# Kinetic Resolution of the Interactions Between Agrochemical Products and Adjuvant Systems upon Mixing

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## Abstract

The addition of an adjuvant to a pesticide usually occurs in a mix-tank, before spray application to the crop. Their interaction is potentially crucial to overall efficacy but has received little attention from a physical-chemical perspective. Study was undertaken by laser diffraction, Raman spectroscopy and small angle X-ray scattering to resolve these physical processes. It was shown that migration of the pesticide into the adjuvant droplet occurred in all cases studied. The level of transfer was dependent upon adjuvant level, adjuvant solubility and surfactant level. For suspension pesticides, dissolution of crystallites within the droplet occurred to a degree limited by solubility. The results directly demonstrate the transfer of the pesticide into the adjuvant carrier. This indicates that for emulsion based pesticides, application to the target is likely as a homogeneously mixed droplet, whilst for suspension pesticides, solubility may limit transfer and dissolution, leading to heterogeneity in the applied particles.

## Keywords

Adjuvant, Pesticide, Mix-tank, Transfer

## Introduction

Activator agrochemical adjuvants are used to increase cuticular uptake of foliar applied pesticides and exist either as an integral part of the pesticide product (formulation adjuvant), or as an additional additive (spray adjuvant).[1] Either type of adjuvant exists to improve the bioavailability of a pesticide and achieves this by two main mechanisms, namely, control over the physicochemical properties of the pesticide system and/or control over the interaction of pesticide with the target crop.[2-8] Control of the physical properties can improve rainfastness,[6-8] increase pesticide activity[9,10] and improve compatibility of the active ingredient with the crop target.[9,11,12]

Activator adjuvants generally consist of an oil/surfactant mixture, in which the oil is based on either a hydrocarbon or vegetable oil source[1] and a non-ionic surfactant, as this reduces environmental toxicity.[13] Other types of adjuvant systems exist and serve a more specific use, such as stickers and spreaders which improve pesticide adherence and pesticide coverage upon a crop, respectively.[1,3] Next generation adjuvants also show some promise based upon nanomaterials such as nanoparticles[14] and liquid crystalline nanoparticles,[15,16] of which the potential benefits are improved rainfastness,[16] reduced environmental toxicity[15,16] and improved pesticide delivery efficiency.[16,17]

The cuticle of a plant leaf is a composite structure made of polymeric cutin, which is both impregnated (intracuticular) and coated (epicuticular) with a complex mixture of waxes.[18] The epicuticular wax matrix prevents good wetting of a plant leaf due to the hydrophobic nature of the wax.[19] Adjuvants have been shown to improve the efficiency of pesticides by modification of the epicuticular wax layer *via* improved contact with the spray droplets.[20,21] Improved penetration of the cuticle also occurs as the adjuvant disrupts the cuticle structure, which allows enhanced foliar uptake of the active ingredient.[8,20,22-24] Although these effects have been well

studied, there has been less attention paid to the nature of the interaction between droplets of the adjuvant system and the particles containing the pesticide itself from a physicochemical standpoint.

Adjuvants are typically added to a mix-tank which already contains the pesticide, usually in the form of an emulsion or suspended solid in water.[25] The mixture formed is then applied onto the crop by spray techniques. Most studies on the interaction between adjuvant and pesticide have concentrated on the overall effects on the plants.[26] A reduction in effectiveness due to the adjuvant-pesticide interaction is often used as a measure of interaction, and mechanisms such as metal ion antagonism[27] or pH,[28] are proposed as the cause. The envisaged modes of interaction between the pesticide product as either a suspension or an emulsion, and the adjuvant, are depicted schematically in Figure 1.

The two extreme cases of interaction are either complete non-interaction or complete interaction. If complete non-interaction occurs, the droplets or particles would not mix, and behave as discrete entities which would deliver the individual properties of each system to the crop. In contrast, complete interaction is when inter-particle mixing occurs through molecular transfer between droplets or through collisional mixing. This would lead to the application of droplets that contain a compositionally averaged mixture of all the components. It may be anticipated that in many cases the interactions between the adjuvant and pesticide falls between these two extremes as a partial or arrested mixing process.

The intention of this work is to study the interactions expected to occur in the mix-tank for selected representative adjuvants and pesticide products. Two agrochemical products were studied as representative emulsion and suspension products, namely Status, an emulsion based herbicide system in which clethodim is the active ingredient, and Folicur, a crystalline suspension based fungicide in which tebuconazole is the active ingredient. The two adjuvants

chosen for this study were selected to represent the common fatty acid ester and mineral oil classes of adjuvants, were an ethyl oleate based adjuvant (product name Hasten, henceforth to be referred as EO adjuvant) and a solvent de-waxed mineral oil based adjuvant (product name Empower, henceforth called MO adjuvant), respectively. The significant chemical components of the systems studied are illustrated in Figure 2.

## Materials & Methods

Adjuvants, Hasten and Empower, and emulsion herbicide product, Sumitomo Status (240EC), were used as supplied by Victorian Chemicals Pty. Ltd.. Suspension fungicide Folicur (430SC) was kindly supplied by Bayer Australia Ltd.. Tebuconazole GC standard was purchased from Sigma Aldrich (Sydney, NSW, Australia). All Milli-Q water (18.2 MΩ resistivity at 25 ºC) was from a Milli-Q Academic water purification system from Millipore (Sydney, NSW, Australia). Borosilicate flat cells (50 x 8 x 0.4 mm) were purchased from VitroCom (Mountain Lakes, NJ).

**Laser Diffraction:** The refractive index of the oil-based liquids was measured directly with a Refracto PX30 refractometer (Mettler Toledo, Columbus, OH) at 20 ºC. The refractive index of the suspension solid based system was calculated by use of the Percepta Platform software (ACD Labs, Toronto, Canada). Density values of the adjuvants and the active ingredients were used as listed on the product safety literature. Laser diffraction was carried out with a Mastersizer S (Malvern Instruments, Malvern, UK) fitted with a 0.05-900 μm lens and a wet mix cell. The volume fraction of the particle size distribution (PSD) of the samples tested was

recorded. Alignment of the Mastersizer S laser took place at the start of a measurement and the background measurement of pure MilliQ water was obtained before each sample was run. All samples were prepared by the same method. A typical example is for the 1:1 Hasten:Status system. Status (0.1 mL) was added to MilliQ water (4 mL) and vortex mixed for 30 s to achieve an opaque mixture. An aliquot (0.5 mL) was removed and used to determine the PSD of the $T_0$ sample, where no adjuvant had been added to the pesticide product. A further aliquot (3 mL) was removed and was stirred with a magnetic follower in a separate scintillation vial. An adjuvant emulsion (0.1 mL) in MilliQ water (4 mL) was prepared, and was vortex mixed for 30 s to achieve a homogeneous mixture. An aliquot of the adjuvant emulsion (3 mL) was removed and added directly to the stirred pesticide emulsion, which coincided with T=0 s for all measurements. A sample (1 mL) was removed after 10 s and added to the stirred (~200 rpm) wet mix cell of the Mastersizer S. Upon equilibration, in which the obscuration level rose to a plateau after 15 s, the particle size distribution of the mixture was recorded. The wet cell was then emptied and flushed with MilliQ water (3 x 130 mL), until no particulate matter registered. Further particle size distributions were determined at 120, 300 and 900 s, after mixing. The PSD of the adjuvant emulsion system was also recorded as a control. Intensity calculations were determined by the difference in intensity between the maximum of the primary particle and that of the adjuvant at the same particle diameter.

**Raman Spectroscopy:** Raman measurements were conducted on a Invia Reflex μ-Raman spectrometer (Renishaw, New Mills, UK) with a Nd:YAG laser (532 nm emission) that was calibrated against silicon. Scans covered the range of 4000 to 400 $cm^{-1}$, with a laser intensity of 50% and 2 accumulations were taken to improve the signal to noise ratio. An agrochemical product solution (0.1% v/v) was taken up into a flat cell by capillary action. The sample was allowed to rest for 5 min to allow all motion of the emulsion droplets to subside. A Raman

spectrum was obtained on an individual droplet, identified by optical microscopy, as well as a background control obtained from next to the droplet. Study of pesticide transfer was achieved by the addition of adjuvant solution (0.1% v/v) by the use of a 29 gauge needle to inject the adjuvant system into the flat cell capillary which contained the agrochemical product solution (0.1% v/v). A Raman spectrum was obtained on an individual mixed droplet, as determined by optical microscope.

**Small Angle X-ray Scattering**: The SAXS/WAXS beamline at the Australian Synchrotron, Clayton, Australia,[29] (flux $10^{13}$ photons/sec) was used to determine the change in crystallite intensity in real time. The set-up utilized to measure SAXS profiles during transfer experiments which involved adjuvants and agrochemical products is shown in Figure 3.[30] Agrochemical products were prepared as a magnetically stirred, aqueous suspension (30 mg/mL, 10 mL) in a scintillation vial (20 mL). The solution was pumped from the scintillation vial, through a cell capillary placed in line with the X-ray beam and then returned to the vial by use of a peristaltic pump (Ismatec, IPL, Switzerland) at a rate of 10 mL/min. The acquisition of SAXS diffraction patterns (2 s acquisition, 10 s delay between frames, q-range 0.05-1.8 $Å^{-1}$) commenced with circulation of the agrochemical product to obtain initial scatter pattern profiles. The adjuvant was then added directly to the mix vessel, in one aliquot, by use of a syringe pump and the adjuvant and agrochemical allowed to mix before circulation through the capillary. SAXS data were collected with a Pilatus 1M camera (active area 169 x 179 $mm^2$ with a pixel size of 172 x 172 μm) and a sample to detector distance of 733 mm. The acquired synchrotron SAXS patterns were integrated from 2D scatter patterns to a one-dimensional intensity of scattering intensity profile (I(q)) vs. scattering vector (q) using Scatterbrain software packages.[29] The scattering vector is defined by the equation $q = 4\pi\sin\theta/\lambda$, where $\lambda$ is the wavelength of the X-

rays (0.661 Å) and θ is the angle of scattering. Comparison of the change in SAXS patterns took place by the change in normalized intensity of the most intense peak of the crystalline agrochemical-product, after the dilution factor caused by addition of the adjuvant was taken into consideration.

**X-Ray Diffraction:** X-ray diffraction data were collected using a D8 Advance X-ray diffractometer (Bruker, Billerica, Mass.) with Ni-filtered Cu kα radiation (1.54 Å) at 40 kV and 40 mA. Data were collected between 5–50° in 2-Theta, with a step size of 0.02° and a scan rate of 0.5 s per step. Folicur samples were run as supplied as a 43% aqueous suspension. Indexation of the XRD pattern obtained took place with the aid of the published crystal structure of tebuconazole and EXPO2014 software.[31,32]

**Solubility Testing:** Folicur product (1.25 mL, 0.54 g tebuconazole) and adjuvant (3 mL) were weighed into a vial (6 mL). The mixture was roll-mixed (30 rpm) for 48 h to ensure complete saturation before an aliquot (0.5 mL) was removed into an Eppendorf tube (1.75 mL). Centrifugation of the sample to separate the undissolved tebuconazole and adjuvant (15513 × g, 15 min) took place. A sample of the active/adjuvant mixture was dissolved in acetonitrile (10 mg/mL). Dilution to a concentration of 0.1 mg/mL took place into a HPLC vial (1.5 mL). An isocratic, reverse phase HPLC method was used to determine the level of tebuconazole present. The column used was a 50 mm x 2 mm i.d., 4 μm, Synergi POLAR-RP (Phenomenex, Torrance, CA). The HPLC system consisted of a CBM-20A system controller (Shimadzu Corp., Kyoto, Japan) LC-20AD solvent delivery module (Shimadzu Corp., Kyoto, Japan), SIL-20A auto sampler (Shimadzu Corp., Kyoto, Japan) and a CTO-20A column oven (Shimadzu Corp., Kyoto, Japan) set at 40 °C, coupled to a SPD-20A detector (Shimadzu Corp., Kyoto,

Japan). Detection took place at 221 nm, which corresponds to the wavelength of maximum absorption of tebuconazole. An injection volume of 5 μL was used with a mobile phase consisting of acetonitrile/water/trifluoroacetic acid (30:69.9:0.1 v/v) at a flow rate of 0.5 mL/min. All samples were run in triplicate. Comparison against a 5 point standard curve of a pure sample which covered a range of 1-20 μg/mL, was used to determine level of tebuconazole solubility in the adjuvant system.

## Results and Discussion

### *Transfer kinetics and extent measurement using change in particle size distribution*

The particle size distribution of both agrochemical products and both adjuvants was determined in water at levels that would expected to be utilized within the mix-tank prior to crop application. The D50, which relates to the median value of the distribution, of the emulsion herbicide product was 4.1 μm and the D50 of the suspension fungicide was determined to be 1.88 μm. The EO adjuvant and MO adjuvant, had D50 values of 8.28 μm and 36.8 μm, respectively.

Transfer studies were conducted to determine the direction of transfer of material between the pesticide product and adjuvant systems indicated by changes in the particle size distribution. The time dependent changes in the measured PSD on mixing of the systems in the four possible combinations are shown (Figure 4b), where a 1:1 ratio of adjuvant:active product was used.

A typical example of the transfer experiments undertaken for an emulsion adjuvant system with the emulsion herbicide is highlighted (Figure 4b), and shows the addition of MO adjuvant to the emulsion herbicide. This experiment shows a clear change in intensity of the PSD of the mixtures studied, as the process was the slowest studied of the four combinations. After only

10 s of interaction, the population of particles at 4.1 μm indicative of the herbicide had changed and shows a decrease in intensity of particle size distribution, whilst the PSD for MO adjuvant PSD was visible. After 120 s, further decrease in the intensity of the small particles attributed to the emulsion herbicide had occurred and after 900 s, no particle population associated with the emulsion herbicide was evident. The adjuvant particle intensity increased with time and coincided with the decrease in intensity of particles attributable to the emulsion herbicide.

The transfer experiments between the suspension fungicide product and both the adjuvants, were undertaken in the same manner as that for the emulsion herbicide, but yielded different transfer behavior. When the MO adjuvant was added to the suspension fungicide, an immediate decrease in intensity of the active particle is observed, again after only 10 s (Figure 4d). However, unlike the case when mixing emulsion-emulsion systems, the intensity of particles present due to suspension fungicide did not change after the decrease in the initial 10 s, and in contrast to the emulsions did not drop to zero.

***Effect of Product: Adjuvant Ratio on kinetics and extent of transfer***

Further study of the effect the pesticide to adjuvant ratio was carried out by increasing adjuvant levels with respect to pesticide levels. The normalized change in intensity of the pesticide particle distribution with time, clearly shows significant differences between the two broad classes of emulsion and suspension systems (Figure 5).

For the emulsion herbicide, the intensity of the major population attributable to the herbicide product decreased rapidly upon adjuvant addition and essentially dropped to zero over the time period observed (Figure 5a and 5b). Increased adjuvant levels caused this process to occur more rapidly. Transfer also occurred more rapidly with the EO adjuvant than with an equivalent level

of the MO adjuvant. A rapid decrease in intensity of the suspension fungicide PSD, upon addition of the adjuvants, was also observed. However, upon mixing low levels of adjuvant with the suspension fungicide the particle intensity did not drop to zero, and was dependent upon the level of adjuvant present. The EO adjuvant was again more effective than the MO adjuvant, as less ethyl oleate based adjuvant was required to achieve complete transfer of the suspension fungicide, to the adjuvant particles. Complete transfer occurred with the EO adjuvant at a 2:1 ratio of EO adjuvant:suspension fungicide, whereas for the MO adjuvant, a 5:1 ratio of MO adjuvant:suspension fungicide was required.

**Spectroscopic evidence for mixing:** Laser diffraction provided interesting differences between the active:adjuvant combinations, but the technique is non-specific and does not distinguish between aggregation of individual droplets from true mixing. Raman studies were carried out in a 2D-flat cell which allowed the determination of the Raman spectrum of individual droplets by using a narrow transverse section and dilute aqueous conditions. Addition of one system (aqueous adjuvant or aqueous product) to the other creates a mixed interfacial area, within the flat-cell, in which both of the systems mix due to diffusion. This allowed the spectra of a specific droplet to be obtained, before and after addition of the pesticide. Spectra of each individual component, associated adjacent background as well as the mixed droplet, are shown (Figure 6).

The first step in the Raman study was to determine which peaks were exclusive to individual adjuvants and pesticides i.e. peaks which only appear in each other's respective spectra and which do not overlap. This is because, upon transfer, the presence of both peaks in the Raman spectrum would be indicative for the formation of a mixed droplet. The Raman spectrum of the EO adjuvant in Figure 6a, shows a unique indicative peak at 1742 $cm^{-1}$ which corresponds to the C=O bond of the oleate ester oil of the EO adjuvant.[33] The key peak for the emulsion herbicide occurs at 1380 $cm^{-1}$ and corresponds to the symmetric $CH_3$ deformation of

232 alkylbenzenes, which are the major components of Solvesso 150, the solvent of the emulsion
233 herbicide product.[34]

234 Comparison of the MO adjuvant with the emulsion herbicide (Figure 6b) was more difficult as
235 there was no unique peak arising from the MO adjuvant that was not present in the emulsion
236 herbicide, as they both contained significant quantities of aliphatic compounds. The MO
237 adjuvant has a strong peak at 1442 $cm^{-1}$ which corresponds to the aliphatic $CH_3$ deformation
238 mode from components of the mineral oil. Although this peak is present in the emulsion
239 herbicide, the intensity of the peak is low, when compared to the $CH_3$ deformation of
240 alkylbenzenes at 1380 $cm^{-1}$. Different peaks were studied for the EO adjuvant:suspension
241 fungicide system (Figure 6c), due to the presence of the carbonyl groups in both systems. In
242 this instance, the peak at 1656 $cm^{-1}$ in the EO adjuvant system, which corresponds to the C=C
243 bond of the ethyl oleate present, was selected. Comparison was against the peak at 1600 $cm^{-1}$
244 in the suspension fungicide, which corresponds to the aromatic C=C stretching vibration of
245 tebuconazole, the active ingredient of the suspension fungicide product. The Raman spectrum
246 of tebuconazole was obtained as a solution in carbon tetrachloride as it was not possible to
247 obtain a spectrum of the native suspension product in its aqueous suspension form through
248 direct measurement. No transfer was observed for the MO adjuvant:suspension fungicide
249 system, as it was not possible to obtain a clear spectra of the aqueous suspension fungicide
250 system or the mixed droplet system.

251 The addition of the EO adjuvant to the emulsion herbicide produced a mixed droplet containing
252 the components of both systems. This is indicated by the presence of absorbance bands at 1742
253 and 1380 $cm^{-1}$ for the EO adjuvant and emulsion herbicide, respectively (Figure 6a). This
254 shows that transfer between the two emulsion systems has occurred which produced an
255 emulsion droplet containing components of both the EO adjuvant and the emulsion herbicide.
256 Whilst comparison of the MO adjuvant and the emulsion herbicide was more difficult due to

partial overlap of Raman peaks, we were still able to show that MO adjuvant and the emulsion herbicide produced a mixed droplet. Upon formation of the mixed droplet, the ratio of the alkane $CH_3$ deformation at 1442 $cm^{-1}$ and that of the alkylbenzene $CH_3$ deformation at 1380 $cm^{-1}$, increased to an almost equivalent level, which would not be possible without the presence of both the mineral oil based adjuvant and the emulsion herbicide within the same droplet. Similar observation for the addition of the ethyl oleate-based adjvuant to the suspension fungicide was made as, in the mixed system, the spectrum from a single mixed droplet contains peaks from both the EO adjuvant, and active ingredient, tebuconazole, at 1600 $cm^{-1}$ and 1656 $cm^{-1}$, respectively.

**Loss of crystallinity of tebuconazole as an indicator of transfer.** Synchrotron based SAXS is a powerful technique for the study of crystalline materials as the wavelength of the incident radiation is similar to that of the intra-molecular spacing of organic crystals.[35] When paired with a high intensity energy source at a synchrotron, this allows for real-time monitoring of dynamic processes such as the transfer process between agrochemical products and adjuvants. A typical transfer experiment lasted up to 1000 s at which point equilibrium was achieved. In this process, 75 scattering profiles (Figure 7) were generated, which showed the change in intensity of the crystalline diffraction peaks of tebuconazole, the active ingredient in the suspension fungicide studied, with time.

A diluted aqueous solution of the suspension fungicide was prepared and circulated through the capillary through which the X-ray beam passes. SAXS patterns were collected to determine the initial diffraction peaks and intensity associated with pure pesticide. After circulating for approximately 100 s, adjuvant was added, in this case, the EO adjuvant at three times the level of the suspension fungicide present. Addition was initiated using a remotely activated syringe

281 driver, delivering the adjuvant into the pesticide product in several seconds. This caused an
282 instantaneous, precipitous drop in intensity of all peaks associated with the crystallites of
283 tebuconazole. The rate of drop in intensity slowed and after about 500 s, equilibrium was
284 achieved whereby the intensity levels of the crystallites remain unchanged. The experiment
285 was continued for a further 300-500 s, with no further change.

286 Comparison of the intensity of the major tebuconazole diffraction peak at q=1.19 $Å^{-1}$, over time
287 was used to indicate dissolution, as this was the most intense in the q-range studied. The peak
288 at q=1.19 $Å^{-1}$ was calculated to correspond to the (2 0 2) crystal plane of tebuconazole and was
289 determined from the X-ray diffraction pattern with use of the published crystal structure of
290 tebuconazole[31] and EXPO2014 software.[32]

291 Multiple experiments were run with different ratios of adjuvant:suspension fungicide. For the
292 EO adjuvant:suspension fungicide systems, ratios of 1:1, 2:1, 3:1 and 5:1 were studied and for
293 the MO adjuvant:suspension fungicide system the ratios studied were 1:1, 3:1 and 10:1.
294 Changes in intensity of the peak at q=1.19 $Å^{-1}$ for the different combinations are presented
295 (Figure 8).

296 In the case of the ethyl oleate based adjuvant (Figure 8a) the level of adjuvant present
297 significantly affected the intensity of the tebuconazole diffraction peak. The greater the level
298 of EO adjuvant that was present, the greater the decrease in tebuconazole peak intensity.
299 Complete loss of the tebuconazole peak intensity occurred between a EO adjuvant:suspension
300 fungicide ratio of 3:1 and 5:1. For the experiments where the mineral oil based adjuvant was
301 studied, there was essentially no change observed in crystallite intensity even at extremely high
302 levels of adjuvant (Figure 8b). High levels of adjuvant gave rise to a highly viscous system
303 which did not mix easily, which precluded further attempts at higher adjuvant levels.

304

**Solubility of Active Species in Adjuvant**. In order to rationalize the transfer data for suspension fungicide into the adjuvants, the solubility of tebuconazole in the both the ethyl oleate and mineral oil based adjuvant was determined by the phase solubility method.[36] Tebuconazole had a solubility in the EO adjuvant of 6.37±0.25% (w/w) and in the MO adjuvant of 0.21±0.01% (w/w).

**Active Ingredient transfer within mixed Adjuvant-Agrochemical Product Systems**

The transfer of emulsion herbicide into the droplets of either adjuvant was complete and most likely occurs by a compositional ripening process, in which only one particle distribution remains and contains components of both emulsion systems after mixing. The rapid nature of this process was facilitated by the complete miscibility of both systems, the presence of high surfactant levels and the significant entropic driving force for the transfer to occur due to significant reduction in interfacial tension.[37] This rapid process has previously been shown to facilitate transfer of lipids between differently composed emulsion and structured lipid particle systems.[38,39] However, this process has not previously been demonstrated using agricultural products. Both adjuvants studied, upon interaction with the emulsion herbicide, showed complete transfer, but transfer of the emulsion herbicide occurred more rapidly for the ethyl oleate-based adjuvant than for the mineral oil-based adjuvant. Significantly, the EO adjuvant has a much higher surfactant content than that of MO adjuvant, which for a micelle mediated transfer process, would cause the difference in transfer rate.[44] These adjuvant systems require surfactants to be present primarily to facilitate aqueous dispersion of the adjuvant oils; we believe this to be the first time that transfer studies of this nature have been undertaken and it is not yet clear how the impact of the individual components separately impact the transfer process. The transfer of material between product and adjuvant droplets is likely to be important in dictating the ultimate performance particularly in extreme cases such as where very little transfer occurs and the product droplet acts as the carrier to the leaf surface for the

active rather than the adjuvant droplet (bottom right Figure 1) , thus an improved understanding of differences between the impact of components on the transfer process warrants further extensive evaluation and may ultimately provide a design parameter for improved adjuvant systems. Nevertheless the presence of surfactant in agrichemical emulsion formulations is by necessity ubiquitous and a micelle mediated transfer process is proposed to govern the movement of material in this instance.

The direction of movement has been proposed to be determined by the relative lipophilicity of the mobile components in the system. In the case of the emulsion adjuvant, the active ingredient clethodim has a partition co-efficient (log P) of 4.14[40] and ethyl oleate has a log P of 8[41], meaning that it is much less mobile than the active, hence dictating the transfer of active towards the adjuvant droplets, leading to the disappearance of the emulsion herbicide product particles and growth in the size of the adjuvant particles. Similarly, Solvesso 150, a major component in the emulsion herbicide product, is primarily comprised of alkylbenzene compounds.[34] A significant component, which is representative of the Solvesso 150 mixture as a whole, is 1,2,4,5-tetramethylbenzene, which has a log P of 4.0.[42] Essentially, the emulsion herbicide is an active component, clethodim, formulated in an adjuvant system (solvent and surfactant). However, as comparison of both the EO and MO based adjuvants has been consistent, then, this will not affect the conclusion. It is felt that different emulsion pesticides, which may contain different blends of surfactants, may affect the rate of transfer but not the overall end point, which is complete transfer into the adjuvant system with the higher partition co-efficient.

The addition of adjuvant to the fungicide suspension system also showed transfer of the pesticide product into the adjuvant emulsion. However, there was the added complication of a dissolution step to get the active ingredient into solution first, before the transfer could occur. Although transfer was rapid, the extent of the transfer was limited and depended upon both the

relative quantity and the type of adjuvant present. The ethyl oleate-based adjuvant was more effective at enabling transfer of the suspension product than that of the mineral oil-based adjuvant. SAXS showed that although a significant amount of tebuconazole dissolved in the EO adjuvant emulsion, only a minimal amount dissolved in the MO adjuvant. Tebuconazole was much less soluble in the MO adjuvant than in the EO adjuvant. Once saturation of the adjuvant droplet occurred, no further dissolution could occur.

These results suggest several implications for the delivery of pesticide products and their use with adjuvants. First, the rate of transfer between agrochemical emulsion products and adjuvant systems does not depend on the choice of adjuvants in the cases studied here. Complete transfer of the active species into the adjuvant will likely occur rapidly. Application from the mix tank, therefore, will consist of a completely mixed emulsion droplets containing the components of the adjuvant and the agrochemical product. However, in cases where more complex mixtures are made in the tank, eg. different fungicides are mixed with insecticides and foliar fertilizers, understanding the individual impact of components in multiple products could ultimately influence decisions on compatibility from a mixing standpoint. In particular addition of more components that reduce the free surfactant concentration, such as oils with a particularly high solubility for surfactant components, might actually hinder transfer.

A second implication relates to the cases where the adjuvant and a suspension pesticide product are mixed and the active ingredient completely dissolves and transfers to the adjuvant. This is essentially the equivalent of application of a fully miscible system, such as the emulsion concentrate products. This would be expected to give an improved application of the active ingredient in a more effective form as it would be fully integrated within the adjuvant and no longer a crystalline material. Upon application and dry down, distribution across the leaf structure would be more uniform than an application in which crystalline particles are present. Adjuvants can also improve efficacy of the active ingredient by prevention of recrystallization

of the active ingredient.[43] However, if the pesticide is not sufficiently soluble in the adjuvant system and the suspension particles are wetted by the oil phase in the emulsion, the adjuvant will form what is termed a suspoemulsion.[44] Suspoemulsions are a relatively new method for use as agrochemical product formulation systems. Suspoemulsions can give the benefits of combination of materials with significantly different properties[45] but present challenges in achieving long term stability due to flocculation and coalescence problems.[46] However, for transient suspoemulsions formed in the mix-tank, with the time scales used for crop application of less than 24 hours and the agitation of the system, the stability of the system would not be problematic. Application of suspoemulsion products have shown interesting properties where good coverage is less important than that of application of high concentration small deposits.[47]

Finally, within the studies undertaken, the optimal ratio of adjuvant to pesticide was about 3:1 (v/v), whereby, essentially complete transfer of the pesticide product system into the adjuvant has occurred. This correlates with that of the empirically determined ratio of the most effective usage rate, by the manufacturer through greenhouse or field trials. On average, the emulsion herbicide Status is typically used at 325 mL/hectare[48] whereas the suspension fungicide Folicur is utilized at a loading of approximately 295 mL/hectare.[49] For both adjuvants studied, and for manufacturer recommended adjuvants for use with the emulsion herbicide and the suspension fungicide, the recommended level of adjuvant use is 1L/hectare.[50]

Laser diffraction was utilized to show that transfer of the emulsion based herbicide took place into both adjuvant systems studied. The transfer was rapid, essentially complete and forms a compositionally homogeneous emulsion system. Thus, use of an adjuvant with an emulsion herbicidal product within a mix-tank would lead to the deposition of a homogeneously mixed emulsion onto the crop, which should allow an effective delivery of the active ingredient. Transfer of the solid suspension fungicide was also rapid, but required sufficient adjuvant to be present as this process halted upon saturation of the adjuvant droplet with the pesticide. Real

time small angle X-ray scattering was used to probe the solid state of the tebuconazole active ingredient upon transfer into the adjuvant droplet. It was found that dissolution of tebuconazole in the ethyl oleate-based adjuvant but not in the mineral oil based adjuvant is due to the solubility limits of the tebuconazole active ingredient in the adjuvant. This has implications for crop application of any poorly soluble pesticides. It could be argued that dissolution of the active ingredient into an adjuvant emulsion particle would deliver the active ingredient in a more effective manner as it would be delivered dissolved in a lipid rather than as a solid particulate mass. If either insufficient adjuvant is present or a poor choice of adjuvant is selected for use with a pesticide, then there will a greater chance of a less effective outcome upon crop application as the physical properties of the delivered pesticide may prevent effective foliar uptake.

## Conflict of Interest

Andrew Killick and Peter Jones are employees of Victorian Chemicals Pty Ltd., manufacturers of Hasten and Empower brand adjuvant systems

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**Figure Captions:**

**Figure 1**: Schematic representation of possible modes of interaction between pesticide product and emulsion adjuvant

**Figure 2**: Chemical structures of significant components of agrochemical systems studied **1**: clethodim (active ingredient in emulsion herbicide), **2**: tebuconazole (active ingredient in suspension fungicide), **3**: ethyl oleate (major component in EO adjuvant) and **4:** generalized structure for mineral oil, where n is typically >12 (major component of MO adjuvant)

**Figure 3**: SAXS Experimental Set-Up

**Figure 4**: Typical laser diffraction studies of transfer of pesticide to adjuvant. The arrow in each panel indicates the starting peak mean size for the pesticide product before adjuvant addition

**Figure 5**: Kinetics of transfer of agricultural products into adjuvant droplets, measured by the normalized change in intensity of the peak due to the agricultural product, at increasing levels of adjuvant (ratio, v/v)

**Figure 6**: Mixing of components between adjuvants and pesticide products shown by Raman spectroscopy.

**Figure 7**: An example of the partial dissolution of tebuconazole in 3:1 EO adjuvant:suspension fungicide system by changes in diffraction of the crystalline material over time

**Figure 8**: Dissolution of crystalline tebuconazole on addition of adjuvant a. EO adjuvant:suspension fungicide; b. MO adjuvant:suspension fungicide monitored by the change in intensity of the main diffraction peak at q=1.19 $Å^{-1}$

Figure 1

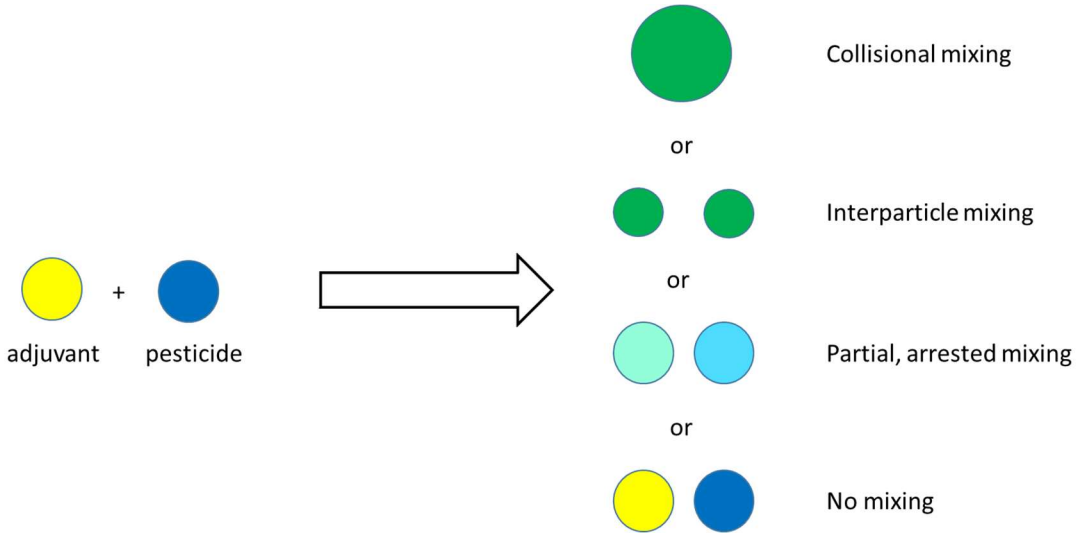
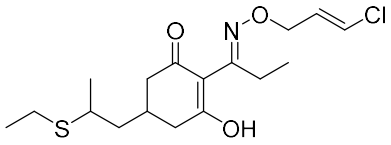
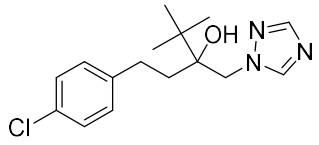

Collisional mixing
or
Interparticle mixing
or
Partial, arrested mixing
or
No mixing
+
adjuvant
pesticide

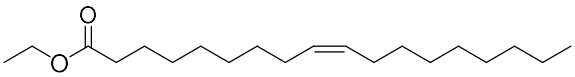
Figure 2




**1**




**2**

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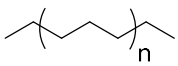



**4**

Figure 3

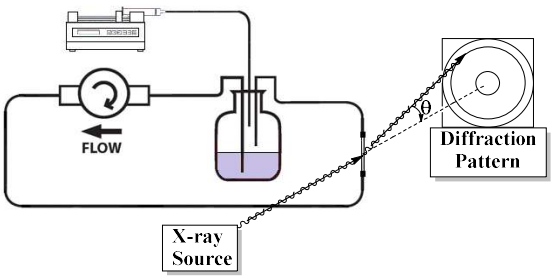


Figure 4

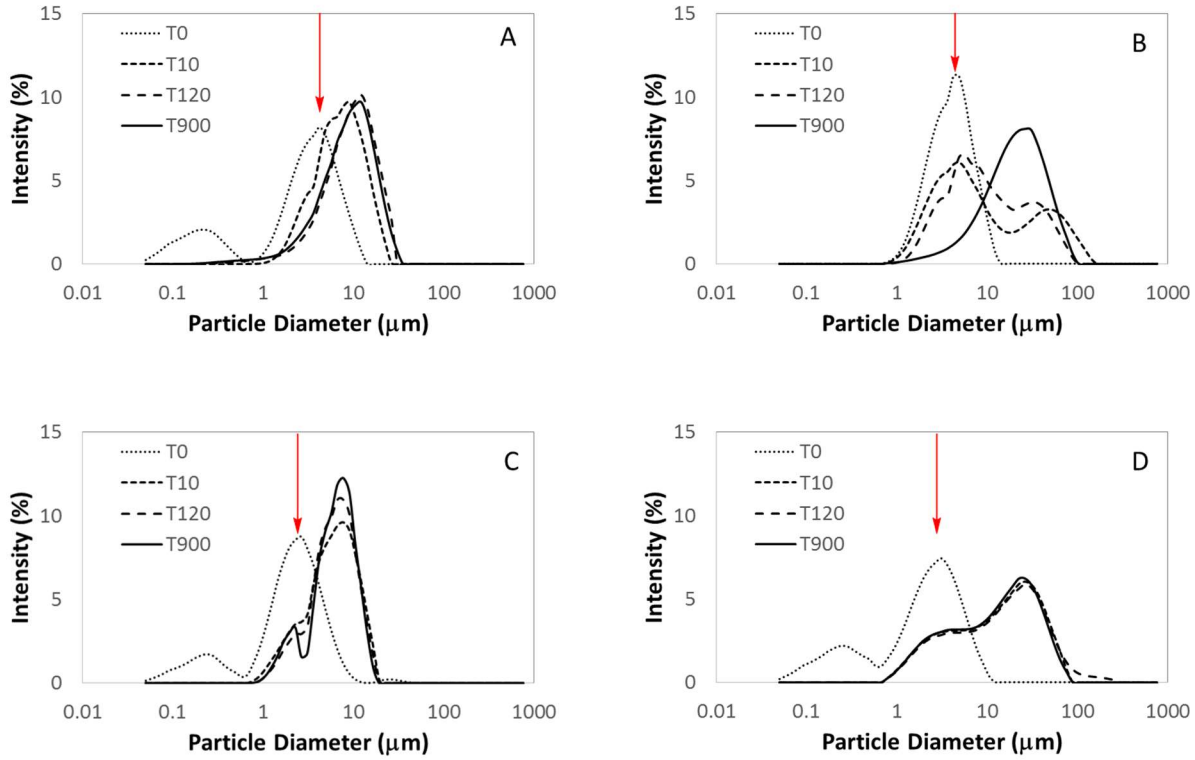

A
B
C
D
T0
T10
T120
T900
Intensity (%)
Particle Diameter (µm)
0
5
10
15
0.01
0.1
1
10
100
1000

Figure 5

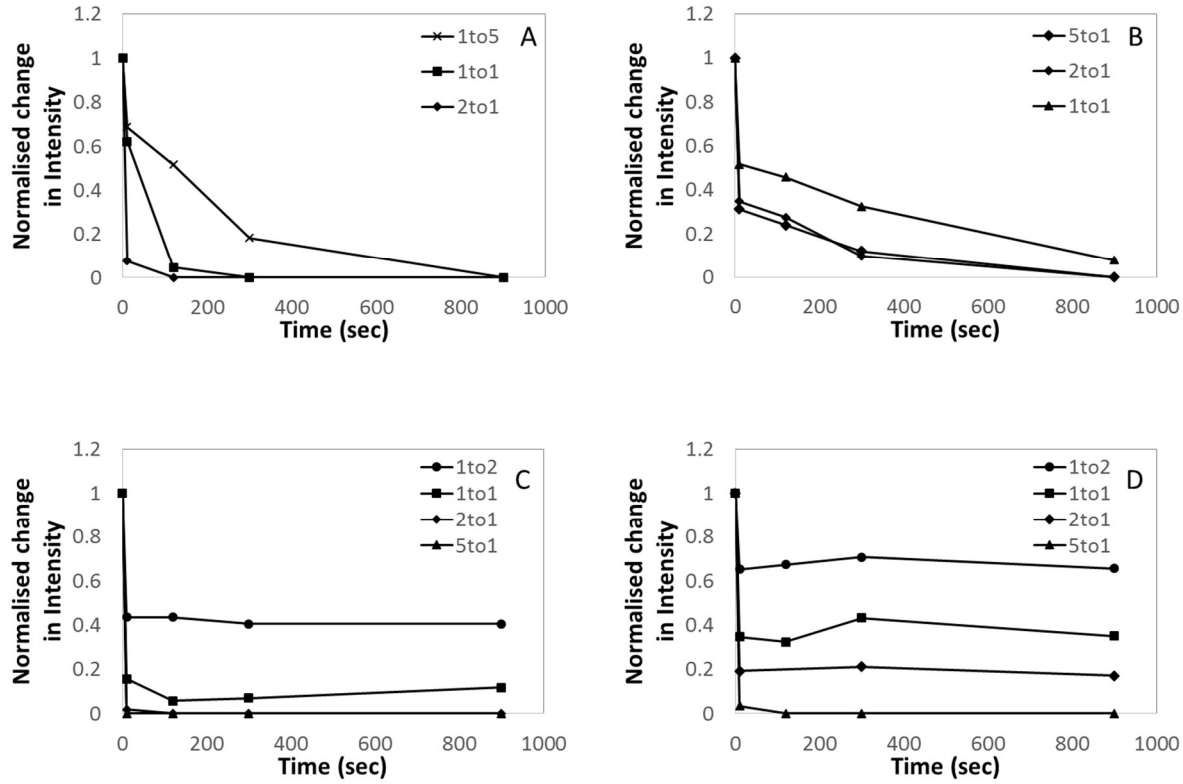

A
1to5
1to1
2to1
Normalised change in Intensity
Time (sec)
B
5to1
2to1
1to1
C
1to2
1to1
2to1
5to1
D

Figure 6

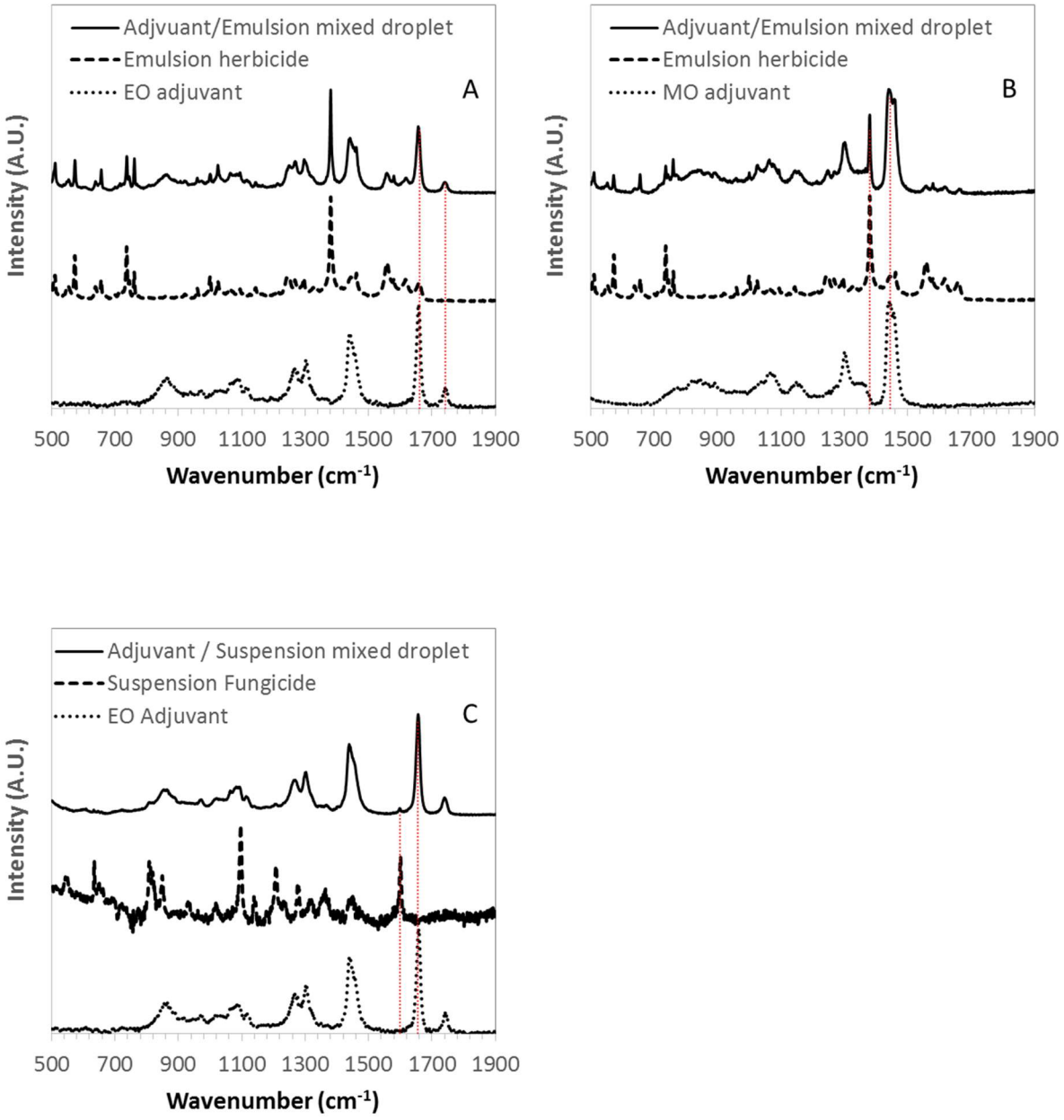

Adjvuant/Emulsion mixed droplet
Emulsion herbicide
EO adjuvant
A
Intensity (A.U.)
500 700 900 1100 1300 1500 1700 1900
Wavenumber (cm-1)
Adjvuant/Emulsion mixed droplet
Emulsion herbicide
MO adjuvant
B
Intensity (A.U.)
500 700 900 1100 1300 1500 1700 1900
Wavenumber (cm-1)
Adjuvant / Suspension mixed droplet
Suspension Fungicide
EO Adjuvant
C
Intensity (A.U.)
500 700 900 1100 1300 1500 1700 1900
Wavenumber (cm-1)

Figure 7

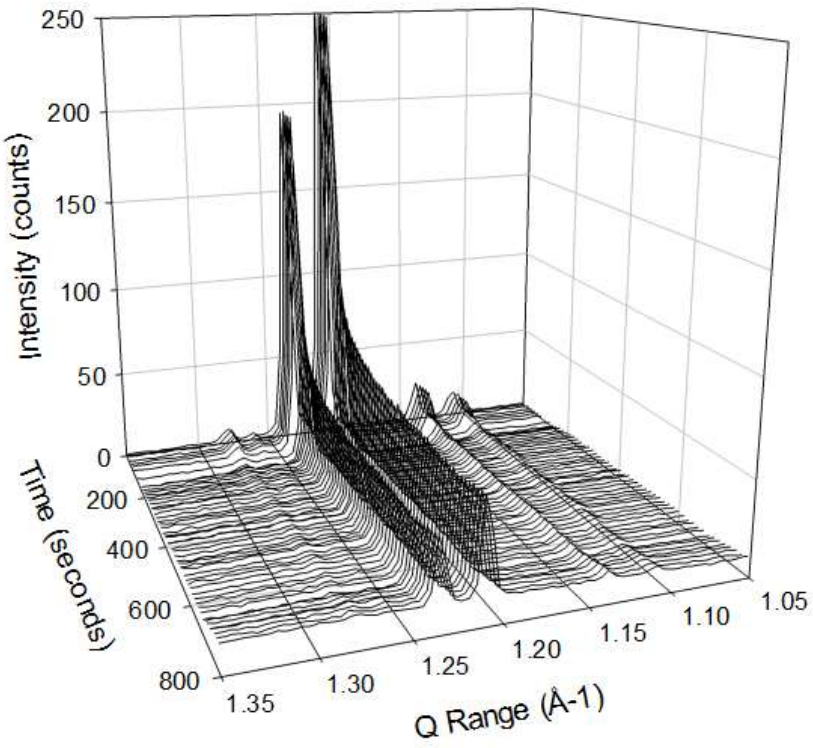
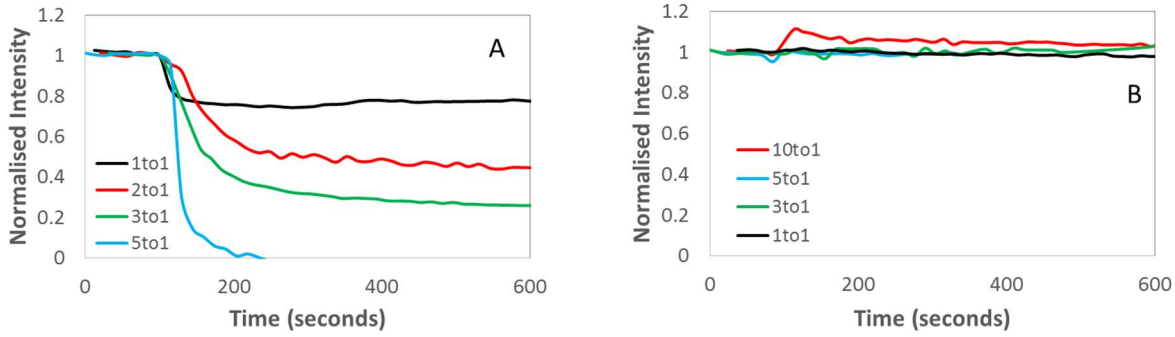
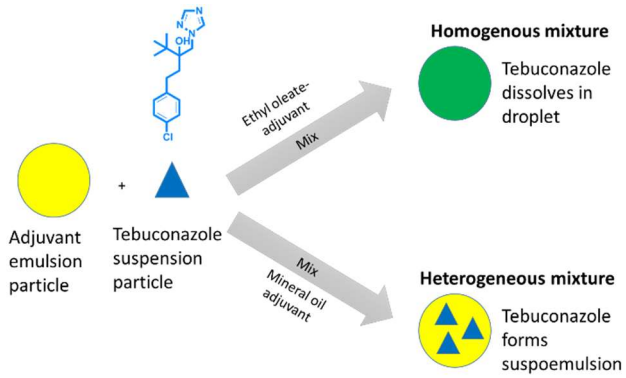

250
200
150
100
50
0
Intensity (counts)
200
400
600
800
Time (seconds)
1.35
1.30
1.25
1.20
1.15
1.10
1.05
Q Range (Å-1)

Figure 8


A
Normalised Intensity
1.2
1
0.8
0.6
0.4
0.2
0
0
200
400
600
Time (seconds)
1to1
2to1
3to1
5to1
B
Normalised Intensity
1.2
1
0.8
0.6
0.4
0.2
0
0
200
400
600
Time (seconds)
10to1
5to1
3to1
1to1

TOC Graphic


Homogenous mixture
Tebuconazole dissolves in droplet
Ethyl oleate-adjuvant
Mix
Adjuvant emulsion particle
Tebuconazole suspension particle
Mix
Mineral oil adjuvant
Heterogeneous mixture
Tebuconazole forms suspoemulsion