwoven materials have shown near ambient micro-climate in the bags and resist bird predation that can further protect investments, particularly in open fields (Gitz et al., 2013; Schaffert et al., 2016, 2018). Schaffert et al. (2016) found paper bags to be the worst for bird damage and the nonwoven SG1 bags the best.

Emerging factors and future directions

Material innovation

Advances aim to develop novel nonwoven fabrics tailored for specific crops and environments, improving seed quantity, quality, and overall cost-efficiency (Clifton-Brown et al., 2018).

Durability and reusability

Synthetic and plastic bags often offer multiple seasons use, amortizing initial costs, provided their integrity is maintained. Conversely, paper bags, though cheaper upfront, are usually single use, increasing long-term costs (Gupta et al., 2022; Schaffert et al., 2016, 2018).

While nonwoven bags generally involve higher initial investments, their benefits in seed quality, quantity, and reusability often offset these costs over time. Nevertheless, further comparative long-term studies are needed to fully evaluate the economic trade-offs across different crops and environmental conditions.

GAPS IN RESEARCH ON PCBs IN CROP PLANTS

Research on PCBs remains limited, with several key gaps that need to be addressed:

1. Optimal material development: There is a need to optimize nonwoven fabrics that combine properties such as durability, light transmission, breathability, and reusability for different crops and environments (Clifton-Brown et al., 2018). While durable nonwoven synthetic fabrics like polyester and polypropylene are increasingly

Table 4. Cost-benefit analysis of different types of PCBs.

Parameter	Nonwoven synthetic bags	Plastic bags	Paper bags	Muslin bags
Initial cost	High (Schaffert et al., 2016)	Moderate	Low	Moderate (Gupta et al., 2022)
Durability	High (reusable over seasons) (Schaffert et al., 2018; Gupta et al., 2022)	Moderate (can last 1-2 seasons)	Low (single-use) (Schaffert et el., 2016)	Moderate (may be reused) (Gupta et al., 2022)
Seed quantity output	High for many crops (Gaddameedi et al., 2017; Gupta et al., 2022)	Moderate (consistent output) (Clifton-Brown et al., 2018)	Moderate, varies by crop (Schaffert et al., 2018)	Moderate (Gupta et al., 2022)
Seed quality	High (better micro-climate) (Gaddameedi et al., 2017; Schaffert et al., 2028; Gupta et al., 2022)	Moderate (good humidity control) (Clifton-Brown et al., 2018)	Moderate (can trap moisture) (Schaffert et al., 2016)	Varies (good for breathable use) (Gupta et al., 2022)
Ease of use	Easy to install and manage (Bonneau et al., 2017)	Easy and flexible	Easy but labour-intensive for large scale	Moderate (bulkier, more work)
Long-term cost	Low (reusable, durable) (Schaffert et al., 2018; Gupta et al., 2022)	Low (Gitz et al., 2013; 2015)	High (repeated purchases needed)	Moderate (Gupta et al., 2022)

used, data comparing their effectiveness to traditional materials across crops are limited, especially regarding seed output and micro-climate control (Gupta et al., 2022).

2. Climate and germplasm specificity: There is a lack of region-specific and variety-specific research to optimize PCB performance under varying climatic conditions and in different genetic backgrounds (Schaffert et al., 2016; Clifton-Brown et al., 2018).

3. Economic analysis: Few studies have examined the cost-effectiveness of various PCB types, considering factors like seed quality, genetic purity, damage from pests or weather, and labour costs. More comprehensive economic evaluations are necessary (Schaffert et al., 2016; Gaddameedi et al., 2017; Gupta et al., 2022).

4. Pollen proofing efficiency: Limited comparative data exist on the pollen-proofing ability of different fabrics, which is critical for maintaining genetic integrity in hybrid breeding, with some studies on crops like sugar beet, mustard, switchgrass, and festuca (Townson et al., 2020; Stevanato et al., 2024; Gupta et al., 2022; Vogel et al., 2014; Trammell et al., 2020).

5. Standardized micro-climate metrics: There is a lack of standardized methods to assess parameters such as light transmission, humidity, and temperature inside bags, complicating cross-study comparisons (Gitz et al., 2013, 2015; Clifton-Brown et al., 2018).

6. Crop diversity: Most research focuses on crops like sorghum, wheat, and mustard, with insufficient data on oilseeds, fruits, and trees, which have unique pollination and environmental requirements (Schaffert et al., 2016; Bonneau et al., 2017; Heine et al., 2020, 2022).

7. Seed quality: Research predominantly addresses seed quantity, with a need for further studies on seed vigour, viability, and genetic purity, particularly how bag materials influence seed health (Clifton-Brown et al., 2018).

8. Environmental sustainability: The environmental impact of non-biodegradable synthetic bags is underexplored. Development of eco-friendly, biodegradable, or reusable options is urgently needed.

9. Plant physiology: Limited evidence exists on how prolonged bag use affects plant growth, photosynthesis, or disease susceptibility over time (Townson et al., 2020; Stevanato et al., 2024).

10. Microbial and pest interactions: The influence of bag materials on microbial activity and pest dynamics remains understudied yet is crucial for seed health management (Gaddameedi et al., 2017; Schaffert et al., 2018).

11. Impact on seed phenotype: The quantity of wavelengths of light falling on seeds during their development influences seed colour (Dennis Gitz, 2024-Pers. Comm.). Therefore, the influence of

pollination bag types with different light transmissibility needs to be studied for their influence on seed phenotype (Clifton-Brown et al., 2018).

CONCLUSION

PCBs are essential in plant breeding programmes for safeguarding genetic integrity and optimizing seed yield and quality. This review demonstrates that nonwoven synthetic fabrics offer substantial advantages over traditional PCB materials, such as paper, muslin, and plastic, by providing better durability, moisture control, and temperature regulation. The choice of bag material impacts pollen proofing efficacy, with nonwoven materials consistently demonstrating superior results across a range of crops. Nonwoven PCBs not only reduce the risks associated with fungal growth and overheating but also enhance seed viability and quantity, making them a cost-effective choice despite their initial expense. Their durability and reuse potential provide an economic advantage, particularly in breeding programmes where contamination prevention and genetic identity are priorities. As plant breeding demands evolve, integrating these advanced materials into pollination control practices can improve the efficiency and success rates of hybridisation efforts across various environmental conditions and crop types.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES

Adhikari L, Anderson MP, Klatt A, Wu Y (2015). Testing the efficacy of a polyester bagging method for selfing switchgrass. BioEnergy Research 8:380-387. https://doi.org/10.1007/s12155-014-9528-3

Ball S, Campbell G, Konzak C (1992). Pollination bags affect wheat spike temperature. Crop Science 32:1155-1159. https://doi.org/10.2135/CROPSCI1992.0011183X003200050019X

Bonneau L, Eli D, Vovola P, Virk DS (2017). Comparing pollination bag types for micro-environmental parameters influencing seed production in oil palm. Journal of Oil Palm Research 29(2):168-179.

Bridgwater FE, Bramlett DL, Byram TD, Lowe WJ (1998). Controlled mass pollination in loblolly pine to increase genetic gains. Forestry Chronicles 74(2):185-189. doi:https://doi.org/10.5558/tfc74185-2

Chowdhury SI, Wardlaw IF (1978). Effect of temperature on kernel development in cereals. Australian Journal of Agricultural Research 29(2):205-223. doi:https://doi.org/10.1071/AR9780205

Clifton-Brown JC, Senior H, Purdy SJ, Horsnell R, Lankamp B, Müennekhoff AK, Virk D, Guillemois E, Chetty V, Cookson A, Girdwood S (2018). Investigating the potential of novel nonwoven fabrics for efficient pollination control in plant breeding. PLoS ONE 13(9):e0204728. https://doi.org/10.1371/journal.pone.0204728

Dahiya BN, Jatsara DS (1979). A rapid method of hand crossing barley. Indian Journal of Agricultural Sciences 49:915-917.

Demirel N, Cranshaw W (2006). Permethrin treatment of pollination bags as a protecting from false chinch bug, *Nysius raphanus* (Howard) (Hemiptera: Lygaeidae), injury to canola in Colorado. Crop Protection 25:1062-1064. https://doi.org/10.1016/J.CROPRO.2006.01.009

Fead M (1960). Nonwoven fabrics. Quarterly Review of Agricultural Economics 13:33. https://www.proquest.com/openview/9f4524d496b07c8417375b9b42b5b5ae/1?cbl=1818559andpq-origsite=gscholar

Foster CA (1968). Ryegrass hybridisation: the effect of artificial isolation materials on seed yield and floral environment. Euphytica 17:102-109.

Foster CA, Wright CE (1970). Variation in the expression of self-fertility in *Lolium perenne* L. Euphytica 19(1):61-70. doi:https://doi.org/10.1007/BF01904667

Gaddameedi A, Kumar A, Phuke R, Virk DS, Senior H (2017). Evaluating the efficacy of synthetic fibre pollination control bags in sorghum during the rainy season. International Journal of Plant Breeding and Genetics 11:39-54. https://doi.org/10.3923/IJPBG.2017.39.54

Gitz DC, Baker JT, Xin Z, Lascano RJ, Burke JJ, Duke SE (2013). Research note: bird-resistant pollination bags for sorghum breeding and germplasm maintenance. American Journal of Plant Sciences 4:571-574. http://dx.doi.org/10.4236/ajps.2013.43074

Gitz D, Baker J, Xin Z, Burke J, Lascano R (2015). The microenvironment within and pollen transmission through polyethylene sorghum pollination bags. American Journal of Plant Sciences 6(2):265-274. https://doi.org/10.4236/AJPS.2015.62030

Griffiths DJ, Pegler RAD (1963). Pollen proof fabrics for isolation purpose. Report of the Welsh Plant Breeding Station, UK pp. 74.

Gupta M, Kaur G, Banga S, Virk D (2022). Increasing seed set and pollen proofing in *Brassica juncea* and *Brassica napus* through novel non-woven synthetic pollination control bags. Journal of Crop Improvement 37:447-462. https://doi.org/10.1080/15427528.2022.2109546

Harsant J, Pavlovic L, Chiu G, Sultmanis S, Sage TL (2013). High temperature stress and its effect on pollen development and morphological components of harvest index in the c3 model grass *Brachypodium distachyon*. Journal of Experimental Botany 64(10):2971-2983. doi:https://doi.org/10.1093/jxb/ert142

Hayward MD, Thomas H, Blythe J (1986). Temperature changes and water loss from pollination bags: a survey of pollination bags manufactured by PBS International. Welsh Planty breeding Station, Aberystwyth, Wales, UK. pp. 1-13.

Hayes C, Virk DS (2016). Assessing the relative efficacy of polyester pollination bags and crossing tents, and isolation chambers for seed harvest in Miscanthus crosses. International Journal of Plant Breeding and Genetics 10(2):79-90. doi:https://doi.org/10.3923/ijpbg.2016.79.90

Heine AJ, Walker TD, McKeand SE, Jett JB, Isik F (2020). Pollination bag type has a significant impact on cone survival in mass production of controlled pollinated seeds in loblolly pine. Forest Science 20(20):1-11. doi:10.1093/forsci/fxaa013

Heine AJ, Walker TD, McKeand SE, Jett JB, Isik F (2022). Pollination bag type affects ovule development and seed yields in *Pinus taeda* L. Forest Science 20:1-13. https://doi.org/10.1093/forsci/fxac052

Light M, Virk D, Senior H (2023). New nonwoven fabrics for pollination control bags for oil palm. International Journal of Oil Palm 6(1):1-8. https://doi.org/10.35876/ijop.v6i1.85

McAdam NJ, Hayward M (1987). Testing the efficiency of pollination bag materials. Plant Breeding 98:178-180. https://doi.org/10.1111/J.1439-0523.1987.TB01113.X

McAdam NJ, Hayward M (1985). The efficiency of Duraweld PBS pollination bags. Report of tests carried out by the Welsh Plant Breeding Station, Wales, UK.

Neal PR, Anderson GJ (2004). Does the old bag' make a good wind bag'?: comparison of four fabrics commonly used as exclusion bags in studies of pollination and reproductive biology. Annals of Botany 93:603-607. doi:https://doi.org/10.1093/aob/mch068, available online at www.aob.oupjournals.org

Nel A, van Staden J (2013). Micro-fibre pollination bags and high viability *Pinus patula* pollen enhance cone survival and seed set during controlled pollination. South African Journal of Botany 69(4):469-475.

Nonwoven Industry (2021). What are the types of nonwovens? Online exclusives. https://www.nonwovens-industry.com/contents/view_online-exclusives/2021-09-08/what-are-the-types-of-nonwovens/

Prasad PVV, Boote KJ, Allen LH (2006). Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [*Sorghum bicolor* (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. Agriculture and Forestry Meteorology 139(3-4):237-251. doi:https://doi.org/10.1016/j.agrformet.2006.07.003.

PBS International (2025a). Why our bags are best? https://www.pbsinternational.com/pbs-research/

PBS International (2025b). Intelligent design-why our bags are best. https://www.pbsinternational.com/our products/intelligent design/

PBS International (2025c). Grasses research-why our bags are best. https://www.pbsinternational.com/our products/grasses-products/grasses-research/

Pickering RA (1977). Production of doubled haploid barley Report of the Welsh Plant Breeding Station, UK for 1976, pp. 61-63.

Pickering RA (1982). The effect of pollination bag type on seed quality and size in *Hordeum* inter- and intraspecific hybridization. *Euphytica* 31(1982):439-449.

Schaffert RE, Virk DS, Senior H (2016). Comparing pollination control bag types for sorghum seed harvest. Journal of Plant Breeding and Crop Science 8(8):126-137.

Schaffert RE, Virk DS, Senior H (2018). Are nonwoven synthetic pollination bags a better choice for sorghum breeding? Journal of Plant Breeding and Crop Science 10(3):58-68. https://doi.org/10.5897/JPBCS2017.0704

Schertz KF, Clark LE (1967). Controlling dehiscence with plastic bags for hand crosses in sorghum. Crop Science 7(5):540-542.

Singh VP, Kour K, Bakshi P, Bhat A, Kour S, Bhat D (2022). Economic analysis of bagging in litchi fruit: a feasibility estimation from Jammu Region. Economic Affairs https://doi.org/10.46852/0424-2513.1.2022.12.

Smith DC, Mehlenbacher SA (1994). Use of Tyvek housewrap for pollination bags in breeding hazelnut (*Corylus avellana* L.). HortScience 29(8):918.

Stevanato P, Ravi S, Townson P, Virk DS, Senior H (2024). Molecular fingerprinting confirms pollen-proofing of nonwoven pollination control fabrics in sugar beet. Discoveries in Agriculture and Food Sciences 12(1):25-41. DOI:https://doi.org/10.14738/dafs.121.16374

Subrahmanyam NC (1977). Haploidy from *Hordeum* interspecific crosses. I. Polyhaploids of *H. parodii* and *H. procerum*. Theoretical and Applied Genetics 49(5):209-217.

Sumangala S, Giriraj G (2003). Seed yield, test weight and oil content in sunflower enotypes as influenced by various pollination methods and seasons. Helia 26:143-148. https://doi.org/10.2298/HEL0338143S.

Townson P, Virk DS, Senior H (2020). Evaluating the pollen proofing of nonwoven synthetic fabric pollination control tents for sugar beet. Journal of Plant Breeding and Crop Science 12(3):228-236. DOI:https://doi.org/10.5897/JPBCS2020.0904

Trammell M, Pittman DG, Virk DS, Senior H (2020). Assessing the effectiveness of nonwoven fabric pollination tents for improved grass breeding. Journal of Plant Breeding and Crop Science 12(3):200-218. https://doi.org/10.5897/JPBCS2020.0893

Vogel K, Sarath G, Mitchell R (2014). Micromesh fabric pollination bags for switchgrass. Crop Science 54:1621-1623. https://doi.org/10.2135/CROPSCI2013.09.0647.

Wang WH, Gong RH (2006). Thermally bonded nonwoven filters composed of bi-component polypropylene/polyester fiber. II. Relationships between fabric area density, air permeability, and pore size distribution. Journal of Applied Polymer Science 102:2264-2275. DOI https://doi.org/10.1002/app.24169

Windham GL, Williams WP (2007). Note: Effect of ear bagging systems on Aspergillus flavus kernel infection and aflatoxin contamination of corn hybrids grown in the field. Phytoparasitica 35(3):277-281. doi:https://doi.org/10.1007/BF02981161.

Yun HG, Kim DJ, Gwak WS, Shin TY, Woo SD (2017). Entomopathogenic fungi as dual control agents against both the pest *Myzus persicae* and phytopathogen Botrytis cinerea. Mycobiology 45(3):192-198. doi:https://doi.org/10.5941/MYCO.2017.45.3.192