

Weed Management Efficiency of Pre- and Post-Emergence Herbicides in Direct-Seeded Rice

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ABSTRACT

Direct-seeded rice avoids puddling and transplanting, but it hands weeds a head start, and herbicides applied before and after crop emergence have become the main tool for managing them. This narrative review asks how well pre-emergence and post-emergence herbicides manage weeds in direct-seeded rice and how much weight the published evidence can bear. It draws on work on the weed flora of the system, the behaviour of soil-applied products such as pendimethalin and of foliar products with different modes of action, the role of water, tillage and crop competition, the spread of herbicide resistance, and the way efficiency itself is measured, and it reports no new data. Pre-emergence products are best seen as a way of suppressing the first flush of germinating grasses and small-seeded broadleaves, post-emergence products as a way of correcting what escapes, and neither group is complete without the other or without good water and crop management. Reported efficiency depends on weed flora, application timing, soil moisture and the definition used, so numbers from different studies are rarely comparable. Repeated use of a few modes of action has selected resistant biotypes and shifted the flora towards sedges, broadleaves and weedy rice. The review concludes that herbicides work best as part of a sequenced, integrated programme, and it lists what a comparable and decisive evaluation would report.

Keywords: Direct-seeded rice; Pre-emergence herbicides; Post-emergence herbicides; Pendimethalin; Weed control efficiency; Herbicide resistance; Narrative review

Citation: Carvalho, McAllister and Holloway [2017]. Weed Management Efficiency of Pre- and Post-Emergence Herbicides in Direct-Seeded Rice. DOI: [10.62649/v5.i04.2017.pp47-56](https://doi.org/10.62649/v5.i04.2017.pp47-56)

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Article Information: Received: February 9, 2017 Accepted: July 3, 2017 Published: November 16, 2017

Article Class: Review Article

1. Introduction

Rice has traditionally been grown by raising seedlings in a nursery, puddling the field and transplanting by hand into standing water. The system works, but it asks for a great deal of labour at a time when labour is scarce, and a great deal of water at a time when water is no longer cheap [1, 2]. Sowing seed directly into the field, either dry into prepared soil or wet onto puddled soil, removes the nursery and the transplanting, and for

that reason direct seeding has spread across many rice-growing regions [2, 3]. What the farmer gains in labour and time at establishment, however, is paid back in weeds.

In a transplanted field the seedlings are already tall when they enter the water, and a standing layer of water holds back many weed species. In a direct-seeded field the crop and the weeds germinate together, there is no water layer to hold the weeds back in the first weeks, and the crop is

small just when the weed flush is at its largest [4, 5]. Weeds are widely regarded as the most serious biological constraint of direct-seeded rice, and losses to weeds have long been recognised as among the largest losses to any group of crop pests [6, 7]. It is not surprising that growers turn to herbicides first.

Two groups of herbicides dominate the practice. Pre-emergence products, applied to the soil soon after sowing, act on weed seeds as they germinate; pendimethalin is a well-known example. Post-emergence products are sprayed on weeds that have already emerged and differ widely in which weeds they kill. Both groups are credited, in reports and in advisory material, with high weed-control efficiency. What is much less clear is what that phrase means from one report to the next, how much of it survives a change of field, season or water regime, and what happens to it when the same products are used year after year.

This article is a narrative review. It draws on published work on the weed flora of direct-seeded rice, the behaviour of soil-applied and foliar herbicides, the role of water, tillage and crop competition, the spread of resistance, and the way efficiency itself is measured and costed, and it reports no new data. Its aim is to say what pre-emergence and post-emergence herbicides can reasonably be expected to do, what limits that expectation, and what a comparable evaluation would need to report. The aim is an honest account of what is known and what is merely repeated from one report to the next.

2. Literature Review

2.1 Direct Seeding and the Weed Problem

The shift to direct seeding is driven by labour, water and cost, and the agronomic literature on it is large [1]. Reviews describe the practice as feasible and often profitable but not free of trouble: stand establishment, nutrient management and weed control are the problems that recur [2]. Weeds head the list. A weed that emerges with the crop competes on equal terms for light, water and nutrients, whereas a weed that emerges after the crop is established is usually at a disadvantage, so the timing of emergence matters as much as the identity of the weed [8, 9].

A comprehensive review of weed management in direct-seeded rice set out the main options: land preparation and stale-seedbed practices, water management, crop and cultivar choice, seed rate and spacing, hand weeding and herbicides [4]. It also made a point that bears on everything below: herbicides are one component of a programme and

rarely the whole of it. A later account for dry-seeded systems in Asia reached a similar view, stressing weed ecology as the basis for choosing a strategy [5]. This review follows that lead and treats herbicides as tools whose performance depends on the system around them. None of these steps is hard, but each one is easy to leave out when a season is busy.

2.2 Weed Flora of Direct-Seeded Rice

The flora of direct-seeded rice is a mixture of grasses, sedges and broadleaf weeds, and the proportions differ with ecosystem, season and water regime. Barnyard grass and related *Echinochloa* species are among the most damaging grasses and have been studied in detail for their germination, emergence and growth [8, 10]. Annual sedges such as *Cyperus difformis*, *Cyperus iria* and *Fimbristylis miliacea* are common and troublesome [11], and broadleaf species add to the mixture. The point of listing them is practical: a herbicide that does well on grasses may do little to sedges, and a report that does not name the weeds present tells a reader very little.

Seed ecology helps explain why the flush after sowing is so large and why it is hard to hit with a single treatment. Weed seeds in the soil differ in dormancy, depth of emergence and requirement for light or fluctuating temperature, so emergence is spread over time rather than concentrated in one week [12]. A pre-emergence product can act only on the cohort that is germinating while it is active; later cohorts must be met by something else. This is one reason sequential programmes are common in practice.

Weedy rice deserves separate mention. It is a weedy form of the crop species itself, it emerges with the crop, and it is a growing problem where direct seeding is practised [13, 14]. Because it is so close to the crop in biology, herbicides that spare the crop tend to spare weedy rice as well, and management leans on seed quality, rotation, water and cultural methods. A review that spoke only of herbicides would miss this weed altogether.

2.3 Pre-Emergence Herbicides and Pendimethalin

Pre-emergence herbicides are applied to the soil surface soon after sowing, before the crop and weeds have emerged, and they work by being present in the upper soil layer when weed seeds germinate. Pendimethalin, a dinitroaniline herbicide that interferes with cell division in germinating seedlings, is one of the best known; other soil-applied products are also used in rice.

The general pattern described for soil-applied products is activity on germinating grasses and small-seeded broadleaves and weaker activity on sedges and on weeds that have already emerged [4, 15].

These products depend on soil. They need enough moisture at the surface to be active and to form an even layer, they bind to organic matter and clay, and they can be lost or moved by heavy rain or irrigation soon after application [16]. In dry-seeded systems the timing of the first irrigation or rain relative to application is therefore not a detail but part of the treatment. Studies of dry-seeded rice that compare establishment methods and tillage with herbicide treatments show how much the outcome of a soil-applied product can change with the system it is applied into [17, 18]. A grower reading a trial report wants an answer to a plain question: would this have worked in my field?

A soil-applied product also has a limited life. Its effect fades as it is degraded, bound or leached, and weeds that germinate after that point meet no barrier. Because direct-seeded rice offers weeds a long season of germination, the question is not whether a pre-emergence product works but for how long, on which weeds, and what follows it. The literature rarely answers all three in the same report.

2.4 Post-Emergence Herbicides

Post-emergence herbicides are applied to weeds that have emerged, and their activity depends on the mode of action. Some act mainly on grasses, some on sedges and broadleaves, and some on a wide range of species; Table 1 sets the two groups side by side. A foliar product is only as good as its match to the weeds that are actually present and to their size at spraying, which is why survey and timing matter [4, 19].

Timing is the practical constraint. Weeds that are sprayed early are small and easy to control, and weeds that are sprayed late are larger, more competitive and less affected [5, 9]. The window is narrow, and a wet spell, a late labour arrangement or a broken sprayer can close it. Some of the appeal of pre-emergence products lies in the fact that they do not depend on the farmer catching the right week, although that convenience is bought at the price of acting before the weeds have shown which of them will need controlling. That is a modest statement, and it is the one the literature can currently carry.

Table 1. Pre-emergence and post-emergence herbicide use in direct-seeded rice compared.

Attribute	Pre-emergence (soil-applied)	Post-emergence (foliar)
Timing	Soon after sowing, before weeds and crop emerge [4]	After weeds have emerged, at early growth stages [5]
Main targets	Germinating grasses and small-seeded broadleaves [4, 18]	Depends on mode of action; some grass-only, some broad [4, 19]
Main strength	Suppresses the first flush when the crop is least competitive [5]	Corrects escapes and late flushes; flexible in timing [17]
Main limit	Needs moisture; weak on sedges and established weeds [15]	Narrow window; resistance risk where one mode of action dominates [26, 33]
Moisture link	Activation and loss depend on rain and irrigation [16]	Foliar uptake depends on weather and weed size; water cover helps afterwards [20]

Note: Qualitative comparison of general patterns; individual products, labels and local conditions differ. No efficacy figures are given because they depend on flora, timing and moisture.

2.5 Water, Tillage, Residues and Crop Competition

Herbicides do not act alone. Water is the strongest ally: a flooded or saturated soil suppresses the emergence of many species that are not adapted to flooding, and rice and weeds differ in how they cope with it during emergence and early growth [20, 21]. The same field with and without early flooding is, from a weed's point of view, a different field, and herbicide trials that do not report water management are hard to interpret.

Tillage and residue change the seedbed. Surface residue can intercept soil-applied product and affect weed emergence, and the tillage system changes which seeds sit near the surface [17, 22]. Reviews of weed ecology under conservation agriculture note the same dependence on the surface layer [23]. Crop competition also counts. Competitive cultivars, narrower spacing and adequate seed rate make the crop a better neighbour and reduce the work the herbicide has to do [19, 24, 25]. Such differences look small in a single season, yet they add up across years of the same programme.

2.6 Herbicide Resistance and Weed Shifts

Resistance is the long-term cost of relying on a few modes of action. Reviews of resistant weeds worldwide record steady growth in the number of resistant biotypes and species, with rice among the affected crops [26, 27]. Resistance can arise through changes at the target site or through mechanisms that reduce the dose reaching it, and

the second kind can confer cross-resistance to products that the weed has never met [28, 29, 30, 31].

Resistance is only one form of change. Where a few products control grasses well, the flora tends to move towards species that those products do not control, such as sedges and broadleaves, and the same logic applies to any product with a narrow spectrum. Resistance to products that act on a particular enzyme or that mimic plant hormones has been documented in broadleaf and sedge weeds of several crops [31, 32]. The management literature is consistent in advice: rotate and combine modes of action, use cultural methods alongside herbicides, and start with clean seed and clean fields [33, 34].

3. Materials and Methods

3.1 Scope and Question

The review asks a single question in two parts: how well do pre-emergence and post-emergence herbicides manage weeds in direct-seeded rice, and how far can the published evidence be trusted to say so? It is limited to herbicides used in the crop and does not attempt a full account of non-chemical methods, though these enter where they change herbicide performance. It does not report any new field trial, and it gives no efficacy percentages or doses because they depend on product, flora and conditions that differ between reports.

3.2 Literature Assembly

The review draws on peer-reviewed work in five areas: weed biology and ecology in direct-seeded rice; the behaviour of soil-applied and foliar herbicides; water, tillage and crop competition; herbicide resistance; and the economics and environmental effects of herbicide use. Sources were taken from reviews and widely cited papers and were extended by following their references. Only publications dated no later than the year of this article were used.

We did not run a formal systematic search and we do not claim one. This is a narrative synthesis, and the choice of sources reflects the authors' judgement of what is established and relevant. Readers should therefore treat the review as a structured reading of the literature and not as a count of it. No effect sizes were pooled, and none are reported; where a source gave a figure that depended on its own conditions, we describe the pattern and leave the figure aside.

3.3 Appraisal Framework

To judge how far a report on herbicide performance can be trusted, we used a short framework of four questions. Is the weed flora described? Is the time of application tied to the weed and crop stage? Are soil moisture and water management reported? Is the measure of efficiency defined? Table 2 lists the factors that these questions are meant to capture. A report that answers none of them can still be correct, but a reader has no way to tell.

Table 2. Factors that modify herbicide performance in direct-seeded rice.

Factor	How it acts	Report
Weed flora	Species differ in susceptibility and in time of emergence [10, 11]	Species present and their density at application
Application timing	Early weeds are easier to control; late sprays meet larger plants [5, 9]	Days after sowing and weed stage
Soil moisture and water	Affects activation, loss and the seedling flush [20, 21]	Irrigation and rain around application
Soil and residue	Organic matter and surface residue bind or intercept product [17, 22]	Soil type, residue cover, tillage
Crop competition	Cultivar, row spacing and seed rate change weed pressure [24, 25]	Cultivar, spacing and seed rate
Spray practice	Volume, nozzle and formulation affect delivery	Product, dose basis and equipment

Note: Factors are those discussed in the cited agronomic literature; the last column is the authors' suggestion of what a report should state.

4. Results

4.1 What Pre-Emergence Herbicides Contribute

The published accounts agree on the role of pre-emergence products: they reduce the first flush of germinating weeds, which is the flush that coincides with the crop's most vulnerable stage, and they reduce the pressure that later treatments must handle [4, 5]. Their strengths are on grasses and on small-seeded broadleaves, with weaker effects on sedges and on weeds that were already up at application [15, 18].

They also come with conditions. Soil moisture, residue and rainfall after application shape the outcome, and the product's effect decays with time, so that Figure 1 shows a window and not a permanent shield. A farmer who sows into dry soil and waits many days for the first irrigation is not applying the same treatment as one who irrigates promptly, even if the label and the dose are the

same [16, 17].

In practical terms, pre-emergence products buy time for the crop. By holding down the first flush they give rice a chance to establish before weeds can compete, which matters because early-emerging weeds do the most damage and late-emerging weeds do the least [8, 9]. The gain is real but it is a gain in time and not a permanent solution. The point is not that a trial is weak, only that its result travels less far than its abstract suggests.

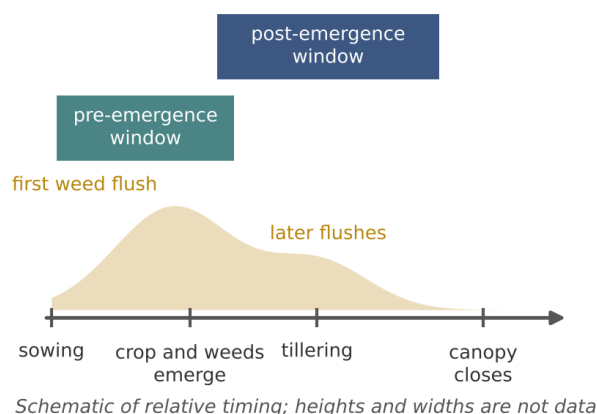


Figure 1. Timeline of the season in direct-seeded rice with typical windows for herbicide action (schematic, not data).

4.2 What Post-Emergence Herbicides Contribute

Post-emergence herbicides contribute flexibility and precision. They can be chosen after the flora has been seen, matched to the weeds present and timed to the weeds' stage, which a pre-emergence product cannot do [4, 5]. Figure 2 sketches the general pattern: a product active mainly on grasses leaves sedges and broadleaves behind, a product of broader action covers more groups, and a product aimed at broadleaves leaves grasses behind.

This pattern explains much of the variation between reports. A trial in a grass-dominated field will give a high efficiency for a grass-active product and a low one for a broadleaf-active product, and the reverse in a field dominated by sedges. Neither result is wrong; they describe different fields [10, 11]. It is only when results are compared across fields without mention of flora that the picture becomes confused.

A further difference is risk. Because post-emergence products act on a defined target in a few modes of action, and because they are often used more than once, they carry much of the resistance pressure described in the literature [26, 33]. A sprayer that relies on one mode of action

every season is, in effect, running a selection experiment. This is why one product can look excellent in one report and ordinary in the next.

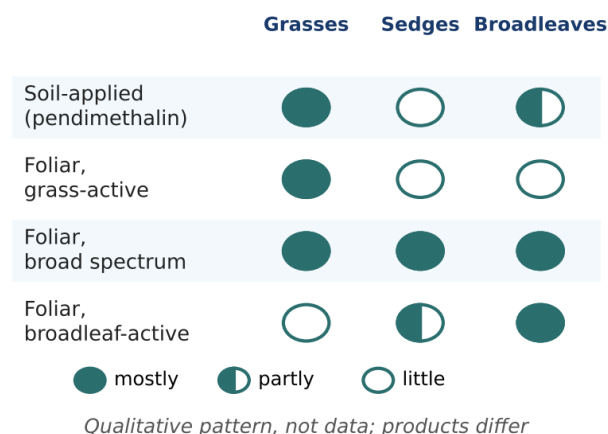


Figure 2. General pattern of weed-group coverage by herbicide type (qualitative schematic, not data; individual products differ).

4.3 Combining and Sequencing Treatments

The consistent message of the reviews and of field studies is that a sequence works better than a single treatment. A pre-emergence product holds back the early flush, a post-emergence product is chosen to deal with what has escaped, and cultural measures such as water, spacing and cultivar reduce the burden on both [4, 18, 19]. The sequence is also the sounder strategy against resistance, because it spreads selection across modes of action instead of loading it on one [33, 34].

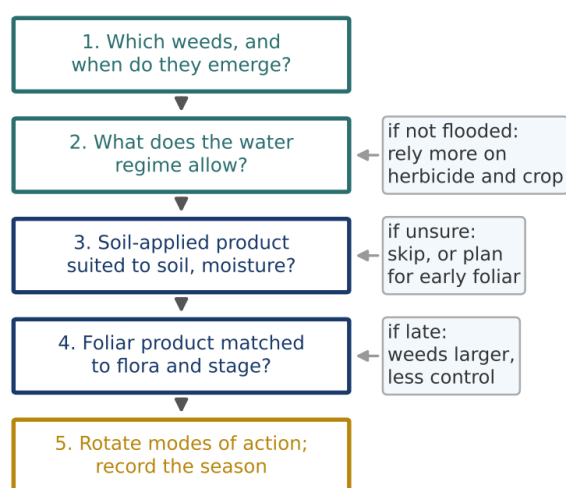
Planning a programme can be set out as a short series of decisions, which Figure 3 sketches. What are the weeds, and when will they emerge? What does the water regime allow? Is a soil-applied product suitable for the soil and moisture at sowing? What will be sprayed after emergence, and with which mode of action? None of these decisions is exotic, but a farmer who skips the first will usually get the rest wrong [35, 36].

Mixtures and ready-made combinations add a further layer. Applying two modes of action together is one of the tactics recommended against resistance, and it can widen the range of weeds controlled in a single pass [33, 34]. But a mixture is not a cure for a poor programme: a partner that the weeds already tolerate adds cost without adding control, and a trial of a mixture alone cannot say which component did the work. Reports that name only the combined product are, for that reason, of limited use to anyone who wishes to rotate or adjust.

Integrated approaches are described in the weed science literature as the more durable option, yet adoption is often slow because the benefits come later and the costs come now [37, 38]. This is a general property of the field and not a feature of rice, but it explains why programmes in direct-seeded rice so often reduce to one herbicide and one hand weeding. A saving that disappears once labour and application are priced is not a saving a hired worker would see.

4.4 How Weed Control Efficiency Is Measured

Weed control efficiency is usually expressed as the reduction in weed biomass in a treated plot relative to an untreated plot, but the term is used loosely, and density-based, biomass-based and yield-based measures all appear under similar names (Table 3). The measures answer different questions. Density says how many weeds are present, biomass says how much they weigh, and the weed index says how much yield was lost against a weed-free standard [7, 39].



Schematic sequence, not a prescription

Figure 3. Decision sequence for planning a weed programme in direct-seeded rice (schematic, not a prescription).

Because a biomass reduction is a ratio, it depends on the denominator. A treatment that leaves the same number of weeds can look better in a field where the untreated plot was heavily infested and worse in one where it was lightly infested [40]. Sampling time matters as well: efficiency measured shortly after a treatment is not the same as efficiency at the end of the season, when late flushes have grown. Studies of dose and response have their own conventions for expressing efficacy, which are not the same as those of field trials [39, 40]. Reviews are more useful when they say where the evidence stops than when they smooth the edges over.

Table 3. Common ways of expressing weed control efficiency and what each leaves out.

Measure	What it expresses	What it hides
Weed density reduction	Fewer plants per unit area than an untreated plot [39]	Plant size and competitive effect
Weed biomass reduction (WCE)	Dry weight relative to the untreated plot, as a proportion [40]	Dependence on how heavy the untreated plot was
Weed index	Yield loss relative to a weed-free plot [7]	Weed-free standard may itself differ in cost
Species-wise control	Efficiency on named weeds [10]	Flora shifts over seasons [29]
Net return	Income after herbicide, labour and application [41, 42]	Price changes and non-market costs

Note: Definitions are those in common use in the agronomic literature; the third column is the authors' reading.

Species-wise reporting is the most informative and the least common. Pooling all weeds into one figure hides the very pattern, grasses controlled and sedges not, that determines whether the programme will hold over seasons [10, 29]. For that reason, comparing a number from one report with a number from another, as advisory notes often do, is rarely justified.

4.5 Economics and Environment

Herbicides are widely used because they save labour and because, in many places, hand weeding is hard to find or costly [41]. A fair economic account counts the product, its application, any labour for follow-up weeding and the value of the yield saved, and it expresses the result as net return and not only as the cost of a spray [4, 41]. Cheap products used with poor timing can cost more than dearer ones used well, and a spray that has to be repeated because the first one missed its window is a cost that few advisory budgets show.

The environmental side is equally part of the sum. Pesticides carry risks to the people who apply them and to the places where they end up, and rice fields drain to ditches, streams and groundwater [42]. Herbicides have been described as a two-edged sword: they bring benefits, they bring risks, and the balance depends on how they are used [16]. Intensive production more generally has been shown to carry environmental costs that sustainable practice must address [43]. A review of efficiency that ignored all this would be incomplete. Read this way, a poor result in one field is neither a failure of the product nor proof that it works elsewhere.

Hand weeding is the usual comparison for herbicides, and it deserves a fair hearing. It is selective, it can be timed to the weeds actually present, and it leaves no residue, but it asks for labour at the same narrow windows when labour is dearest, and in many regions that labour is no longer available at a price growers will pay [2, 41]. The realistic choice for most growers is not between herbicides and no herbicides, but between a thoughtful programme and a careless one.

5. Discussion

5.1 Interpretation and Practical Reading

The main conclusion of this review is a conditional one. Pre-emergence and post-emergence herbicides both work, and each works best against particular weeds at particular times. A pre-emergence product is most useful where the first flush is large and where moisture at application is reliable; a post-emergence product is most useful where the flora has been assessed and the spray can be timed to the weeds' stage. Used together and alongside cultural methods, they give the most dependable control [4, 5, 19].

The second conditional concerns evidence. High efficiency figures in advisory material are seldom portable, because they depend on the flora, the timing, the water regime and the definition used. A reader who wants to apply a result to a new field has to ask whether that field resembles the one in the study, and the reports often do not say enough to answer [17, 20].

A third point concerns the long run. Repeated use of a narrow set of products will, sooner or later, select for resistance and shift the flora, as the resistance literature makes clear [26, 28]. The weed that remains after a successful programme is not a random sample of the weeds that started; it is the part of the flora that the programme could not control, and next season's problem begins there.

Three findings would change this reading. A body of well-reported comparisons showing that a single treatment matched a sequence across flora and water regimes would weaken the case for programmes. Evidence that efficiency measures converge when applied to the same plots would reduce the concern about definitions. And a clear demonstration that resistance does not arise under repeated use in direct-seeded rice would remove one of the main arguments for diversity. None of these has been shown. It is a habit worth keeping even when the answer seems obvious.

5.2 Limitations

This is a narrative review and shares the limitations of that form. The selection of sources reflects judgement, and a different reader might have chosen differently. No formal search was run, no quality scoring was applied, and no effects were pooled. Readers who need a quantitative answer should look to systematic reviews and meta-analyses of field trials, where these exist or can be made.

The review also draws on work from several regions and cropping systems, and the weed flora, the products registered and the water regimes differ between them. A finding from one region may not transfer to another. Finally, the review does not cover every herbicide used in direct-seeded rice, and it says little about newer products and tolerant cultivars, which may change the picture. A field that is wet at the right moment behaves very differently from one that is not.

5.3 Implications for Evaluation Design

A study that could settle the question of efficiency would describe the weed flora at the start and the end, tie each application to the weed and crop stage, report soil moisture and irrigation around application, and use plots large enough and replicated well enough that the treatment, not the plot, is the unit of analysis. It would include an untreated plot and a weed-free plot, express efficiency in more than one way, and report it by species group [39, 40].

On the economic side, the study would price every input, including labour for follow-up weeding, and report net return alongside efficiency [41]. It would run for more than one season, so that shifts in the flora and early signs of resistance can be seen [33]. These requirements add cost, but a trial that omits them gives a number that cannot be used by anyone else.

5.4 Directions for Future Work

Three needs stand out. First, a formal systematic review of field comparisons in direct-seeded rice, with a transparent search and an appraisal of reporting quality, ideally with a standard way of expressing efficiency. Second, multi-season studies of programmes that rotate and combine modes of action, with monitoring of flora and resistance [27, 34]. Third, studies that connect herbicide use to environmental fate and to farm economics, so that efficiency can be judged against its costs [42, 43].

5.5 Practical Reading for Advisers and Growers

For an adviser, the sensible position is neither to dismiss herbicides nor to promise results. A grower can make a programme from a few questions asked in order: what are the weeds, how will the field be watered, what will go on before emergence and what will follow after, and which modes of action have been used before? A written record of products, dates, weather and weed stage is as important as the product itself, because it is the only way a season's experience can be used the next time [35, 36].

Such records are not a substitute for a trial, and they should not be reported as one. They can nonetheless tell a farm whether a programme is working, whether a flora is changing and whether a product is losing its effect, and they allow rotation of modes of action to be planned and not improvised [33, 37]. Nothing here argues against using herbicides; it argues for using them with the field in view.

A last practical point concerns expectations. A grower who hears that a product gave very good control in a trial should ask where, against which weeds and compared with what, because the same product can disappoint in a field that differs on any of the three. Advisers who pass the question on, instead of passing on the number, serve growers better over the long run [7, 35].

6. Conclusion

Pre-emergence and post-emergence herbicides are both useful in direct-seeded rice, and neither is sufficient alone. Soil-applied products such as pendimethalin hold back the early flush when moisture is right, foliar products correct what escapes when they are matched to the flora and timed to the weeds, and water, tillage and crop competition decide how much work either has to do. The evidence, as we can responsibly summarise it, does not support a single efficiency figure for either group, because the figure depends on flora, timing, water and the definition used.

For the practitioner the message is practical rather than discouraging. Sequence the treatments, match the product to the weeds, record what was done, and rotate modes of action. For the researcher, the opportunity is a set of multi-season, well-described and fully costed comparisons that report efficiency in comparable ways. These points apply with equal force to any new product or mixture, not only to those

discussed here.

7. Acknowledgements

The authors thank colleagues who commented on earlier drafts of this review.

8. Funding

This work received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

9. Conflict of Interest

The authors declare no conflict of interest.

10. Author Contributions

C.C. conceived the review and wrote the sections on weed ecology and water management. D.M. wrote the sections on herbicide use and resistance. A.H. wrote the sections on crop competition, efficiency measures and economics. All authors revised the manuscript and approved the final version.

11. Ethics Statement

This is a review of published literature. No human participants or animals were involved and no ethical approval was required.

12. Data Availability

No new data were generated. All sources are cited in the reference list.

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